CW ELECTRON ACCELERATORS: A REVIEW

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Abstract

CW electron accelerator facilities providing beams with energies from a few hundred MeV to several GeV, high currents (~100 μA), good energy resolution (~10^{-4}), good emittance (~10^{-8} m-r) and polarized beams are presently under construction. They will provide capability for carrying out coincidence experiments over a broad kinematic range. Three basic design approaches are being followed; microtrons, linacs with pulse stretcher ring, and recirculating superconducting linacs. The designs have been optimized to take advantage of existing facilities or for cost in a specific energy range.

I. Introduction

Electron accelerators, operating at "high duty factor" have for the past 20 years made fundamental contributions to our understanding of nucleons and nuclei. Single-arm electron scattering provides us the most precise information on nuclear charge and magnetization densities. The systematic measurement of transition-charge densities allows for definitive tests of nuclear models. Some experiments involving the simultaneous detection of ejected hadrons, at the most favorable kinematics, have also been carried out. Such coincidence experiments can provide much more detail on nuclear structure than is obtained from inclusive scattering. They may in fact be particularly important for understanding the transition from a meson-nucleon to a quark-gluon description of nuclear matter.

To explore in detail some of the suggestive results observed so far requires the development of new and upgraded electron accelerators spanning the range from a few hundred MeV to several GeV. Desirable features include: cw operation, good energy resolution, high current and low emittance. Polarized beams are essential for exploring nuclear spin degrees of freedom. An evolution in accelerator technology has now made the construction of such cw machines practical. The three approaches being exploited include microtrons, linacs with a pulse stretcher ring, and recirculating superconducting linacs. In this review we briefly describe each of these schemes in the context of major construction projects which are presently underway.

II. Microtrons

In a microtron[1] the beam is recirculated through the accelerating structure many (N) times making it a very economic device for cw operation. N is typically in the range of 20 to 90. The path length difference (ΔL) between successive orbits in the microtron, for fully relativistic particles, must be an integral multiple of the rf wavelength (λ),

$$\Delta L = \nu\ \lambda .$$

Particle acceleration occurs off the crest of the rf wave and oscillations occur about a certain stable phase angle. The longitudinal bucket size depends strongly on this angle and is drastically reduced with increasing ν. In practical terms ν = 1 or 2.

The total energy gain is given by

$$E^2 = r\ L\ P\ N^2$$

where r = shunt impedance/unit length, L = length of accelerating structure, P = total rf power and N is the number of passes through the structure. Along with their very energy efficient operation, microtrons allow for the simultaneous extraction of beams with different energies and also have excellent beam quality.

The race track microtron (RTM) is the most common type. The Illinois, NBS and Mainz accelerators are based on such designs. All of the high energy designs are cascade RTM's. The Illinois[2] microtron, which uses a superconducting accelerating structure and was in operation for many years, is presently being decommissioned. The 185 MeV NBS[3] microtron is in an advanced stage of construction. It was originally planned as a cw accelerator prototype for nuclear research. Its new mission is as a free electron laser (FEL) facility.

Emittance growth due to synchrotron radiation and large uneconomical end magnets limits RTM's to an energy of ~1 GeV. Higher order microtrons (multisided polytrons) with two or more linac segments have been designed to overcome some of these difficulties. For example, designers in the Soviet Union have proposed[4] a 4.5 GeV 3-stage cascaded "polytron" (Fig. 1) for the Lebedev Physics Institute at Troitsk. It would have a maximum current capability of ~300 μA and an energy resolution of ~10^{-4}. A first-stage prototype is being constructed in Moscow.

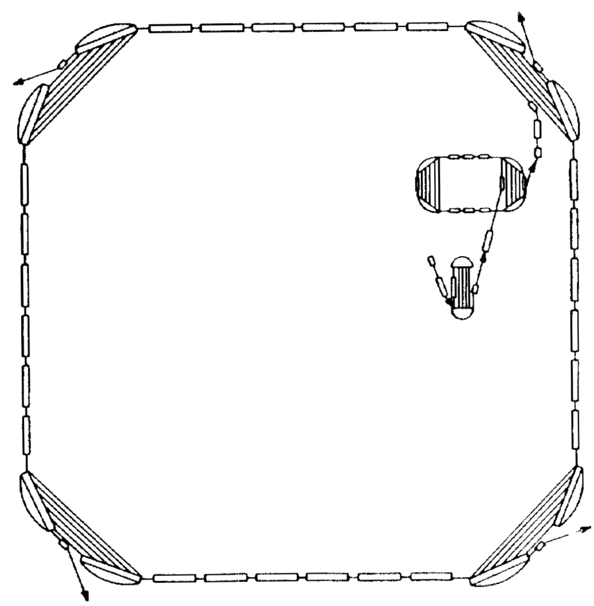

Fig. 1. Schematic Layout of a cascaded polytron, Troitsk, USSR.

MAINZ (MAMI)[5]

A major microtron accelerator construction project is nearing completion at the Institut für Kernphysik of the University of Mainz, FRG. It is designed to produce an 855 MeV, 100 μA beam with ~10^{-4} energy resolution and 100% duty-factor. A beam splitter will allow for the use of three beams simultaneously in the experimental halls.

MAMI consists of a cascade of three normal conducting RTM's. This scheme allows the magnetic flux density and the energy gain per turn to be tailored to provide a dynamically safe and economic approach spanning the energy range from a few MeV at injection to 855 MeV. Table 1 summarizes the design parameters for the accelerator and a plan view is shown in Fig. 2.

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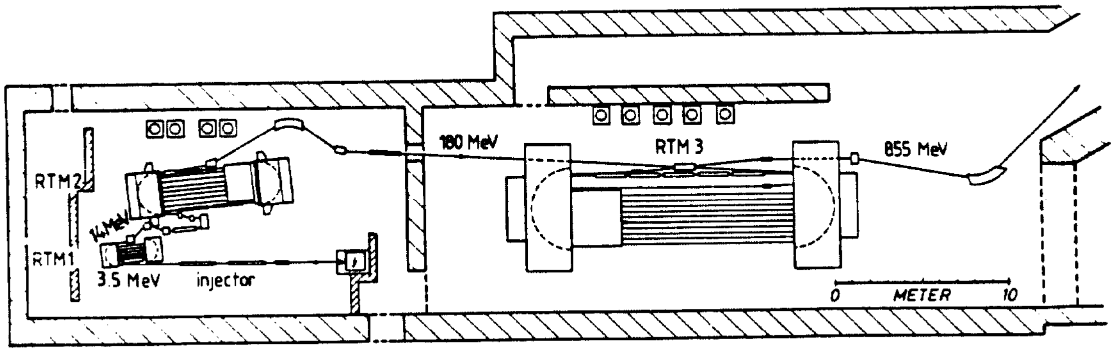

Fig. 2. Plan View of MAMI.

A 3.5 MeV linac serves as the injector for RTM1. Following 18 passes through an 0.8m on-axis coupled biperiodic accelerating structure (modified Chalk River design) operating at 2450 MHz the beam energy is increased to 14 MeV. In RTM2, 51 traversals through a pair of 1.78m accelerating sections operating at 3.24 MeV/turn increases the energy to 180 MeV. In the final stage, RTM3, 90 traversals through a five-section 7.50 MeV/turn linac results in a maximum energy of 855 MeV.

The total cw rf power required at 100 μA beam intensity is 275kW. RF amplitude and phase are feedback stabilized at each klystron. In order to control beam blowup, the higher order mode resonant frequencies are multiply split by changing the relative orientation of the pairs of coupling slots in the accelerating cells along the structure. All beam focusing and beam position monitoring occurs only on the linac axis.

TABLE 1
MAMI Design Parameters

		RTM1	RTM2	RTM3
Flux density	Tesla	0.10	0.56	1.28
Energy gain/turn	MeV	0.60	3.24	7.50
No. of Klystrons	TH 2075	1	2	5
r.f.power at 100μA	kW	9	65	168
No. of turns		18	51	90
Magnet distance	m	1.7	5.6	12.8
Input energy	MeV	3.5	14	180
Output energy	MeV	14	180	855
Emittance at output:				
horizontal	mm*mrad	$\le 0.17\pi$	$\le 0.014\pi$	$\le 0.14\pi$
vertical	mm*mrad	$\le 0.17\pi$	$\le 0.014\pi$	$\le 0.04\pi$
Energy width	keV	18	36	≤ 120
Beam intensity	μA	>100	70	100
		(achieved)		(design)
Injection	100 keV gun and three linac sections, fed by another klystron			
Extraction	from each even numbered return path of RTM3, i.e.in steps of 15 MeV each			

Extraction, in the energy range 180-855 MeV takes place in RTM3. A small inward inflection of the beam in one of the return paths causes the beam to be deflected into the extraction line. This is possible for every second return path, allowing the output energy to be varied in steps of approximately 15 MeV.

In addition to the 100 keV gun, a polarized injector is also under development. Its operation depends upon photoemission from a GaAs crystal surface producing beams with a longitudinal polarization of approximately 40%. A spin rotator, using electrostatic deflection and solenoids, will allow for arbitrary spin orientation at injection providing longitudinal polarization in the experimental areas.

MAMI is in the final stages of construction. The first two stages were completed in 1983 and have operated for some 19000 hours of usable beam for experiments. They are now being reinstalled in the new accelerator hall along with the components for RTM3 The large end magnets for RTM3 have been field mapped and pole face correction coils to meet the required field homogeneity of a few x10^{-4} are being installed. The first 855 MeV beam is expected in 1990.

III. Pulse Stretcher Rings

There are many room-temperature linacs which operate up to a few GeV at relatively low duty factor. They are used with typical pulse durations of 1 to 50 μs and pulse rates of a few Hz to several kHz. Duty factors range from <0.1% to a few precent. Recirculation schemes have been used to increase maximum energy at relatively low additional cost.

The duty factor of a pulsed linac can be increased to more than 85% by injecting the beam into a pulse stretcher ring (PSR)[6] and extracting it in a time uniform manner during the interpulse period. The ring circumference is usually an exact sub-multiple of the injection pulse length. PSR's have been designed which typically involve one-, two- or three-turn injection. Resonant extraction (1/2-integer, 1/3-integer, eg) is used to extract the beam during the few thousand circulations between successive injection pulses.

Pulse stretcher rings are a very cost-effective approach for upgrading electron linacs for essentially cw operation. They can also provide an important new capability for doing internal target experiments. Polarized electrons for both internal and extracted beams are being incorporated in some of the designs. When combined with an energy compression system, at the output of the linac, beam quality (emittance and energy spread) is comparable to the direct cw approach using microtrons or superconducting linacs. Beams of only one energy are possible at a time. Major design issues involve the control of instabilities and achievement of a smooth time structure in the extracted beam.

Operating PSR systems include those at Tohoku, Lund, Saskatchewan, and Bonn.[7] Construction projects for a cw upgrade are now underway at MIT-Bates and NIKHEF-K in Amsterdam.

SSTR, Tohoku[8]

This 150 MeV PSR was the first to be constructed and has been used for experiments since 1981. It is in the form of a regular octagon of 15.5 m circumference. Operating near the 1/3-integer resonance in combination with synchrotron radiation loss drives the extraction process. Extracted beams ~1μA with an energy spread of 0.2% and a duty factor of 80% have been achieved. Fig. 3 shows the layout of the SSTR.

EROS, University of Saskatchewan[9]

It was the earliest proposed PSR, which has just recently been commissioned. The ring has a circumference of 108 m and operates in the range 100 - 300 MeV. Low intensity high duty factor extracted beams have been obtained and a coincidence research program has started. Possibilities for future experiments using internal targets are being evaluated.

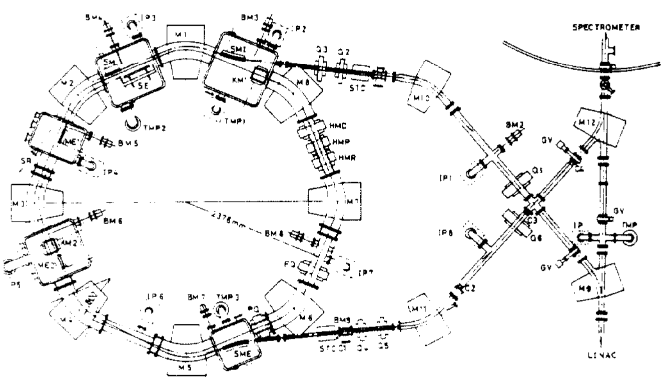

Fig. 3. Layout of the Tohoku SSTR.

NIKHEF- "UPDATE"[10]

The maximum energy of the present 500-MeV, 1% duty factor linac is being upgraded to 900-MeV (unloaded). The PSR will operate with 3-turn injection and an energy compression system in the injection line will be used to reduce the energy spread.

Extracted beams of at least 90% duty factor and a maximum current of 40μA for energies between 150 to 700 MeV (up to 900 MeV at lower currents) are planned. Internal target experiments with up to 200 mA circulating current will also be possible. In this case, multi-turn injection at relatively low peak currents (10mA) will be used.

The project is scheduled to be completed by 1992. Its estimated cost is 12M$.

MIT-Bates South Hall Ring[11]

The South Hall Ring (SHR) under construction at the MIT Bates Linear Accelerator Center will provide high duty factor (cw) electron beams and an internal target capability for nuclear research. It is designed to take maximum advantage of an existing pulsed accelerator-recirculator system. A site plan of these new facilities is shown in Fig. 4.

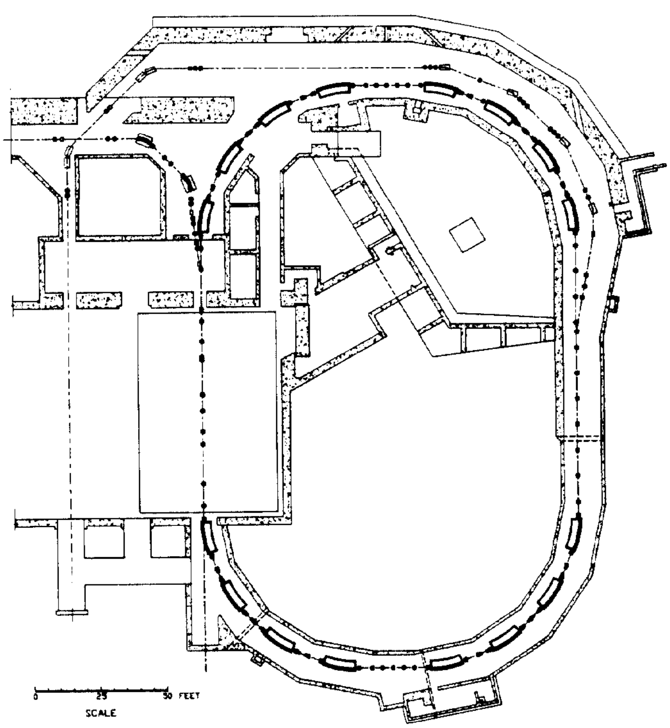

Fig. 4. Site plan showing the Bates South Hall Ring.

The project involves the construction of a pulse stretcher/storage ring, an energy compression system, and the development of an internal target area. An existing set of large magnetic spectrometers and a polarized beam capability make this project cost-effective.

a. South Hall Ring. The South Hall Ring is designed to operate in the energy range of (0.3 - 1) GeV at peak circulating currents up to 80mA and average extracted currents up to 50 μA. Operation is based on repetitive injection of a short (1.3 μs) high peak current (40 mA) pulse followed by time-uniform extraction of the stored beam during the interpulse period. The ring parameters are summarized in Table 2.

TABLE 2
SOUTH HALL RING
Design Parameters

Energy	(0.3-1.0) GeV	
Circumference	190 m	
Dimensions	43x67 m	
Bending Radius	9.14 m	
Circulating Current	40 mA/turn	
Turns	1-2	
Charge Density/Bunch (40mA)	0.90×10^{8} el	
Bunch Length	~23 mm	
Injection Frequency (maximum)	1 kHz	
Revolution Frequency	1.58 MHz	
Betatron Tune, horizontal-ν_x	7.46	
vertical-ν_y	7.80	
Synchrotron Tune		
Average Betatron Function		
Horizontal, $\langle\beta_x\rangle$	8 m	
Vertical, $\langle\beta_y\rangle$	8 m	
Momentum Compaction	.029	
Harmonic Number	1810	
Natural Chromaticities, hor	-14	
ver	-11	
RF Frequency	2856 MHz	
RF Power (CW)	30 kW	
RF Voltage (maximum)	28 keV	
Synch. Energy Loss/turn (1 GeV)	10 keV	
Energy Spread, injection	.04 %	
	0.3 GeV	1.0 GeV
Synchrotron Frequency	28.3	15.8 kHz
Damping Time	2.40	.065 s
Damped Emittance	$.0022\pi$	$.0240\pi$ mm-mr
Damped Energy	.017	.056%
Vacuum	$< 1\times10^{-9}$ torr	
Vacuum Chamber Aperture	60.2 mm	
Internal Target		
Betatron Function, hor	1.0 m	
ver	3.0 m	
Beam size, horizontal 1-turn	±0.18 mm	
vertical	±0.31 mm	
horizontal 2-turn	±0.45 mm	
vertical	±0.31 mm	
Duty Factor	~100 %	
Extraction		
1/2 - integer resonance extraction		
Current (maximum)	50 μA	
Duty Factor	~85%	
$\Delta E/E$	~.04%	
Emittance	$.01\pi$ mm-mr	

This design is based on a technique using two-turn injection followed by half-integer resonant extraction and is capable of operation at injection frequencies up to 1 kHz. Calculations which simulate the extraction process show that it is reasonable to expect an output emittance of ~0.01π mm-mr and duty factors up to ~85%. The internal and extracted beams will be within an energy spread of ±0.02%. These beam qualities are comparable to that expected of microtrons and recirculating cw linear accelerators.

The ring configuration is made up of four 90° bend regions which are connected by four straight sections. The ring circumference is 190 m. The bend regions, which make use of existing surplus dipoles (PPA: ρ = 9.14m) are designed as 2nd order optical achromats. The short straight sections provide an identity matrix match between the bends. The long straight sections are used to adjust the machine tune and to produce a low-β region at the internal target location.

An important consideration in the design of the SHR was the ring circumference. The accelerator single pass beam for energies below 500 MeV is variable in pulse length from (1-20) μsec, so that the required injection conditions, with respect to both pulse length and peak current, are easily met and have been demonstrated. The recirculated beam required for energies above 500 MeV, however, is fixed in pulse length for high peak currents. This pulse length, using head-to-tail recirculation is 1.3 μsec. The 190m circumference ring (0.65 μsec) will be operated with two-turn injection. With a peak current of 40 mA in the accelerator and operating at 1 kHz, this provides a circulating current of 80 mA and an average current of 50 μA in the extracted beam.

Injection into the ring is controlled by fast kicker magnets, and electrostatic and magnetic septa. The beam is injected in the horizontal plane. For one-turn internal target operation it will be possible to inject the beam directly on the closed orbit.

A half-integer resonant extraction technique will be used. During extraction the horizontal tune of the SHR, initially at 7.46, is slowly adjusted towards the 7.50 resonance by means of ramped air-core quadrupoles. An octupole element, operating at constant strength, separates the particle motion in phase space into stable and unstable regions. During extraction, as the stable phase space area is slowly reduced, all the particles eventually become unstable and are extracted.

A relatively low power (30 kW at 1 GeV) RF system operating cw at 2856 MHz will be used in the ring to maintain the injected energy spread (±0.02%) and the mean energy. A relatively large aperture cavity will be used to provide the required accelerating gradient. An alternative approach would use a travelling wave structure. Computer simulation of the multi-bunch, multi-turn transverse instabilities, driven by the excitation of higher order modes in the cavity, has been carried out. The results indicate that beam lifetime limitations set by these instabilities will not interfere with the operation of the PSR. Recent experience with multi-bunch operation at Daresbury, Bessy and LUND with circulating currents in excess of those proposed here gives added confidence.

An instrumentation and control system has been designed which will allow for optimized operation of the ring. Its basic elements include beam position and intensity monitors coupled to steering correctors through a computer-based operating system. It will allow for total control of the closed-orbit and ring tune. Closed-loop feedback systems will control duty factor and emittance of the extracted beam.

Longitudinally polarized electrons will play an important role in the proposed nuclear physics program for both extracted cw beams as well as for the internal target measurements. For extracted beams, the spin in the SHR will be injected and maintained parallel to the guide fields. A combination of successive solenoidal rotations combined with achromatic bends, in the extraction line, is used to reorient the spin longitudinally in the experimental area. Maintaining proper spin orientation for internal target studies is more difficult. Calculations have demonstrated that a resonant snake approach for operation at the "magic" energies of 440 and 880 MeV would be feasible. Indeed much of the physics program can be carried out at these energies. At Bates energies a broadband approach using a Siberian snake (180° - solenoid precession on the opposite side) appears quite feasible.

<u>b. Energy Compression System</u>. For experiments resolving a nuclear final state, it will be important to maintain a very small energy spread on the scattering target. The energy compressor system, located at the output of the accelerator, will be used to reduce substantially the beam energy spread. Proper phasing and amplitude control of the applied RF reduces the injected energy spread by a factor of up to ~15. Calculations predict that our worst case input energy spread of ±0.3% will be reduced to ±0.02%.

Such energy compression techniques have been successfully applied at many of the older generation electron linear accelerator facilities. The system of the Saskatoon PSR, has demonstrated excellent performance with compression factors in excess of 10.

<u>c. Schedule/ Cost</u>. The project was approved for construction in January 1988. Engineering and design efforts are underway for all of the technical components. Building construction has started and will to be completed by January 1990. We expect to commence beam tests by the end of 1991 and a physics program using cw beams would begin in 1992. The total cost of the project is 15M$.

IV. CW Linear Accelerators

The most direct approach for achieving cw operation is a single linac which the beam traverses only once. Room temperature structures would require inordinate amounts of power and as a consequence are impractical. Superconducting linac structures with their very high Q and high shunt impedance reduce the required power to manageable levels. In such designs, more than 99% of the rf power goes into the beam, and only a small amount into the walls.

Superconducting linacs were first proposed in the 1960's and prototype machines were constructed. R&D on accelerating structures has been carried out at Stanford, Karlsruhe, Cornell, CERN, DESY, Wuppertal, Saclay, University of Illinois and KEK. The principal goal is to achieve high energy gradients at high Q. This requires good materials, control of surface defects, clean assembly techniques, and a cavity design which eliminates multipacting and field emission. Transverse breakup modes must be highly suppressed to achieve high beam stability and quality.

In recent years a lot of progress has been made. Accelerating gradients in excess of 5MV/m and Q's in excess of 10^9 are routinely achieved in both laboratories and industry. As a result of this, major new accelerators and retrofitting is underway to take advantage of this maturing new technology.

At a design gradient of 5MV/m, for accelerator designs in the energy range of a few GeV, several recirculations through the accelerating structure are normally used to reduce capital costs. Aggressive counter measures against multipass beam blowup are required since the Q of the superconducting structure is so high. Particular attention in the cavity design is paid to damping these destructive transverse modes to acceptable levels. The recirculation arcs require careful design to minimize emittance growth caused by synchrotron radiation.

In addition to the accelerators discussed here, new designs are also under consideration at Saclay and Frascati.

<u>Recyclotron, Darmstadt</u>[12]

A 130MeV superconducting recirculator is presently under construction at the Institut für Kernphysik, Technische Hochschule Darmstadt. The design is based on some initial research on structures at Wuppertal and advanced further by the Darmstadt staff. The structure is a 1-m long, 20-cell cavity which operates at 3 GHz. The design gradient is 5MV/m and the design Q is 3×10^9 at 2.0 °K. The linac has four cryostats containing two cavities each. The beam makes three passes with an energy gain of 40MeV/pass through the structures.

The injector is operating routinely at an energy of 8.5 MeV. The cryostats of the main linac are presently being commissioned.

HEPL-Recyclotron, Stanford[13]

This was the pioneering attempt aimed at a cw electron accelerator with a maximum energy of 2 GeV. It operates at 1.8 °K at 1.3 GHz and uses a recirculating system. The accelerator operates cw up to 40 MeV and at decreasing duty factors for higher energies (10% at 70 MeV). It has a maximum current capability of 500 μA but the recirculated current is limited to < 100 μA due to multipass beam blowup. The accelerator is now used for FEL research.

Continuous Electron Beam Accelerator Facility[14]

A new laboratory for electronuclear research, the Continuous Electron Beam Accelerator Facility, is presently under construction at Newport News, VA. The state-of-the-art design is based on a recirculating linac concept using superconducting accelerating structures. It is designed to provide cw beams in the energy range (0.5 - 4.0) GeV, currents up to 200μA and an energy spread $< 1 \times 10^{-4}$.

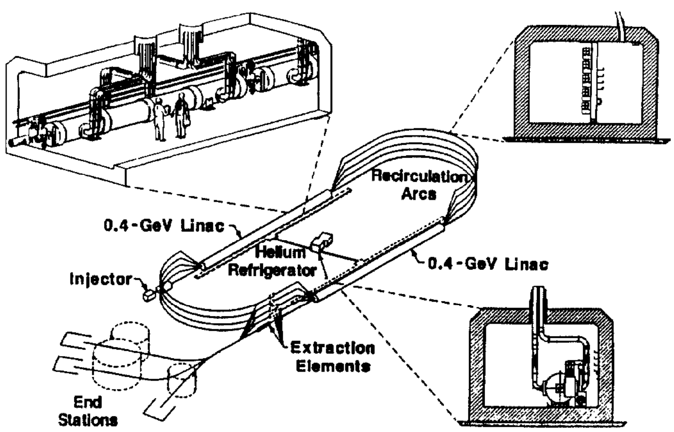

Fig. 5. Schematic representation of the CEBAF five-pass recirculating sc linac concept.

The CEBAF recirculating linac concept is shown schematically in Fig. 5. The race track configuration consists of two superconducting linacs (80 m active length) with nominal energy gains of 0.4 GeV each. These are connected by a five-pass recirculation scheme which has been chosen to minimize overall cost at an acceptable level of complexity.

The superconducting cavities (active length 0.5m) are based on a CEBAF-Cornell design. Each cavity consists of 5-cells operating at 1497-MHz. They are assembled in pairs (Fig. 6) in a cryounit and four such pairs are housed in a common cryomodule. At a gradient of 5MV/m, each linac segment consists of 20 cryomodules. Each cryomodule is connected to its neighbor with a warm section which includes vacuum components, beam monitors (position and current), and magnetic elements (quadrupoles and steering correctors).

The elliptical cavity design has been optimized to have maximum gradient, high Q and damping of higher order modes (HOM). They are operated in π-mode and have a fundamental and an HOM coupler on opposite ends of the beamline. The HOM Q's are damped by up to five orders of magnitude. The cavities are powered by individual 5-kW klystrons which are precisely phase (~1°) and amplitude ($\sim 10^{-4}$) regulated.

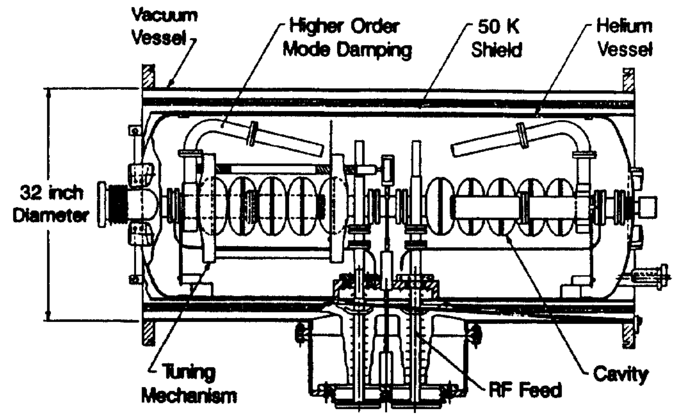

Fig. 6. An assembled pair of CEBAF-Cornell superconducting five-cell cavities in a cryounit assembly.

Prototype cavities have been successfully manufactured by industry. Test results for single cavities and for cavity pairs show that the design specifications can be met reliably for both the gradient and Q values.

The operating temperature of 2 °K was chosen on the basis of cost optimization. The total cooling power of the central helium refrigerator is 4.8 kW, about half of which is due to the rf load.

The recirculating arcs are designed to be isochronous and achromatic. They are vertically separated by a combination of reverse bending spreader and recombiner systems. To provide for a possible future energy upgrade, the recirculation system allows for increasing the number of dipoles.

A multi-beam delivery system is part of the design. The injector creates a beam of three interspersed pulse trains whose individual intensities can be adjusted over a wide dynamic range. An rf-separator (deflecting cavity) in the extraction line allows for simultaneous beam delivery to three end stations. These beams can each have different but correlated energies (multiples of one-fifth the maximum energy). Such a multi-beam capability is very important to the proposed research program.

CEBAF was approved for construction in FY87. Initial technical emphasis was on cavity prototyping and cryostat development. Preconstruction R&D is actively underway in areas such as magnetic elements, magnet measurements, injector and rf separator development, beam diagnostics and control modelling. Some recent progress includes:

- 100 keV injector gun is complete, tested and meets the beam quality requirements.
- central helium liquifier under construction
- accelerator enclosure and recirculator arcs under construction.
- tests on prototype cavities and cavity pairs have exceeded expectations. Prototype cryounits and half cryomodules have been successfully assembled.
- qualified industrial firms have responded to the cavity RFP's. These are being evaluated.

Table 3 summarizes the CEBAF design parameters.

Three large experimental end stations are part of the construction effort. Collaborations are being formed to specify, design and construct the research equipment for each of the experimental halls. An international Program Advisory Committee advises CEBAF management on the feasibility, scientific merit and priority for the proposed physics program.

The schedule calls for 45-MeV beam tests to occur in 1990. Preoperations and subsystem commissioning will continue through 1992. Final commissioning and the delivery of beam to experiments is scheduled for 1994.

TABLE 3
CEBAF Design Parameters

Beam characteristics	
electron energy E [GeV]	$0.5 \le E \le 4.0$
average current [μA]	200
trans. emittance (95%,1 GeV) [m]	2×10^{-9}
energy spread (95%)	1×10^{-4}
duty factor	100% (cw)
simultaneous beams	3
Linac parameters	
concept	superconducting cw recirculating linac
number of passes	5
number of linac segments	2
maximum energy gain per pass[GeV]	0.8
recirculation time per pass [μs]	4.2
focusing	FODO
phase advance per cell (pass 1)	120°
half-cell length [m]	9.6
cavities per half-cell	8
half-cells per segment	20
vacuum (before cooldown) [Torr]	10^{-9}
Cavity parameters	
type	superconducting
frequency [MHz]	1497
electric length [m]	0.5
shunt impedance (r/Q)[Ω/m]	960.0
design gradient [MV/m]	5.0
design Q_0 at 2 K, 5 MV/m	2.4×10^{9}
typical HOM $Q_{external}$	10^{3} to 10^{5}
clear aperture [mm]	70
transverse HOM $Z''T^2$ /Q[Ω/m^3]	$\le 16.4 \times 10^{4}$
loaded Q (fundamental mode)	6.6×10^{6}
Superconducting structures rf system	
number of klystrons	338
klystron power rating [kW]	5.0
phase control	<1°
gradient regulation	$<10^{-4}$
Injector parameters	
gun energy [MeV]	0.10
injection energy [MeV]	45
average current [μA]	200
transverse emittance (at 0.1 MeV) [mm.mr]	1
long. emittance [keV.degrees]	<15π
bunch length [degrees] at 45 MeV	<1.0
pulse capability [μs]	0.05 to 10
Recirculation arc beam lines	
number	9
magnetic radii [m]	5.1 to 30.6
phase advance per period	2 π (5/4)
periods per arc	4
Cryogenic system	
total rf load (2.0 °K) [W]	2050
total heat load (2.0 °K) [W]	2700
system capacity (2.0 °K) [W]	4800
total heat load (45 °K) [W]	8000

The total estimated cost of the project, including contingency and experimental equipment, is 265M$. The yearly operating costs will be approximately 40M$. An on-site staff of 355 FTE will be associated with the accelerator operation and research program. The CEBAF site plan is shown in Fig. 7

V. Summary

The last remaining frontier in accelerator technology, for intermediate energy nuclear physics research, has been duty-factor. There is no additional technological advance in electron accelerators that would have the same impact on the physics as these developments to achieve cw operation. Achieving this goal while maintaining high beam quality, emittance and energy spread, has been the principal objective. We have seen in this review that there are several viable

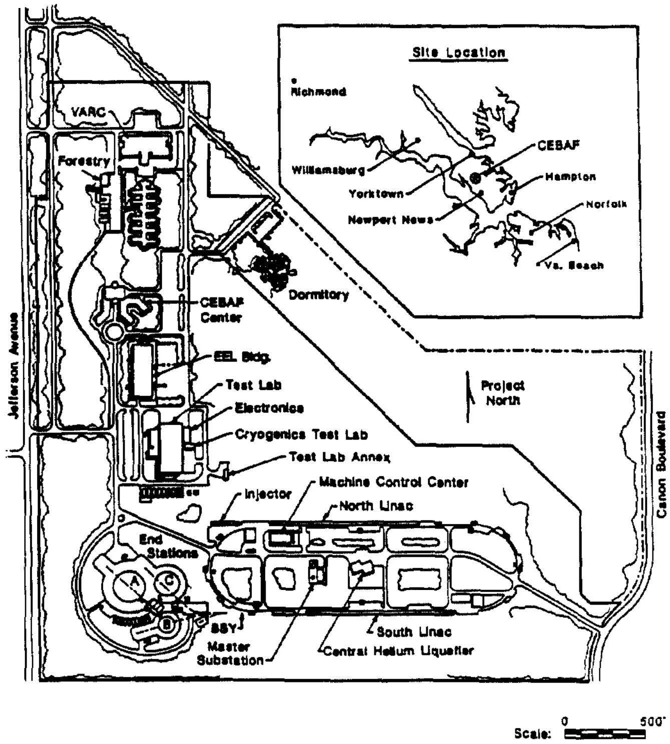

Fig. 7. Site plan of the CEBAF accelerator facility.

approaches which can achieve this over the important energy range from a few hundred MeV to over 4 GeV.

The decade of the 90's promises that for the first time the precise power of the electron probe will be fully exploited in medium energy nuclear physics.

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