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CW ELECTRON ACCELERATORS FOR NUCLEAR PHYSICS

Samuel Penner
National Bureau of Standards
Washington, D.C. 20234

Introduction

In principle, the electromagnetic interaction is the ideal experimental tool for studying nuclear structure because it is weak and well understood. In fact, the study of electronuclear and photonuclear reactions has contributed greatly to our understanding of nuclei. Nevertheless, electron accelerators are relatively little used compared to proton and heavy ion machines, largely because it is difficult to perform experiments with electrons or photons. These difficulties arise from the small size of electromagnetic cross sections, the unavailability of monoenergetic photon sources, and the poor duty cycle of most existing electron accelerators. Recent technological advances have raised the exciting possibility that new types of electron accelerators can be built, at acceptable cost, that will provide high-current, continuous-duty (that is, cw) electron beams, thus alleviating the experimental difficulties mentioned above.

The need for a new generation of electron accelerators has been generally recognized in the US for several years.[1,2] In 1979 the Nuclear Sciences Advisory Committee (NSAC) recommended the construction of a major new accelerator in the US,[3] to provide high current cw electron and photon beams in the 1 to 2 GeV range, as well as other cw accelerators at lower energies. The nuclear physics research that would become feasible with these new accelerators has been examined in a recent workshop.[4] The experiments proposed and evaluated in the workshop serve to define the operating parameters of the new accelerators: Energies from about 100 MeV to several (at least two) GeV are needed. Beam Currents up to ~ 100μA are needed to perform important experiments. Even at 100μA, many experiments will require weeks or months of beam time. Higher currents usually cannot be tolerated by the target and/or experimental apparatus, and therefore multiple simultaneous beams are needed to handle the expected large demands for beam time, in a cost effective way. CW beams are needed because many proposed experiments involve coincidences between two or more reaction products in the presence of large background fluxes. In such cases, the signal-to-noise ratio of the experiment is directly proportional to the duty factor (D) of the beam from the accelerator. Coincidence experiments which are impossible or difficult with present day linacs ($D \lesssim .02$) become feasible or easy with a cw beam. The measure of D which is significant is a macroscopic one; time structure in the beam at frequencies above 500 - 1000 Mhz is not detectable in experimental apparatus having typical coincidence resolving times of 1 - 5 ns.

The problem faced by the accelerator designer in satisfying the need for cw electron beams is easily seen from the power balance equation for the classical electron linac, which has been the preferred machine type for electrons for over 20 years:

$$P_{rf} = \frac{DE^2}{RL} + P_{beam}. \qquad (1)$$

In equation (1), P_{rf} is the total time average rf power supplied to the accelerator, E is the accelerator energy gain, L is the accelerator length, R is the rf structure shunt impedance per unit length, and P_{beam} ($= E \cdot I_{ave}$) is the beam power. There are practical problems associated with the rf power that can be handled per unit length of the structure and the maximum energy gradient that can be attained, but the real significance of equation (1) is that the construction cost of a linac contains large terms that are linear in P_{rf} and in L (the two terms being roughly equal at optimum), and the operating cost per year contains a large term linear in P_{rf}. These cost considerations make it prohibitive to build and operate a conventional electron linac with duty factor greater than a few percent.

The first serious attempt to circumvent the duty factor limitations implied by equation (1) was the effort at Stanford University to replace the conventional disc-loaded travelling wave OFHC copper accelerating structure ($R \sim 40 M\Omega/m$ at S-band frequencies) by superconducting rf structure,[5] thus increasing R by several orders of magnitude so that $(E^2/RL) << P_{beam}$. This approach has not proven to be completely successful because the originally-envisioned energy gradients of 20 - 40 MeV/m have not been attained in practice. In CW operation, the Stanford superconducting accelerator achieves energy gradients of about 2 MeV/m,[6] and 5.5 MeV/m has been observed in test sections.[7] With these gradients, and considering the high unit cost of superconducting rf structure with its associated cryostat and helium refrigerator, high energy superconducting linear electron accelerators remain unreasonably expensive.

The major cost items, P_{rf} and L, can be reduced very substantially by using one accelerating section repeatedly. If the beam is circulated N times through an rf section with energy gain E/N, equation (1) becomes

$$P_{rf} = \frac{DE^2}{RLN^2} + P_{beam}. \qquad (2)$$

Clearly, recirculation results in a substantial saving in rf power even though it is not feasible to reduce the accelerating gradient (E/LN) arbitrarily. Several recirculation methods are feasible for CW electron machines, including the race-track microtron[8] (RTM) and variations thereof, and a class of accelerators in which the (N - 1) return paths are essentially independent as in the Stanford superconducting recyclotron (SCR).[6] Either type can employ superconducting or room temperature accelerating sections. In the room temperature case, improvement in the shunt impedance remains a high priority consideration. At S-band frequencies, $R \simeq 100 M\Omega/m$ appears feasible with disc-and-washer standing wave rf structure,[9] an increase by a factor of ~ 2.5 compared to conventional disc-loaded travelling-wave structure.

An alternative approach to obtaining high duty cycle uses a low-duty cycle accelerator as an injector into a storage ring which functions as a pulse stretcher. The beam is extracted continuously between pulses of the injector thus achieving a duty factor near 1.0. The pulse stretcher approach appears most advantageous for a laboratory with an existing (pulsed) accelerator suitable for injection service.[10] However, this type of machine has recently been proposed for a laboratory without an existing injector,[11] although a recent comparative study[12] has shown that a recirculating type accelerator would be significantly less expensive for energies up to at least 2 GeV.

A very lively debate is underway at present between the proponents of the various types of cw electron accelerators, especially for the energy region around 2 GeV. In the body of this report, we present a survey of the several types of CW electron accelerators which are being built or have been recently proposed, and attempt to give an unbiased view of the advantages and disadvantages of each type.

Recirculating Accelerators

Race-track Microtron

The classical microtron[13] employs a uniform magnetic field so that successive orbits are circular, with a single accelerating cavity located at their point of tangency. This configuration is not suitable for high-energy CW applications because of limitations on the energy gain and rf power dissipation in the cavity, among other considerations. These limitations are eliminated by splitting the guide-field magnet into two equal halves, allowing the insertion of an accelerating section of arbitrary length, as shown in figure 1. As in the classical microtron, the circumference of successive orbits in the race-track microtron must increase by an integral number of rf wavelengths. This resonance condition is expressed by the relation

$$\frac{2\pi}{c}\,\Delta V \cos\phi_r = \nu\lambda B, \qquad (3)$$

where ΔV is the energy gain of an electron which traverses the accelerating section at peak rf phase, λ the free-space rf wavelength, ν an integer, B the value of the (uniform) magnetic field in the two end magnets, and ϕ_r the resonant phase. It can easily be shown that acceleration in the RTM is stable against small perturbations in the particle phase and energy if

$$0 < \phi_r < \tan^{-1}\left(\frac{2}{\pi\nu}\right). \qquad (4)$$

(Our sign convention is $\phi_r > 0$ for particles traversing the section after the time of peak electric field.)

A crucial point in the design of an RTM is the elimination or compensation of the vertical focussing associated with traversal of the fringing field regions of the end-magnets.[14] Numerical simulations have shown that this can be accomplished with very little growth in the transverse or longitudinal emittance of the beam due to geometrical or chromatic aberrations in the optics. Transverse focussing of the beam is obtained by quadrupole magnets located either (or both) on the common axis containing the accelerating section or the individual return paths. In the former case the focussing necessarily grows weaker as the energy increases, resulting in a larger beam size than in the latter case, which, however, introduces undesireable transverse-longitudinal coupling (since the beam is dispersed in energy on the return paths).

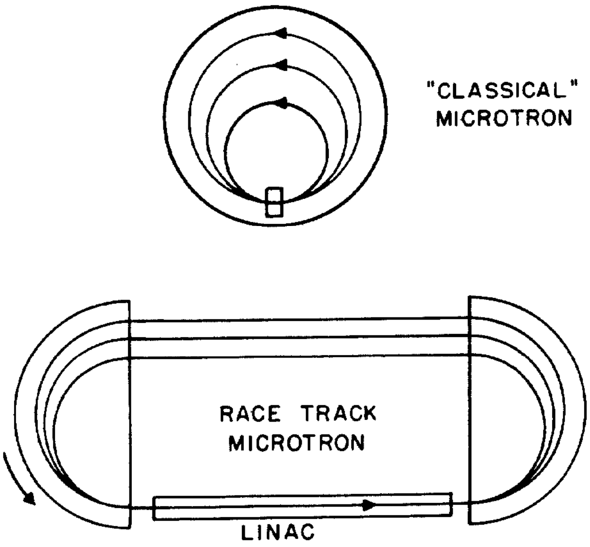

Figure 1

In the RTM, as well as all other recirculating accelerators, the beam stability criteria which are well known for more usual cyclic accelerators are applicable. Even though the number of circulations is small, the stronger tune resonances must be avoided. The RTM is normally a weak focussing machine, operating in the tuning range $1.0 < Q_x < 1.5$ and $0 < Q_y < 0.5$ where Q_x and Q_y are the usual betatron tune parameters for the horizontal (orbit plane) and vertical planes, respectively.

The first operating CW RTM was MUSL-1 at the University of Illinois. Using a superconducting accelerator section it achieved an energy of about 19 MeV in 6 passes by 1972.[15] It was superceded by MUSL-2, which uses a Stanford-type (6 meter, 12 MeV/pass) accelerating section,[6] achieving energies up to 66 MeV in 6 passes, with stable and reliable performance.[16] However, the beam current in MUSL-2 is limited to about 0.5 μA in 6 pass operation by a "beam blowup" phenomenon which is a potentially serious problem in all recirculating electron accelerators, and particularly severe in those which use superconducting accelerating sections. The first (and as yet, only) CW RTM to employ a room temperature accelerating section is MAMI-1, the first stage of the Mainz project.[14] In operation since spring 1979, MAMI-1 now achieves 14 MeV in 20 passes with beam currents approaching 100 μA.[17] There is no evidence of beam blowup. Several other CW RTM's are in the planning or construction stage, as listed in Table I.

Double-sided Microtron

The RTM appears to be an excellent choice for energies up to 500 - 800 MeV, from consideration of both costs and performance. However, it does not scale well for higher energies. The stringent requirements on magnetic field uniformity[14] limit the end-magnet fields to 1.5 or 1.6 Tesla (for non-superconducting magnets[18]). In the geometry of the RTM, at constant B, the weight of the end-magnets increases as E^3, becoming excessive for energies above about 800 MeV. The size of the RTM magnets can be reduced by a large factor (~ 7 for a machine of the same energy) by replacing each end-magnet by a pair of uniform-field quadrant magnets. Since this results in all return orbits being coincident on the path parallel to the accelerating section it seems natural to use a second accelerating section, as shown in figure 2. The resulting accelerator configuration has been dubbed the "bicyclotron" by K.H. Kaiser who has studies its optics in detail.[19] We prefer to call the device a double-sided microtron (DSM) because it uses uniform magnetic guide fields and must obey a microtron-like synchronism condition:

$$\left(\frac{\pi-2}{c}\right) \Delta V \cos\phi_r = \nu\lambda B. \qquad (5)$$

The symbols here have the same meaning as in equation (3), with $\Delta V \cos\phi_r$ being the resonant energy gain for

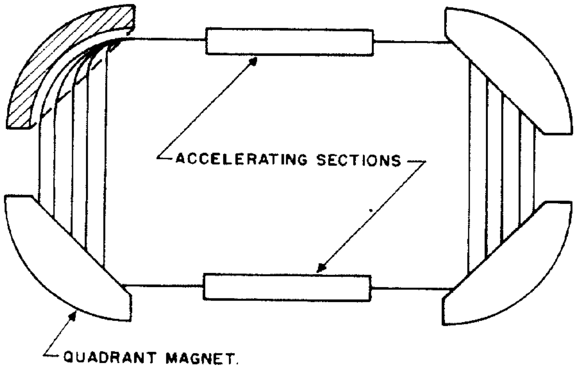

FIGURE 2. DOUBLE SIDED MICROTRON

a full circulation. For the same values of ν, λ, and B a DSM requires an energy gain per pass 5.5 times as large as an RTM. This is not necessarily a disadvantage at high energies where an RTM would require a very large number of return paths and be subject to large beam loading effects at high currents.

The phase stability criterion for a DSM is

$$0 < \phi_r < \tan^{-1}\left(\frac{4}{\pi\nu}\right), \qquad (6)$$

which should be compared to equation (4) for the RTM. The DSM has a very large longitudinal phase-space acceptance, some twenty times larger than an RTM with the same ν, λ, and B.

The greatest disadvantage of a DSM is the strong vertical defocussing forces at the field boundaries of the quadrant magnets. The seriousness of this effect can be reduced by appropriate shaping of the magnetic field near the pole edge[19] and injecting into the DSM at relatively high energy, say 200 MeV for a 2 GeV DSM. (An RTM with the same rf frequency would be a suitable, cost effective injector.) Even with the use of a high injection energy, the magnet-edge defocussing must be compensated with quadrupoles on the short sides of the machine where the return paths are separated. Although it adds complexity, the strong focussing tends to reduce magnet costs by reducing aperture requirements, to decrease growth of transverse beam emittance due to geometrical aberrations, and to increase the beam-blowup threshold current of the machine. Studies of DSM designs are in progress at Mainz[19, 17] and Argonne.[12]

Independent Return-Path Accelerators

Recirculation can be achieved with a set of return paths which are essentially independent, as in the Stanford SCR.[6] We consider such machines to be conceptually distinct from the microtron (RTM and DSM) because they do not use common uniform-field bending magnets and do not obey a microtron-like synchronism relation like equation (3) or (5). Of course, the requirement that the circumference of successive orbits differ by an integer number of wavelengths remains, but the integer need not be a constant for all orbits, and could in principle be zero or negative. In addition to removing the restrictive connection between energy gain per pass and magnetic field, an independent return-path (IRP) recirculation system may reduce the cost of the magnets (due to a large decrease in magnetic-field volume) and allows much greater freedom in the optical design. In particular, the transit time per circulation can be made isochronous with respect to all transverse phase-space coordinates,[20] which is not the case in a microtron.

The Stanford SCR, the only existing machine of the IRP type, has been in operation for several years. It has recently demonstrated a beam current of 7.5 µA (average) in 4 pass operation at 155 MeV (with D = 0.75).[21] In common with other recirculating CW electron accelerators, the SCR exhibits excellent beam quality.[6] The emittance of the beam is very small, with little emittance growth during recirculation. The energy spread of the accelerated beam is about 2 parts in 10^4 (FWHM). Like other recirculating machines using superconducting rf accelerating structures, the current obtainable is significantly restricted by beam blowup.

Multiple Beams

Since recirculating accelerators (at least those not using superconducting accelerating structures) can be built to efficiently produce beam currents much higher than most nuclear physics users can tolerate, there is great scientific and economic benefit in being able to deliver multiple simultaneous beams. It is straightforward to split an extracted beam by means of a subharmonic rf splitter. For example, a third subharmonic rf deflector can provide three spatially separated beams. Because of the small transverse phase space of the beam, the splitter has to provide deflection angles of less than one milliradian, if followed by a drift distance of several meters and some sort of electrostatic or magnetic septum. If the fundamental rf frequency is in the S-band (2400 Mhz), the split beams would have a frequency of 800 Mhz, which would still be effectively continuous for most nuclear physics experiments. It appears feasible to have independent control of the currents in the multiple beams by subharmonic chopping in the injector system,[22] but independent control of the energy of the simultaneous beams is less straightforward. An ingenious scheme for providing three simultaneous beams with different energies has been suggested by C. P. Sargent as part of a design study for a 2 GeV CW machine using IRP recirculation.[23] The electron bunches in successive rf buckets are modulated in energy by a small subharmonic rf accelerating section before the beam is injected into the recirculator. Because the longitudinal emittance of the beam is very small compared to the acceptance of the accelerator, the modulation in longitudinal phase space is preserved during acceleration. It is then possible to extract the modulated beams selectively by turning on an electrostatic septum at a point where the momentum dispersion is large, the beam size small, and the phase of the synchrotron oscillation suitable. (Note that the longitudinal tune of all types of recirculating accelerators is typically near $Q_z = 0.25$, i.e. a synchrotron oscillation period of four passes.) A similar scheme can probably be used in a DSM, but probably not in an RTM because its longitudinal phase space acceptance is too small.

Beam Blowup

The blowup phenomon which limits the current in recirculating accelerators is caused by an interaction between the beam and certain (presumably TM_{11}-like) rf modes of the accelerating structure. The transverse magnetic field of such modes is maximum on the accelerator axis and deflects the beam. Energy is transferred between the beam and the mode via the axial electric field, which has a node on the axis of the structure, and a linearly increasing amplitude for small displacements from the axis. Energy is dissipated from the mode at a rate inversely proportional to the quality factor, Q, of the mode. Above some threshold current, I_s, the rate of dissipation will not be large enough to damp an initial perturbation, and the deflection amplitude will grow until the beam is lost from the machine. Several numerical simulations[24] have led to a reasonable qualitative understanding of beam blowup. In summary, the main findings (most of which seem obvious) are: (1) I_s can be increased by increasing the (transverse) focussing strength, the injection energy, and/or the accelerating gradient. (2) For reasonable focussing conditions, I_s is inversely proportional to the number of circulations (N). (3) The most dangerous potential blowup modes are those whose frequency is related to the fundamental accelerating frequency as the ratio of any two small integers. The last finding offers little hope of an easy cure, since any multi-cavity rf structure will support many TM_{11}-like modes over a wide band of frequencies. Perhaps the most effective means of increasing I_s is to decrease the Q of the blowup modes by external loading.[25] This has proven to be effective for the superconducting machines, but may not be necessary for machines using room temperature accelerating structure even for beam currents of several hundred microamperes, because of their inherently lower Q's.

Survey of Projects

Table I lists all CW electron accelerator projects using recirculation techniques, whether operating (O), under construction (C), or in an active planning stage (P). The basic machine types, RTM, DSM, and IRP, are defined above. The symbols (SC) or (RT) after machine type indicate whether the accelerating structure is superconducting or room temperature. Maximum energies, E, number of passes, N, and maximum currents, I, are design values if in parenthesis. For operating machines, the E, I, and N numbers were achieved simultaneously at duty factor, D = 1.0 unless otherwise indicated.

Pulse Stretcher Systems

System Design

A nearly-cw electron accelerator can be built by combining a conventional low duty factor linear accelerator with a storage ring. The beam injected into the ring from the linac during one linac pulse is extracted from the ring during the interpulse time, thus achieving a duty factor very close to unity. The linac peak current, I_p, and duty factor, d, are related to the (time average) total current extracted from the ring by $I_{ave} = I_p \cdot d$, ignoring beam losses at injection and extraction. These losses can and must be held to a small fraction of the total beam power. For an accelerator system of 2 GeV with capability for three simultaneous beams of 100μA each, the necessary linac parameters are within the range of present experience, e.g. I_p = 300 ma at d = 1.0×10^{-3}, with a beam power (for full-energy injection) of 600 kW. The peak current, pulse length, and repetition rate are selected to optimize system cost and performance. The electrical efficiency of the linac increases with the pulse length (due to the rf filling time of the waveguides). However, a pulse length equal to or less than the circumference of the ring is needed for single-turn injection which is desirable because of the reduced transverse beam emittance compared to multiturn injection. The peak current in a linac is limited by a beam breakup effect which is well-understood and predictable to reasonable accuracy.[26] Existing technology is adequate for building the linac for a pulse-stretcher system. There may be economic advantage in using high shunt impedance standing wave rf structures instead of the conventional travelling wave structures, although the potential cost saving is not as dramatic here as in the cw case.[27]

Table I. Recirculating CW electron Accelerators

Lab	Machine Type	Status	E, MeV	N	I, μA	Remarks
Stanford	IRP(SC)	O	155	4	7.5	D = 0.75
		P	(300)	(5)		
Illinois	RTM(SC)	O	66	6	<1	MUSL-2
	RTM(SC) or DSM	P	(≥450)	(~30)	(10)	MUSL-3, injected from MUSL-2
Mainz	RTM(RT)	O	14	20	~100	Stage I
	RTM(RT)	C	(175)	(51)	(100)	Stage II, Injected from I
	DSM(RT)	P	(1250)	(27)	(100)	Stage III, injected from II
NBS-LASL	RTM(RT)	C	(185)	(15)	(550)	
Darmstadt-Wupperthal	IRP(SC)	P	(130)	(3)	(20-30)	
Montreal	RTM(RT)	P	(200)	(26)	(200)	
Argonne	DSM(RT)	P	(2000)	(40)	(300)	Multiple beams
MIT-Bates	IRP(RT)	P	(2000)	(14)	(300)	Multiple beams at different energies

The design requirements on the ring itself do not appear difficult to meet. In many ways, it is a simpler machine than a true storage ring: depending on machine energy and the extraction method chosen, the ring may not need an rf system; the circulating current (equal to I_p of the linac in the case of single-turn injection) is within present experience; vacuum requirements are greatly relaxed. The main technical problem in the design of the ring is to achieve uniform continuous multiple beam extraction with very small energy spread in the extracted beams. The most promising method appears to be the use of resonant extraction as illustrated in figure 3, which shows the motion of particles in transverse phase space for a machine tune near a 1/3 integer resonance. Particles lying within the triangle of stability follow bounded orbits. Orbits outside the stability limit are unbounded. The area of the triangle of stability is proportional to the square of the tune difference from the resonance. If the tune is brought closer to resonance, more particles will fall outside the stability limit and be extracted. The tune variation could be obtained by making the tune energy-independent and varying the tune with pulsed quadrupoles, but a better method appears to be the use of an energy-dependent tune (non-zero chromaticity).[11] The stability triangle shrinks with decreasing particle energy. Thus as electrons lose energy by synchrotron radiation, they move outside the stable region and enter an extraction channel. This method requires no pulsed components (except for injection) and, over a wide range of energies, no rf system in the ring. Extraction is made to occupy the full interpulse time of the injection linac by matching the energy spread from the linac to the rate of energy loss from synchrotron radiation. A good match ($0.3\% \leq \Delta E/E \leq 2\%$) can be achieved for beam energies in the range of roughly one to two GeV. The range can be extended downward by the use of a wiggler. To extend the energy range upward requires rf in the ring. This extraction method is readily adaptable to producing three simultaneous beams due to the threefold symmetry of the stability region near a 1/3 integer resonance: one simply uses three extraction septa located 120° apart in tune space. This method reduces the energy spread of the extracted beams significantly compared to the energy spread of the linac beam, but obtaining an energy spread much below $\Delta E/E = 10^{-3}$ appears difficult,[11] Another question is the time dependence of the extracted beam current. Uniformity requires precise control of both the energy distribution and the transverse phase space of the injected beam. Uniformity is important because the effective duty factor (for a two-fold coincidence measurement) is inversely proportional to the time average of the square of the instantaneous beam current.

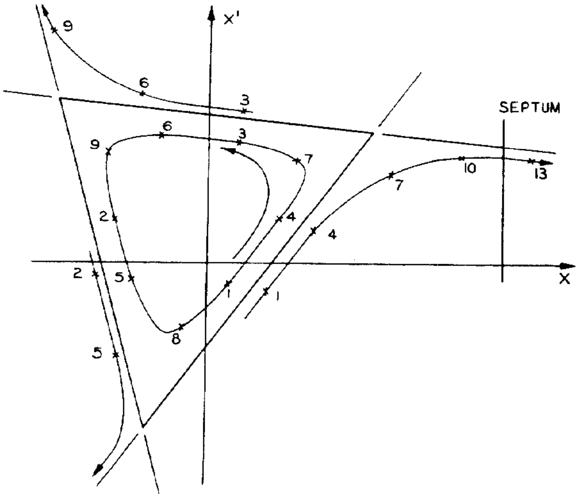

Figure 3

Survey of Projects

Table II lists all cw accelerator projects using the pulse stretcher method. There are no operating machines of this type. Only one, the Lund machine,[28] is presently under construction. Unlike the other projects listed, it uses a pulsed race-track microtron as an injector, and accelerates in the ring after injection. The other projects listed are in the design or proposal stage, and specific data is limited. In addition to published information,[11,28] we have used recent private communications for which we thank M. Eriksson (Lund University), B. Aune (Saclay), Y. Torizuka (Sendai), and C. Guaraldo (Frascati).

Conclusions

By way of conclusion, we will attempt to identify the advantages and disadvantages of the several possible cw machine types. Our discussion will be aimed primarily at machines designed for beam energies at or above one GeV. Clearly this discussion is at least partly speculative, because no accelerator has been built with performance at all close to what is needed.

The first point to be considered is general feasibility. Here the pulse-stretcher type systems have a clear advantage in that they are based entirely on existing, well understood technology. We can expect them to perform as calculated. In the case of machines using recirculation, existing experience is confined to rather low energies and currents. The existing machines give us a fairly high level of confidence in the performance of future machines with respect to energy spread, emittance and stability, but the current limit in recirculating machines due to beam blowup is still an open question. It does seem clear (although the opinion is probably not unanimous) that superconducting rf structures are not a good choice for high-current cw electron accelerators.

Assuming that both pulse stretcher systems and recirculating machines are generally feasible, and capable of the required beam current, the two types of machines can be compared on their merits, economic and technical.

Capital Cost

A comparative study[12] of the cost of a 2 GeV linac and ring system compared to a double-sided mictrotron showed the DSM to have a lower capital cost by 40%. Since other estimates of costs of the two types of machines are in reasonable agreement with reference 12, this conculsion seems reliable. For a 2 GeV machine, the cost difference would be of order $10 million.

Operating Cost

If the high shunt impedance standing-wave rf structures now being developed perform as expected, a recirculating machine will use significantly less electrical power than a linac-ring system. The difference at 2 GeV is probably of order 1 MW or roughly $250K/year at present electrical rates. Probably more important for total operating cost is the absence of high peak power (klystrons or modulators) in a recirculating machine. This should reduce maintenance and staffing costs significantly.

Table II. Stretcher Ring CW Accelerator Projects

Lab	E, MeV	rf in ring	Remarks
Lund	100-500	yes	Multipurpose machine. See reference 28
Saclay	1500-2000	undecided	Upgrade existing 600 MeV linac as injector
Sendai	1500	yes	
Frascati	1100	no	Multipurpose design including true storage ring operation to 3.5 GeV and monoenergetic photon beams from backscattering of laser light
Southeastern Universities Research Association	2000	above 2 GeV	Expandable to 4 GeV. 3 beams

Higher Energies

If energies much above 2 GeV are needed, the linac-ring system has a clear advantage since the technology scales to any energy, and only the cost of rf in the ring, to supply the power for synchrotron radiation, increases faster than linearly with energy. The cost of a recirculating machine will be dominated by rapidly increasing magnet costs for higher energies. The Argonne study[12] indicates that a DSM costs more than a linac-and-ring system at energies above about 3 GeV.

Beam Energy Spread

This is probably the most important performance criterion for nuclear physics applications. Experimental results[6] as well as several calculations[12,14,22] show that $\Delta E/E \simeq 10^{-4}$ (FWHM) is attainable in recirculating machines. For a linac-ring system[11] it appears difficult to obtain an energy spread much below 10^{-3}.

Multiple Beams

Both types of accelerators are capable of delivering multiple simultaneous beams. In the case of stretcher-ring systems, the multiple beams are necessarily all of the same energy. For recirculating designs, simultaneous beams with independently selectable energy may be feasible.

Emittance

Most studies indicated that recirculating type machines should have better transverse emittance, by a factor of 2 to 10. The performance and costs of beam transport systems and spectrometers should improve as the emittance decreases.

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