LINACS FOR MICROTRONS AND PULSE STRETCHERS

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Abstract

For many applications, continuous (CW) beams of electrons are strongly preferred over the low duty cycle beams available from RF linacs. The two preferred methods for realizing high-energy CW beams are (1) a pulsed linac followed by a pulse-stretcher ring, and (2) a recirculating CW accelerator. In both methods, a high performance electron linac is required. Recent advances in the technology and understanding of standing wave structures appear to make them preferable to travelling wave linacs for the pulse-stretcher method. Recirculating linacs, whether of the racetrack microtron type or some other topology, are built with CW standing wave linacs. Both room temperature and superconducting structures have been used. Recent exciting advances in superconducting structures make them the structures of choice for high energy CW electron accelerators.

Introduction

Over the past several years, the goal of increased duty factor of high-energy high-current electron beams has been vigorously pursued. For a laboratory with an existing "conventional" RF linac, a straight-forward approach is to add a pulse-stretcher ring to the facility.[1] In the absence of this favorable starting position, a superior approach appears to be an accelerator system which produces a continuous-wave (CW) beam "from the beginning." A purely CW device should have superior beam quality for two major reasons. First, for a given average current the injector system beam quality will be best for a CW device because both the space-charge forces (proportional to peak current), and the electron gun emittance (proportional to square root of peak current for a given cathode temperature and current density) will be smaller. Second, the CW RF system will have lower instantaneous power and, unlike pulsed systems, is not subject to transient effects. RF amplitude and phase can therefore be controlled more accurately in a CW accelerator than in a pulsed accelerator.

Except for accelerators of very low energy or extremely high current, cost considerations dictate that the beam should be recirculated through the same linac several times, as opposed to the simple approach of a single-pass linac. The many length-associated costs, such as linac structure, cryostats (for superconducting linacs), and RF power dissipated in the structure (for normal-conducting linacs) tend to outweigh the cost of recirculating the beam. The optimum number of recirculations is dependent on many factors, with the type of linac (super- or normal-conducting) being a major consideration. For the highest possible current, a single-pass linac is necessary because the beam-breakup (BBU) threshhold current is much lower for a recirculating accelerator than for a single-pass device.[2] For example, the calculated single-pass BBU limit of the first 500 MeV of the CEBAF accelerator design is >100 mA,[3] while the calculated BBU threshhold of the full CEBAF machine (4 circulations to a final energy of 4 GeV) is ~10mA.[4]

CW Accelerator Types

The designs of recirculating electron accelerators can be grouped into two classes: recyclotrons as illustrated in figure 1, characterized by essentially independent bending paths for each recirculation; and microtrons as illustrated in figure 2, characterized by uniform-field bending magnets common to all recirculations. In both classes, the bends must be achromatic and must return the beam to the linac at the correct phase for continued acceleration on every recirculation. In recyclotrons, which can be either single- or double-sided,[4,5] the recirculating arcs are nominally isochronous, i.e. $d\phi/d\Delta E = 0$, where ϕ is the phase of an electron and ΔE is the difference between its energy and the central-orbit energy. Thus, to first order, the longitudinal particle motion is the same as for a single-pass linac. In the end magnets of a microtron, $d\phi/d\Delta E$ has a non-zero value, determined by the energy gain per pass, and the geometry of the accelerator (racetrack, double-sided, etc.) such that the first order longitudinal particle motion is a stable phase oscillation.

For very high energy applications ($E>>1$ GeV), recyclotrons will have smaller energy spread and transverse beam emittance than microtrons due to the effects of synchrotron radiation. The energy spread, σ_E, of the accelerated beam due to synchrotron radiation is

$$\sigma_E = C_1\left[\sum_{k=1}^{n} \frac{E_k^7}{\rho_k^2}\right]^{1/2}, \qquad (1)$$

where C_1 is a constant that depends on the total angle of bend in each of the n bends in the accelerator, E_k is the beam energy in the k^{th} bend, and ρ_k is the bend radius in the k^{th} bend.[6] In a microtron, n will be larger and ρ_k will be smaller than in a recyclotron of the same final energy, as a result of cost considerations. The emittance growth due to synchrotron radiation is

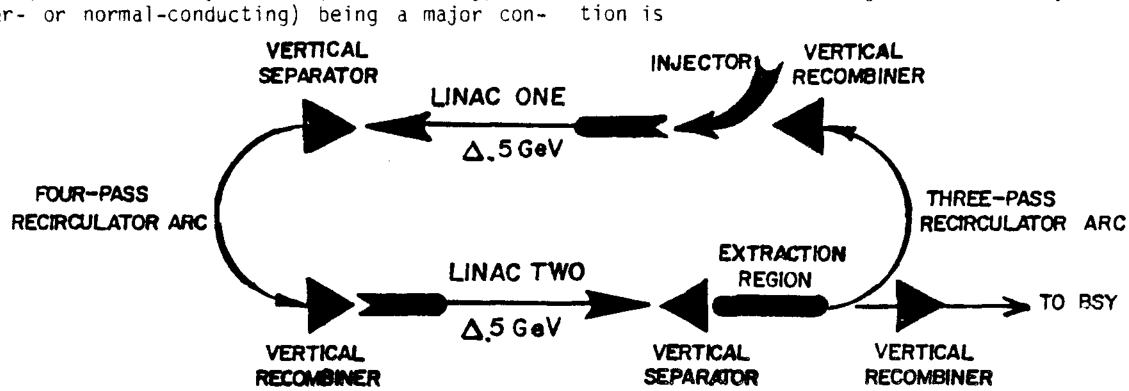

Figure 1 CEBAF Recirculating Linac

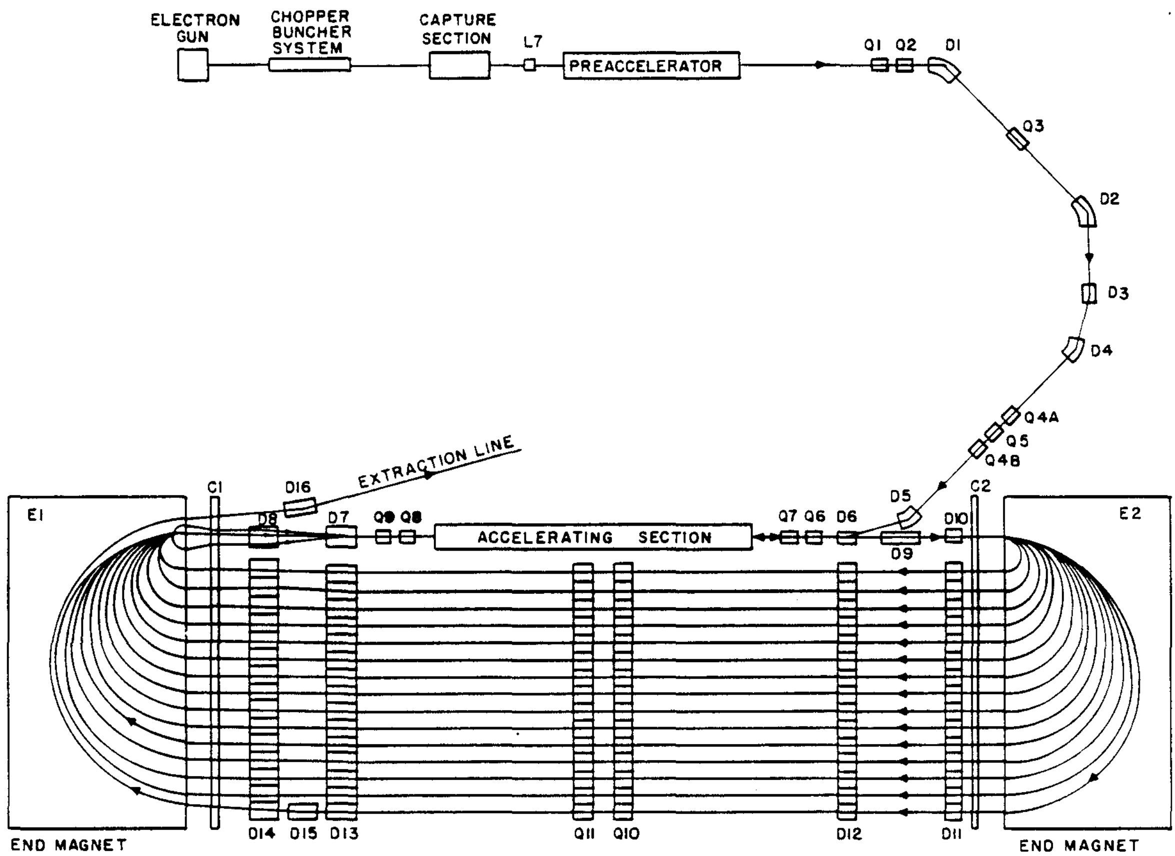

Figure 2 NBS-Los Alamos Racetrack Microtron

$$\Delta\varepsilon = C_2 \sum_{k=1}^{n} \frac{E_k^5}{\rho_k^2} \langle H\rangle_k , \qquad (2)$$

where C_2 is a constant and $\langle H\rangle_k$ is a function of the lattice functions in the k^{th} bend.[6] The emittance growth in a microtron is much larger than in a recyclotron, not only because n is larger and ρ_k smaller, but $\langle H\rangle$ is fixed in a microtron, but adjustable in a recyclotron. For example, $\langle H\rangle = 2\rho$ in the 180° bend of a racetrack microtron, and thus would be ~4.4 meters at E_k = 1GeV using a bending field of about 1.5 Tesla, whereas in the CEBAF design,[4] $\langle H\rangle \approx 0.1$m at E_k = 1 GeV.

Superconducting Linacs

Recent advances in the technology of superconducting accelerators make them uniquely suitable for very high energy recyclotrons. These advances include improvements in niobium quality, fabrication and processing of RF cavities, and development of techniques for decreasing the effective Q of the higher order modes responsible for BBU.[7,8] The test cavities for the CEBAF facility have operated with CW gradients in the range 6 to 8 MV/m, with $Q \gtrsim 5 \times 10^9$. The coupling impedance in cavities of this design for the dipole modes responsible for BBU is of the same order of magnitude as for room-temperature structures.[9]

Racetrack Microtrons (RTM)

The racetrack microtron configuration is an excellent choice for a CW electron accelerator in the energy range below 1 GeV where beam quality degradation due to synchrotron radiation is not a dominant factor. Its advantages include relative simplicity, compactness, high current capability, excellent beam quality and stability, ease of changing beam energy, and efficient use of electrical power. Although limited in accelerating gradient compared to the superconducting linac, the room temperature linac costs considerably less (per unit length), and of course eliminates the need for a cryogenic refigerator. The small a transverse dimension of the room temperature structure makes it much more compatible with the geometrical requirements of an RTM than the superconducting structure with its bulky cryostat. The RTMs at NBS, Mainz,[10] and Moscow State University[11] employ room- temperature linacs. The University of Illinois has proposed to replace the superconducting linac of their MUSL-2 microtron with room-temperature structures in a cascaded 450 MeV microtron system.[12]

RTM Injectors

The NBS-Los Alamos and Moscow State microtron systems use CW linacs of the same design in both the microtron proper and the injector system, with the sole difference that the capture section, which accelerates the beam from 100 keV to $\gtrsim$ 1 MeV must have a tapered β design to match the varying velocity of the electrons. Both Mainz and Illinois are planning to replace their Van de Graaff injector systems with Linac systems based on the NBS-Los Alamos design.[13,14] This injector system, shown in figure 3, consists of a 100 keV, 5mA DC electron gun with excellent stability and emittance, an emittance filter which limits the transverse emittance to 4π mm mrad (2.6π mm mrad normalized emittance), an RF chopper and recombiner which selects a 60° phase bunch in every RF cycle, and a single-cavity buncher which compresses the phase spread to approximately 10° at the entrance to the capture section. The chopper-buncher system is described in reference 13. The capture section is a one meter long side-coupled structure which bunches the beam farther to ~ 3° total width, while accelerating it to 1.3 MeV. Following a short drift space containing focussing, steering and diagnostic

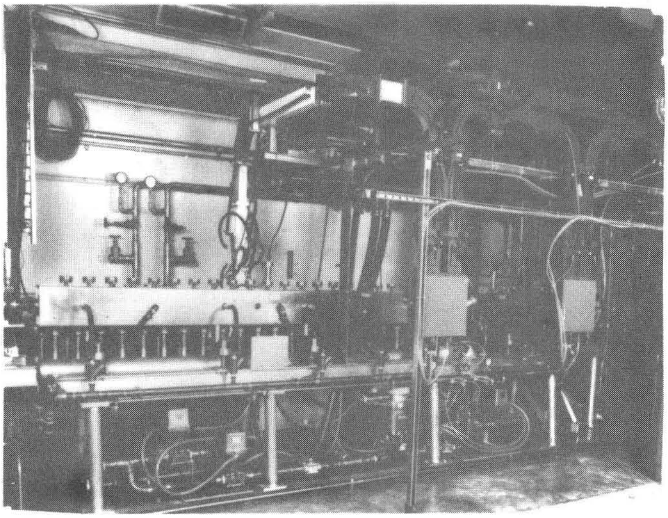

Figure 3 Photograph of Injector Linac of NBS-Los Alamos RTM. The chopper-buncher system and the capture section is at the right side of the figure, partially obscured by the RF power splitters and phase shifters. The preaccelerator section enclosed in its magnetic shield, is in the left half of the picture.

elements, the 2.7m long preaccelerator section increases the beam energy to approximately 5 MeV. The design and construction of this linac are described in reference 15.

Installation of the NBS-Los Alamos RTM injector linac system was completed in August 1985. Initial performance measurements have been very encouraging. The RF structures condition to full power very quickly under computer control of frequency and the power levels in the two structures. After conditioning, the stability of field strength and phase is excellent. The measured phase stability of each structure is better than ±0.1 degree. The upper limit on short term amplitude stability is less than one part in a thousand. Our best evidence of RF stability is the mean energy of the accelerated beam, which is stable within ± 1 keV at 5 MeV. The actual linac stability may be even better, since the fluctuations in the magnetic field of the analyzing magnet were of the order of one part in 5000. The energy spread of the 5 MeV beam was 11 keV full width, somewhat better than predicted by the particle simulation code, PARMELA.[16] We have not completed beam emittance measurements, but the observed spot sizes are consistent with the predicted beam emittance of <5π mm mrad normalized. These measurements were made with a CW beam of ~300μA and pulsed beams up to ~600μA (30 nS pulse length, rep rate 10^3-10^4 Hz).

RF Structures for RTMs

The most important considerations for a linac for use in a CW racetrack microtron are stability, electrical efficiency, gradient, and beam breakup. In some microtrons, the injection scheme requires that the beam be accelerated in both directions through the linac, which demands a standing wave structure.[17] A standing wave design would be chosen in any case, because of its higher shunt impedance, compared to a travelling wave structure.[18]

The requirements of stability and electrical efficiency conflict with the need for high gradient. A high gradient allows a smaller distance between end magnets and thus makes the problems of focussing, steering and beam blowup easier, at the price of a higher power consumption. The power dissipated in the structure is given by

$$P_D = \frac{(\Delta V)^2}{RL}, \qquad (3)$$

where ΔV is the energy gain per pass, $R = ZT^2$ is the effective shunt impedance, and L is the linac length. In an RTM, ΔV is not a free variable, being determined by the microtron resonance condition $(2\pi/c)\,\Delta V \cos\phi_R = \nu\lambda B$, where c is the speed of light, ϕ_R is the resonance phase angle ($\cos\phi_R$ is close to one), ν is a small integer, λ is the free-space RF wavelength, and B the magnetic field in the end magnets. Various performance requirements dictate that λ be in the range 10-20 cm and ν = 1 or 2. In high energy microtrons, B must be large for cost reasons. It is thus clearly desirable to have a high shunt impedance. Equation (3) can be rewritten as

$$\frac{P}{L} = \frac{G^2}{R}, \qquad (3')$$

where $G \equiv \Delta V/L$ is the gradient. It is increasingly difficult to maintain stability of field strength and phase as the power per unit length increases.[19] This would be the limiting factor on the gradient of a microtron linac if the costs of the RF power supply and electrical power were ignored. In practice, cost considerations have led to designs using gradients in the range 0.8 to 1.5 MeV/m, significantly below the power dissipation limit. A summary of observed high power, high gradient structure results is given in Table I. It is important to note that only the results of reference 19 can be interpreted as a true power dissipation limit. At present there is insufficient experimental data available to define a meaningful limit on attainable

Table I. High Power Structure Tests

Reference	20	19	19	15
Structure type	On axis-coupled	On axis-coupled	On axis-coupled	Side-coupled
Cooling geometry	Circumferential	Circumferential	Circumferential and web	Circumferential and web
RF frequency, MHz	804	2450	2450	2380
P/L, kW/m	105	70	210	50
G, MeV/m	1.8	2.2	3.5	2.0
Limiting factor	RF power	Stability	Stability	Coolant pump

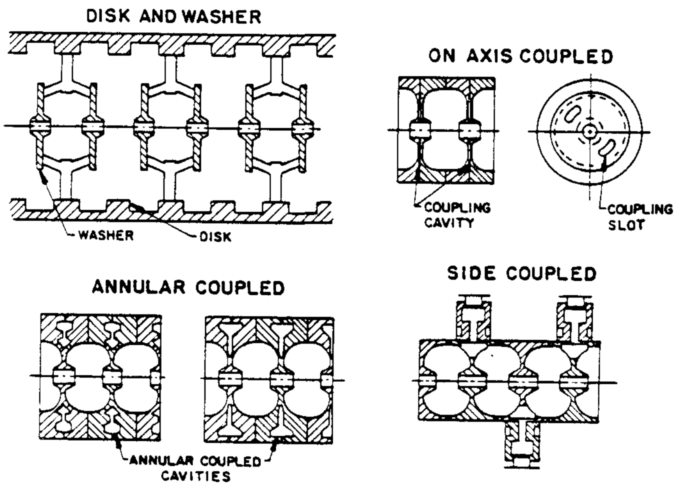

Figure 4 RF Structure Types

gradient in CW RF room-temperature electron linacs, because relevant data exists for only one structure at one frequency. However, because of the quadratic dependence of P/L on G and the weak dependence of gradient on frequency, it seems unlikely that gradients above 5-7 MeV/m will be practical. This is in contrast to the superconducting case where 7.5 MeV/m is readily obtainable, and gradients in excess of 20 MeV/m have been observed in single-cell tests.[7]

In considering structures for very high gradient room temperature CW linacs, the disc and washer (DAW) structure, shown in figure 4, should, perhaps, be reexamined. The DAW structure was studied[21] for use in the NBS microtron because of its high shunt impedance and very high first-neighbor coupling constant, k, factors which would help to achieve high gradient and good stability. The observed effective shunt impedance of 90MΩ/m at 2380 Mhz is significantly higher than either on-axis or side- coupled structures at the same frequency, and k ≈ 0.5 roughly an order of magnitude higher than the other structures. The DAW was rejected for the NBS microtron because of its complex higher mode structure, which included dipole deflection modes very close to the accelerating mode frequency and its harmonics. In a high current microtron these modes would be expected to reduce the BBU threshhold by, possibly, a large factor compared to more conventional structures. This consideration may not be as important in a single-pass device.

The Mainz Microtron

The largest CW microtron now in operation is MAMI-A, the 180 MeV, 100μA machine at Mainz University.[22] Its present injection system consists of a 2.1 MeV Van de Graaff, and a 14 MeV, 20 pass racetrack microtron. A third microtron, MAMI-B, is now being built. It will use MAMI-A as an injector, with the Van de Graaff replaced by a 2.8 MeV linac.[10] MAMI-B will have 88 passes through a 7.5 MeV linac to achieve a maximum energy of 840 MeV. This linac consists of five 1.78 m long sections, each driven by a 50 kW klystron. The linac is of the on-axis coupled type. The Mainz design philosophy is to use a relatively low gradient (<1 MeV/m) to obtain a relatively high electrical efficiency at a beam current of 100μA. Relevant parameters of MAMI-B are given in Table II.

Table II. Parmeters of Mainz and NBS Microtrons

Parameter	MAMI-B (third stage only)	NBS
Design energy, MeV	840	185
Design current, i, μA	100	550
Injector energy, MeV	180	5
Energy gain per pass, ΔV, MeV	7.5	12.0
Number of passes, N	88	15
Total current, Ni, mA	8.8	8.25
Beam power, P_B, kW	66	100
Gradient, G, MeV/m	0.85	1.5
Effective shunt impedance, R, MΩ/m	67	82.5
Electrical length of linac, L, m	8.87	7.94
Dissipated power, P_D, kW	102	225
RF efficiency, $P_B/(P_B + P_D)$, percent	39.1	30.8
Dissipated power per unit length P_D/L, kW/m	11.5	28.3
RF frequency, MHz	2450	2380

The NBS Microtron

The NBS-Los Alamos microtron now under construction is designed to deliver 185 MeV at a current of 550μA. Its injection system is the 5 MeV CW linear accelerator described above. The linac of the 15 pass microtron consists of two 3.97 m long sections of side-coupled structure to obtain an energy gain of 12 MeV/pass. Except for length, these sections, shown in figure 5, are identical to the preaccelerator section described above. The linac has been built, low power RF tests performed, and installation has been completed. Full power operation is scheduled for this summer. A significant difference from the Mainz design philosophy is the use of a single 500 kW klystron to power the entire accelerator system, using a system of high power power splitters and phase shifters to distribute the RF power to the capture section, preaccelerator, and two sections of the main linac.[23] There is a significant cost savings in using a single large klystron and DC power supply compared to many small klystrons, although this is partially compensated by the cost of the power splitters and phase shifters. The control system, which performs extremely well when only the capture section and preaccelerator are in operation, is necessarily slower than a multi-klystron system because of the mechanically driven phase shifters. Relevant parameters are summarized in Table II.

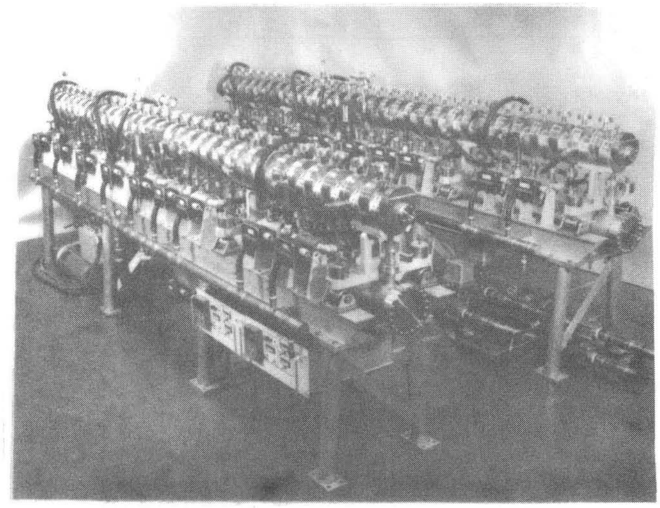

Figure 5 Photograph of the Main Accelerating Structures for the NBS-Los Alamos Linac, taken before installation. Each structure is four meters long.

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