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DOUBLE-DRIFT BEAM BUNCHING SYSTEMS*

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Summary

The double-drift beam bunching system consists of two bunchers that are separated in space, independently driven but phase-locked together. The second buncher to be encountered by the beam is driven at twice the frequency of the first. This system offers an attractive alternative to conventional one- and two-frequency systems since it's bunching efficiency is about twice that for a single frequency system and about 25% larger than that for a two-frequency system in which both harmonics are imposed on the same electrode. The independence of the two bunchers provides for greater ease in the adjustment and stabilization of the rf amplitudes and phase to the accuracy of ±1% and ±0.5° that is required. A double-drift system, designed to operate as 4.5 to 14 MHz, has been installed on the ORNL EN-tandem and evaluated using ^{16}O, ^{32}S, ^{58}Ni, and ^{63}Cu ion beams. Performance was in close agreement with predictions; about 60% of the dc beam was bunched into a phase angle of 6° of the fundamental frequency. A brief discussion of the principles of operation, predicted performance and practical design considerations are given. Results of a theoretical study of the dynamic focussing effects and energy-modulation imperfections of ungridded klystron bunchers are presented as approximate formulas.

Introduction

Since the subject of beam bunching has been reviewed by several authors,[1-3] we will give only a brief summary of some of the fundamental aspects. The function of most beam bunchers in use today is to modulate the dc beam velocity in such a way that portions of the beam initially separated in space and time are made to arrive at the target (point of time-focus) at nearly the same time. The beam energy spread intrinsic to the ion source opposes the action of the buncher and leads to a spreading of the bunch. Consider a beam of average energy EO with intrinsic energy spread ΔES. Let ΔTO represent the length (in time) of the beam segment to be bunched, ΔEO the energy modulation imposed by the buncher and ΔTB the length (in time) of the final bunch. Liouville's theorem leads to the relation,

$$\Delta EO \cdot \Delta TB \geq \Delta ES \cdot \Delta TO \quad (1)$$

It is easily shown[3] that the energy modulation required for the bunching of non-relativistic particles in field free space is given by,

$$\Delta EO_i = EO[(T/(T+\Delta TO_i))^2-1] \quad (2)$$

where T is the time required for a particle of energy EO to travel from the buncher to the target and ΔEO_i is the energy required to time-focus a particle i which is initially displaced from the center of the bunch by an amount of time ΔTO_i. If ΔTO << T, as is often the case, an almost linear energy modulation function is required. That is,

$$\Delta EO_i = 2EO \cdot \Delta TO_i/T \quad (3)$$

If we require a final bunch width that is no greater than ΔTB_{max}, we find (by imposing (1) and (3)) that the maximum drift time T_{max} is given by,

$$T_{max} \leq 2(EO/\Delta ES) \cdot \Delta TB_{max} \quad (4)$$

The time T required for a particle of mass M and initial energy EO to traverse a uniform accelerating region of length L is given by

$$T = 2 \cdot L/[(2/M)^{1/2}(EO^{1/2} + Ef^{1/2})] \quad (5)$$

where Ef denotes the final energy. The change in transit time per unit change in initial energy is given by,

$$dT/dEO = -L(M/2)^{\frac{1}{2}}(EO^{-\frac{1}{2}} + Ef^{-\frac{1}{2}})/(EO^{\frac{1}{2}} + Ef^{\frac{1}{2}})^2 . \quad (6)$$

As an example, assume that a 0.1 MeV beam traverses a buncher, a) drifts 1M, b) is accelerated to 5.1 MeV in a distance of 4M, is stripped to charge state +4, c) drifts 2M, d) is accelerated to 25.1 MeV in a distance of 4M, and e) drifts 30M to the point of time focus. An application of (5) and (6) shows that the fraction of the total transit time spent in regions a) through e) is 22, 22, 6, 8, and 42%, respectively while the fraction of the total time compression occurring in these regions is 86.6, 11.9, 0.5, 0.3, and 0.7%. Thus, for design considerations, one should use an effective drift time which is about 14% larger than that associated with region a).

The type of buncher most commonly used in conjunction with electrostatic accelerators is the klystron which consists of three coaxial cylinders separated by two gaps. The cylinder on either end is grounded and the central element is driven sinusoidally at a radio frequency (rf) in the range of ~ 4-20 MHz. The length of the driven element should be such that a beam particle traverses the distance between the gaps in about 1/2 (or possibly 3/2) of the rf period. Particles which traverse the first gap while the central element is driven positive will traverse the second while it is driven negative (and vice versa) and thus receive the same acceleration at both gaps. The ends of the cylinders adjacent to the gap are often equipped with grids which produce an axial field which varies little with radius and is confined to the region within the gap.

Only about 20-30% of the sinusoidal waveform is sufficiently linear to produce bunching of the quality usually required. Two or more frequencies may be mixed to produce a waveform which is linear over an extended range.[4] A buncher so driven is called a harmonic buncher. A variation of the harmonic buncher is the double-drift buncher[5-7] which actually consists of two bunchers; the first driven at a frequency f1 and the second (located downstream from the first) driven at 2f1. The fraction of the total dc beam that can be bunched into a given rf phase angle is shown in Fig. 1 for a signle frequency (SIMPLE), two-harmonic (HARMONIC) and double-drift buncher. The bunch full width to which this phase angle corresponds is also shown for a buncher whose fundamental frequency

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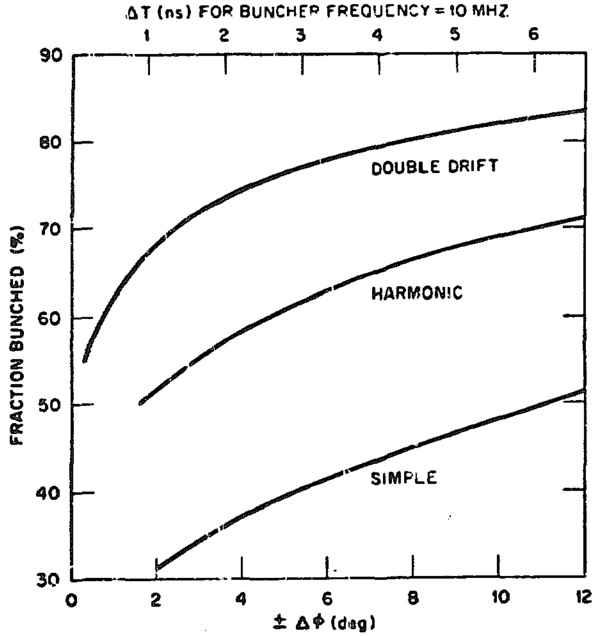

Fig. 1. Theoretical buncher efficiency as a function of the final phase angle (Δφ) that is acceptable.

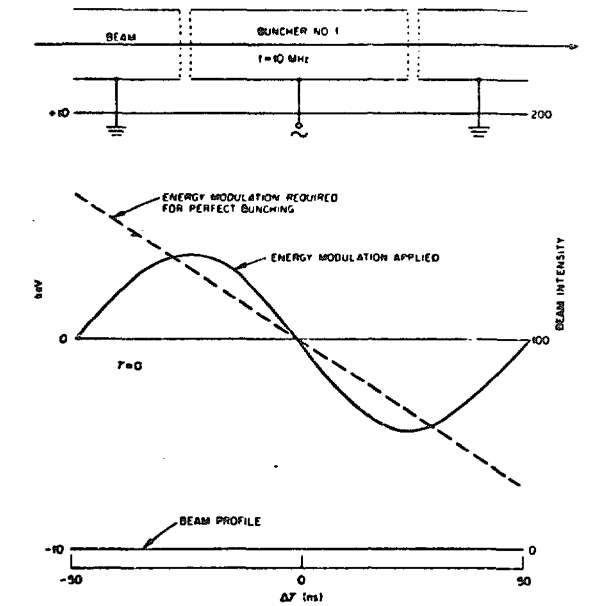

Fig. 2. Illustration of the action of the first of two bunchers (the fundamental) in a double-drift system.

is 10 MHz. Although the double-drift buncher is about 25% more efficient than the two-harmonic it's most important advantage (derived from the fact that the two rf systems do not interact) is the greater ease with which it may be adjusted and stabilized. Disadvantages are the additional space and equipment needed as well as the possible requirement for four additional grids which intercept up to 20% or more of the beam.

The Double-Drift Buncher

Figs. 2 and 3 illustrate the operation of the double-drift buncher. The beam encounters buncher-1, is somewhat "overmodulated" and drifts to buncher-2 where the modulation is "corrected". Since some bunching has already taken place when the beam encounters the second buncher, a larger fraction of the beam can be effectively corrected than would be possible if no drift space had been provided.

A numerical study, in which each buncher is assumed to be composed of a single perfect gap, has been carried out to determine how the system performance varies with buncher separation. Figure 4 presents the maximum beam utilization efficiency as a function of the ratio of buncher separation to total drift distance. Curves are given for rf phase acceptance angles of ±3°, ±6°, and ±12° of the fundamental period. Ratios of the rf amplitude for buncher-2 to that of buncher-1 (AMP2/AMP1) are also shown. The sudden decrease in efficiency that occurs immediately following each curve maximum is not to be interpreted as an "observable catastrophe" but is simply an indication that the final bunch width has become larger than that specified as acceptable. Note that a separation of zero corresponds to the conventional two-harmonic buncher.

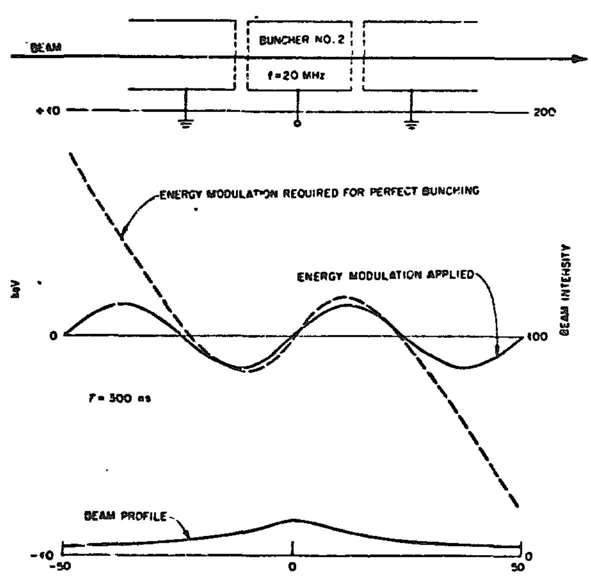

Fig. 3. Illustration of the action of the second harmonic buncher in a double drift-system.

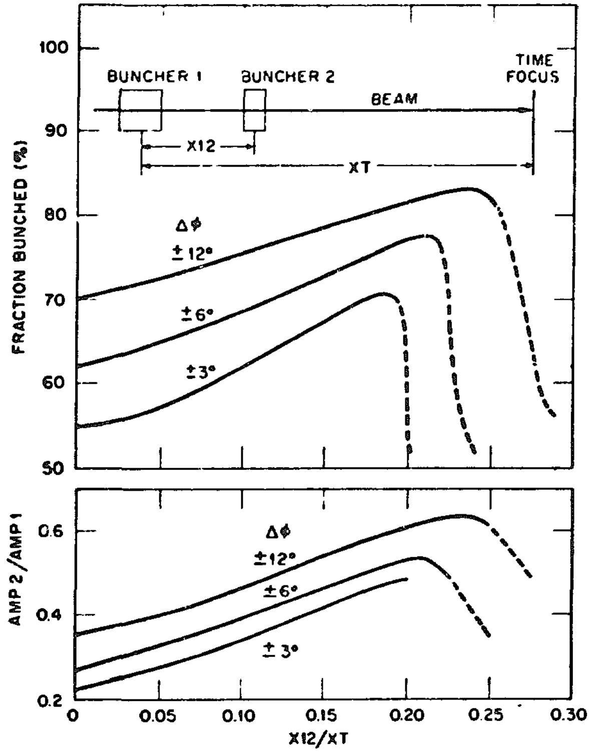

Fig. 4. Calculated double-drift buncher performance as a function of buncher separation and the final phase angle (Δφ) that is acceptable. AMP2/AMP1 is the ratio of the rf amplitude required for buncher-2 to that required for buncher-1.

Experimental Results

A double-drift bunching system (illustrated in Fig. 5) has been installed on the EN tandem accelerator. The system is designed to operate over a frequency range of 4.5 to 14 MHz and will eventually be used to produce bunched beams from the ORNL 25-MV Pelletron for injection into the ORIC. Tests have been conducted with four ion beams (^{16}O, ^{32}S, ^{58}Ni, and ^{63}Cu at 22.5, 25, 20, and 30 MeV, respectively) with observed results very close to those predicted. Beam pulses were detected with a capacitive pickup unit (CPU) and a 50Ω coaxial Faraday cup and were observed with a sampling oscilloscope. In the case of the ^{16}O beam a time-to-amplitude converter (TAC) spectrum was obtained by using timing pulses derived from the CPU and a plastic scintillator that detected Coulomb excitation γ rays produced in the stainless steel beam stop of the coaxial cup. Pulses from the CPU and the coaxial cup were amplified by wide-band preamplifiers (HP-8447F, gain = 48db) prior to being fed into the time-pickoff unit (ORTEC-260) and the oscilloscope. The use of such equipment enables one to easily observe pulses with average beam currents as small as 50 to 75 electrical nA (enA).

Pulse widths (FWHM) of about 1.2, 1.6, and 1.1 nsec were observed with the sampling oscilloscope for the beams of ^{16}O, ^{32}S, and ^{58}Ni, respectively. The ^{63}Cu beam was too weak (less than 10 enA) for an

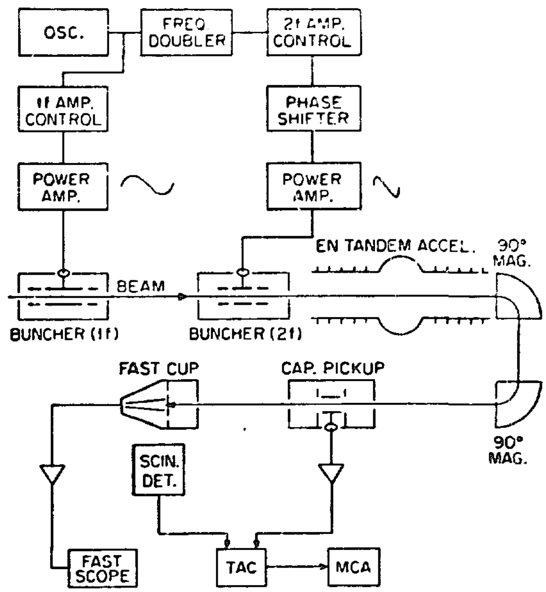

Fig. 5. Block diagram of the beam-bunching and pulse-detection test facility.

accurate width estimate. The TAC spectrum shown in Fig. 6 shows that about 59% of the dc ^{16}O beam was bunched into a phase angle of ±3°. For the facility on the EN tandem, X12 = 26 cm, XT = 150 cm and

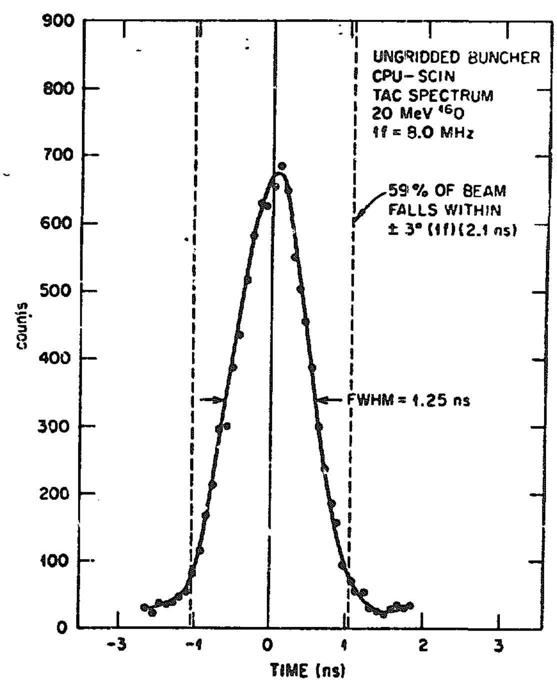

Fig. 6. Time profile of an ^{16}O ion-beam pulse produced by the double-drift klystron bunching system.

X12/XT = 0.17 (see Fig. 4). The field-free drift distance (130 cm) between buncher-1 and the accelerator has been increased by 15% to account for the effect of the remaining accelerating and drift regions. Fig. 4 shows that for X12/XT = 0.17, the theoretical maximum efficiency for bunching into ±3° is 70%. An application of Eqn. (3) shows that an energy modulation of about 11 keV is required to bunch 70% of the ^{16}O beam with a fundamental frequency of 8 MHz and an injection energy of 90 keV (our operating parameters). If an intrinsic energy spread of 40 eV is assumed for the sputter source used, we find (using Eqn. (1)) a time spread of about 0.35 ns which should (when summed in RMS) increase the observed pulse by less than 5%. The finite time resolution of the pulse detection system probably contributed a similar amount. In order to realize the theoretical performance of the double-drift system, an amplitude stability of about ±1% and a phase stability (between the two bunchers) of about ±0.5° is required. Since about 15 minutes was required to accumulate the TAC spectra and no stabilizing circuitry was employed, some degradation in the observed efficiency probably occurred. Finally, the use of ungridded bunchers whose lengths were 6 and 3 cm and diameters were about 2 cm undoubtedly contributed a small amount to the degradation of performance (see the following section for more details) although a meaningful estimate cannot be made since we were not able to measure the beam diameter at the location of the bunchers.

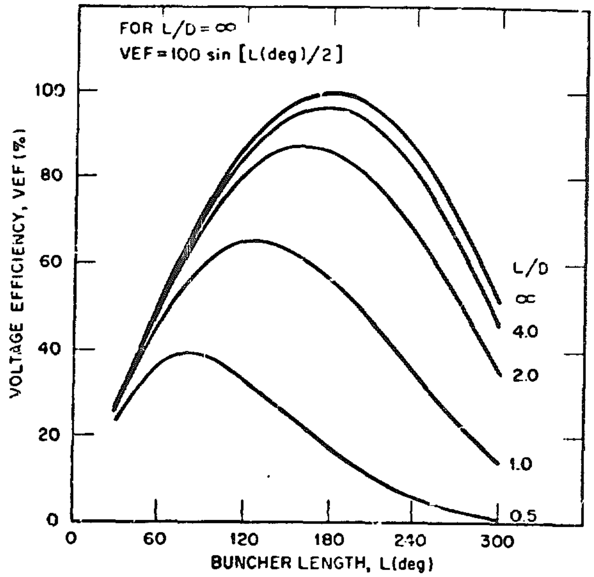

Fig. 7. Calculated voltage efficiency VEF of ungridded klystron bunchers as a function of buncher length in degrees L(deg.) and length to diameter ratio L/D.

Performance Characteristics of Ungridded Bunchers

If the buncher length L is large compared to the diameter D, particles traverse the gaps in a time which is small compared to the rf period and energy modulation varies only slightly with the radius of traversal. However, heavy ions move so slowly at normal injection energies that L/D may not be very large for desirable frequencies. In addition, it is not always convenient to match the buncher length precisely to the rf period, especially when a wide variety of ion species is involved. A study has been carried out to determine the voltage efficiency, energy modulation characteristics and optical properties of ungridded klystron bunchers of length (in degrees of rf phase) L(deg.) = 60 to 300° and L/D = 0.5, 1, 2, 4, and 8 for beam diameters = 0.0 to 0.9D. A gap length of zero was assumed and Poissons' equation was solved numerically (potentials calculated at 16,000 mesh points) for geometries corresponding to the values of L/D given above. A small sinusoidal time variation was imposed on the potential distribution and particles were "injected" parallel to the symmetry axis at various radii (up to 0.45D) and rf phase angles. Both axial and radial components of the particle velocity modulation were calculated. Fig. 7 presents the gap voltage efficiency as a function of L(deg.) for L/D = 0.5 to 8. As L/D becomes smaller the curve maxima shift toward smaller values of L(deg.) because the axial field becomes asymmetrically distributed about the gap and produces an effective length which is larger than the gap separation.

Particles which traverse the gap on axis encounter a field which is more widely distributed in space than those which pass closer to the wall and consequently receive a smaller energy modulation. The results of the numerical study have been parameterized to produce the following practical formula,

$$\frac{\Delta E(R) - \Delta E(R=0)}{\Delta E(R=0)} = 10.8\left[1+0.05\left(\frac{D}{L}\right)^2\left(\frac{L(\text{deg.})}{180^\circ}\right)^2\right]\left(\frac{R}{X}\right)^2 \quad (7)$$

where $\Delta E(R)$ denotes the energy modulation received by a particle which traverses at radius R and X is the distance traveled by the particle in one rf period (i.e. X is twice the ideal buncher length). For example, if we assume an ideal buncher length of 10 cm, an actual length L(deg.) = 240°, a buncher diameter of 2.5 cm and a beam diameter of 1.0 cm, we find that the energy modulation at R = 0.5 cm is 0.7% larger than for R = 0.0. Thus, for an initial beam segment length of 100 ns, a maximum time spread of 0.7 ns would be introduced. It appears that if the ratwo of beam diameter to ideal buncher length is less than ~ 1/5, ungridded operation may be feasible.

One is tempted to view the ungridded klystron as optically equivalent to an ungridded einzel lens composed of three equidiameter coaxial cylinders (see Ref. 8, Chapter IV). This analogy can be misleading, however, if one fails to consider the fact that the klystron field may vary considerably during the time required for the particle to traverse the region of the gap. This changing field can lead to optical properties which are much "stronger" than those estimated using static lens formulas.[8] A parameterization of the results of the numerical study has lead to the following approximation for the minimum focal length F_{min} for a klystron buncher driven sinusoidally with an rf amplitude ΔVO whose gap voltage efficiency is VEF.

$$F_{min} = \pm\, 0.30\ EO \cdot X/(FLF \cdot VEF \cdot \Delta VO) \quad (8)$$

where

$$FLF = 1.0 + 0.105\left(\frac{D}{L}\right)^2\left(\frac{L(\text{deg.})}{180^\circ}\right)^2 .$$

EO denotes the beam energy. Note that $VEF \cdot \Delta VO$ is the maximum actual energy modulation per gap. The reciprocal of the focal length varies sinusoidally with the particle phase. Extreme values $(1/F_{min})$ occur for particles which arrive at the center of the buncher at 90° (diverging for negative ions) and 270° (converging for negative ions). As an example, let EO = 100 keV, ΔVO = 3 kV, D = 2 cm, L = 6 cm, X = 12 cm, VEF = 0.9, and L(deg.) = 180°. By using Eqn. (8), we find that the absolute value of F_{min} is about 130 cm. If, however, we consider the buncher as a "static lens", we obtain a focal length of about 6600 cm. The approximation given by Eqn. (8) obviously does not produce the static lens result in the low-frequency limit (i.e. as $X \to \infty$). However, the ray-tracing program used in the numerical study was run with the frequency set to zero and the static lens result was reproduced to within 5 to 10%.

Since the simple buncher uses only a small portion of the sinusoidal waveform for bunching, the dynamic focussing action of the buncher can be partially overcome by a readjustment of the static lenses of the beam transport system. Although this is true to a lesser degree for the double-drift system, the second buncher operates 180° out of phase with the first and tends to have comparable strength with the smaller applied voltage and, thus, acts to oppose the action of the first buncher.

It should be pointed out that the results presented in Fig. 7 and Eqns. (7) and (8) are valid only for cases where the beam energy change per gap is a relatively small fraction (say less than 2.5%) of the beam energy.

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References

1. J. H. Neiler and W. M. Good, *Fast Neutron Physics I*, (Interscience, 1960).

2. C. D. Moak *et al.*, Rev. Sci. Instr. 35, 672 (1964).

3. K. H. Purser *et al.*, University of Rochester Report, UR-NSRL-2 (1967) p. 28.

4. F. J. Lynch *et al.*, "Beam Buncher for Heavy Ions," accepted for publication in Nucl. Instr. Methods.

5. S. Ohnuma, Minutes of the Conference on Proton Linear Accelerators, Yale University (1963) p. 279.

6. R. Emigh, Proceedings of the 1966 Linear Accelerator Conference, Los Alamos Laboratory Report, LA-3609 (1966) p. 338.

7. W. T. Milner *et al.*, IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, June 1975, p. 1697.

8. A. B. El-Kareh and J.C.J. El-Kareh, *Electron Beams, Lenses and Optics*, Vol. 1 (Academic Press, 1970).