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DESIGN AND APPLICATIONS OF RF SEPARATOR STRUCTURES AT SLAC*

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ABSTRACT

Since early studies of rf separators started at SLAC approximately two years ago, new designs and measurements have been carried out and new applications for these structures have been found. This paper describes the measurements and results obtained with two "TM_{11}-type" structures, both operating at 2856 Mc/sec in the $2\pi/3$ mode but at different group velocities. Also given are results obtained with a structure of the "TM_{01}-type," consisting of a disk-loaded waveguide with an off-centered hole. These results include figures of merit such as the transverse shunt impedance and the factor $E_o/\sqrt{P_o}$ (input electric field intensity divided by the square root of input rf power). Substantial increases in these figures of merit have been found as compared with measurements reported earlier. Aside from the original proposal to use these structures to separate particles of different masses, two other applications have been found at SLAC: One is to measure electron bunch width; the other is to use the rf structure together with a pulsed magnet to separate electrons from positrons produced by a radiator installed at the one-third point along the two-mile machine. Both applications are described.

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I. INTRODUCTION

This paper summarizes the work done at SLAC on rf deflecting structures since the 1963 Dubna conference.[1,2,3] Because there is no plan to have an rf-separated beam available immediately upon turn-on of the two-mile accelerator (mid-1966), this interim period has been used to investigate different structures and their applications in other areas of the machine. The work described here includes new results obtained with the conventional "TM_{11}-type" structure as well as with a new "TM_{01}-type" structure, a brief survey of the experimental setups used in the measurements, and the description of two immediate applications of these devices at SLAC: an electron-bunch-width analyzer and a positron-electron deflector.

II. PROPERTIES OF THE TM_{11} AND TM_{01}-TYPE DEFLECTING STRUCTURES

Two basic structures have been investigated. The first one is the conventional "TM_{11}-type" disk-loaded waveguide described earlier by SLAC[1] and other laboratories.[4,5] This structure, which is shown in Fig. 1, operates at 2856 Mc/sec with a phase shift of 120° per cavity. As will be remembered, the two small lateral holes in the disks are used to prevent mode rotation. Most of the work on this structure was done to maximize the deflecting efficiency. As discussed in earlier references,[1,2] except for considerations of beam acceptance, the choice of parameters for an rf separator structure is very similar to that for a linear accelerator. The problem of beam loading can generally be neglected because the currents involved in most rf-separated beams are extremely low. Using the definition of transverse shunt impedance per unit length defined by

$$r_T(x) = \frac{\left[(1/k)(\partial E_z/\partial x)\right]^2}{-(dP/dz)} \tag{1}$$

where k is the free space wave number, P is the power flow in the structure, E_z is the longitudinal electric field, and x is the transverse direction of deflection, one can express the total transverse energy gained by a particle riding the crest of the deflecting wave in a structure of length ℓ, attenuation per unit length I, and input power P_o by

$$p_\perp c = q\sqrt{2I\ell}\,\frac{1 - e^{-I\ell}}{I\ell}\sqrt{P_o \ell r_T} \quad . \tag{2}$$

This transverse energy can be optimized by the proper choice of the parameters r_T, I, and ℓ. However, it must be remembered that whereas in accelerators r_T generally varies slowly as a function of dimensions, this is not the case for "TM_{11}-type" rf deflecting structures. A typical three-meter-long structure was assumed, and several cases with different values of I were investigated. The results for two models are tabulated in Table I. For historical reasons, these were called LOLA II and LOLA III. The attenuation length $I\ell$ for LOLA III comes very close to the optimum of 1.26 which maximizes the function of $I\ell$ in Eq. (2). The values of transverse shunt impedance corrected for the fundamental space harmonic mode, $r_{o,T}$, measured both by a microwave perturbation method and indirectly with an electron beam (see Section III below), are seen to be considerably higher than reported earlier.[1,2] After some investigations, it was found that the earlier measurements were in error because of an incorrect directional coupler calibration which invalidated the microwave power measurements. These new values of shunt impedance are also in much better agreement with a theoretical calculation done at Brookhaven.[4] From Table I it is seen that LOLA III, with a somewhat lower shunt impedance but a larger value of $I\ell$, yields a better deflection than LOLA II. In addition, the larger aperture (2a) provides a better acceptance. Because the acceptance varies as the deflecting field and the cube of the deflector diameter, the improvement of LOLA III with respect to LOLA II is about 80%.

The new "TM_{01}-type" structure which has recently been investigated is shown in Fig. 2. The basic idea for this structure was obtained from the understanding of the amplitude and phase asymmetry problem encountered in the coupling cavities of the accelerator sections for the two-mile-long machine.[6] The amplitude variation in the longitudinal electric field over the cross section of the iris in such an uncorrected coupler cavity is of the order of 10%. By extending this idea, it was found that by strongly off-centering the iris, as shown in Fig. 2, it was possible to obtain much larger gradients in longitudinal electric field. In the process of off-centering the iris, the pass-band of the structure gradually changes because the coupling from one cavity to the next becomes more magnetic than electric. As a result, the structure can become of the backward-wave type. The dimensions of the first model, baptized LOLITA I, are also given in Table I. The group velocity for these dimensions is negative. The transverse shunt impedance is about twice that obtained for LOLA III for approximately the same value of $I\ell$. However, the useful diameter and acceptance of the structure are greatly reduced.

Preliminary experiments seem to indicate that, to first-order, the TM_{01} structure may also be aberration-free. However, it exhibits another characteristic not present in the TM_{11} structure, i.e., it has a non-zero longitudinal accelerating or decelerating field on the axis, in time quadrature with the deflecting field. Hence, by varying the phase of the input power, one can cause the particles to be either deflected or accelerated (or decelerated). For rf separators, this property added to the lower acceptance may be a serious disadvantage. However, in other applications it may be put to use, for example, as a phase controllable steering element or a stabilizing device in machines where one wants to control the coupling of phase-dependent longitudinal and transverse deflections. For such purposes, one might think of using a less off-centered iris, thereby making it possible to practically balance the transverse and longitudinal forces.

III. EXPERIMENTAL MEASUREMENTS

The values of transverse shunt impedance, $r_{o,T}$, given in Table I were obtained by two independent methods. The measurement obtained by the microwave frequency perturbation method followed the technique described in Ref. 2 (pages 19 and 24). This technique basically consists of measuring the variation in the transverse direction of the fundamental space harmonic component of the axial electric field. The total axial electric field is obtained by measuring the frequency perturbation caused by a dielectric rod in a resonant test cell. The value of the fundamental space harmonic is derived from an axial field plot obtained by drawing a short metal (hypodermic) needle through the same test cell and recording the frequency shift as a function of position.

The other value of shunt impedance was obtained by measuring the actual deflection of a 6-MeV beam. The experimental setup for this measurement is illustrated in Fig. 3, which shows the deflector (LOLITA I) and a large experimental evacuated tank. At the end of this tank, there is a ZnS screen which can be viewed by a television camera and allows measuring the actual deflection of the beam. The coils around the deflector are used for steering purposes; the small magnet seen upstream of the deflector is the momentum spectrometer used to measure the beam energy of this experimental accelerator.

IV. APPLICATIONS

A. The Bunch-Width Analyzer

Figure 4 illustrates how the deflector is being used as a bunch-width analyzer. For a given position of the calibrated phase shifter, electrons in positions (1) and (3) are deflected and stopped by a steel plate, whereas electrons in position (2) remain undeflected and are collected. The device can be calibrated by varying the input rf phase by known amounts and observing the beam deflection at the steel plate by means of a ZnS screen. The fraction of electrons reaching the collector through the slit is then the current contained within a given phase interval. By means of this analyzer, it has been possible to ascertain that the injection system for the two-mile accelerator is capable of bunching 90% of the current within 5°.[7]

B. The Positron-Electron Deflector

For certain experiments with the two-mile machine, positron beams[8] will be desired, either at the two-thirds point along the accelerator length (for injection into a proposed positron-electron storage ring) or at the main end stations (for positron scattering experiments). With reference to Fig. 5, when electrons accelerated through Segment I of the machine impinge on the positron radiator, they create electron-positron pairs. Depending on the rf of the accelerating field in Segment II with respect to Segment I, either the electrons or the positrons find themselves on the crest and are accelerated. However, it has been found experimentally that because of the high accelerating fields, a substantial fraction of the other particles are also captured and accelerated after slipping by 180°. In order to eliminate these particles which could cause some difficulties in the instrumentation and in the Beam Switchyard, an rf deflector combined with a pulsed magnetic dipole is being installed downstream of the positron source. Since the positron and electron bunches are 180° apart in phase, they are both deflected by the same angle. The magnetic dipole is designed to produce a transverse force, F_B, which either adds to or cancels the force, F_{RF}, from the rf deflector. Depending on the combinations of rf phase and sign of the magnetic field shown in Fig. 5, one can either reject electrons or positrons. The deflector selected for this function has the dimensions of

LOLA II. It will be supplied with 0.2 MW of peak power to produce a transverse momentum of 0.4 $\frac{\text{MeV}}{c}$. The resulting angle of deflection is sufficient to dump the unwanted particles into the accelerator wall within 3 meters.[9]

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TABLE I

CHARACTERISTICS OF DEFLECTORS

Designation	Symbol	LOLA II	LOLA III	LOLITA I
Mode family	—	"TM_{11}"	"TM_{11}"	"TM_{01}"
Phase shift per cavity	—	$2\pi/3$	$2\pi/3$	$2\pi/3$
Periodic length (cm)	d	3.5	3.5	3.5
Disk thickness (cm)	t	0.584	0.584	0.584
Cavity inside diameter (cm)	2b	11.7894	11.5712	7.9598
Beam aperture diameter (cm)	2a	4.064	4.732	2.324
Beam aperture offset (cm)	e	0	0	2.497
Suppressor holes diameter (cm)	2p	1.905	1.905	0
Suppressor holes offset (cm)	c	3.619	3.810	0
Length of experimental section(cm) Including both couplers	ℓ	52.5	28.0	28.0
Quality factor	Q	9030	11000	11360
Cold test frequency(75°F,air)(Mc/sec)	f	2857.0	2856.0	2856.8
Relative group velocity	v_g/c	-0.0296	-0.00779	-0.00745
Attenuation per meter (NP/m)	I	0.1105	0.3457	0.3514
$E_o/\sqrt{P_o}$ $(MV/m/\sqrt{MW})$	$\sqrt{Z}$	1.94	3.04	4.06
Transverse shunt impedance (MΩ/m) Measured with beam	$r_{o,T}$	15.70	11.70	20.50
Measured by microwave perturbation method	$r_{o,T}$	15.50	12.4	21.58
PREDICTED PERFORMANCE FOR THREE-METER STRUCTURE				
Attenuation (NP)	$I\ell$	0.331	1.0371	1.0542
$(1 - e^{-I\ell})\sqrt{2I\ell}/I\ell$	—	0.670	0.894	0.895
Predicted deflection $(MeV/\sqrt{MW})$	$p_\perp c/\sqrt{P_o}$	4.60	5.29	7.02

LIST OF FIGURES

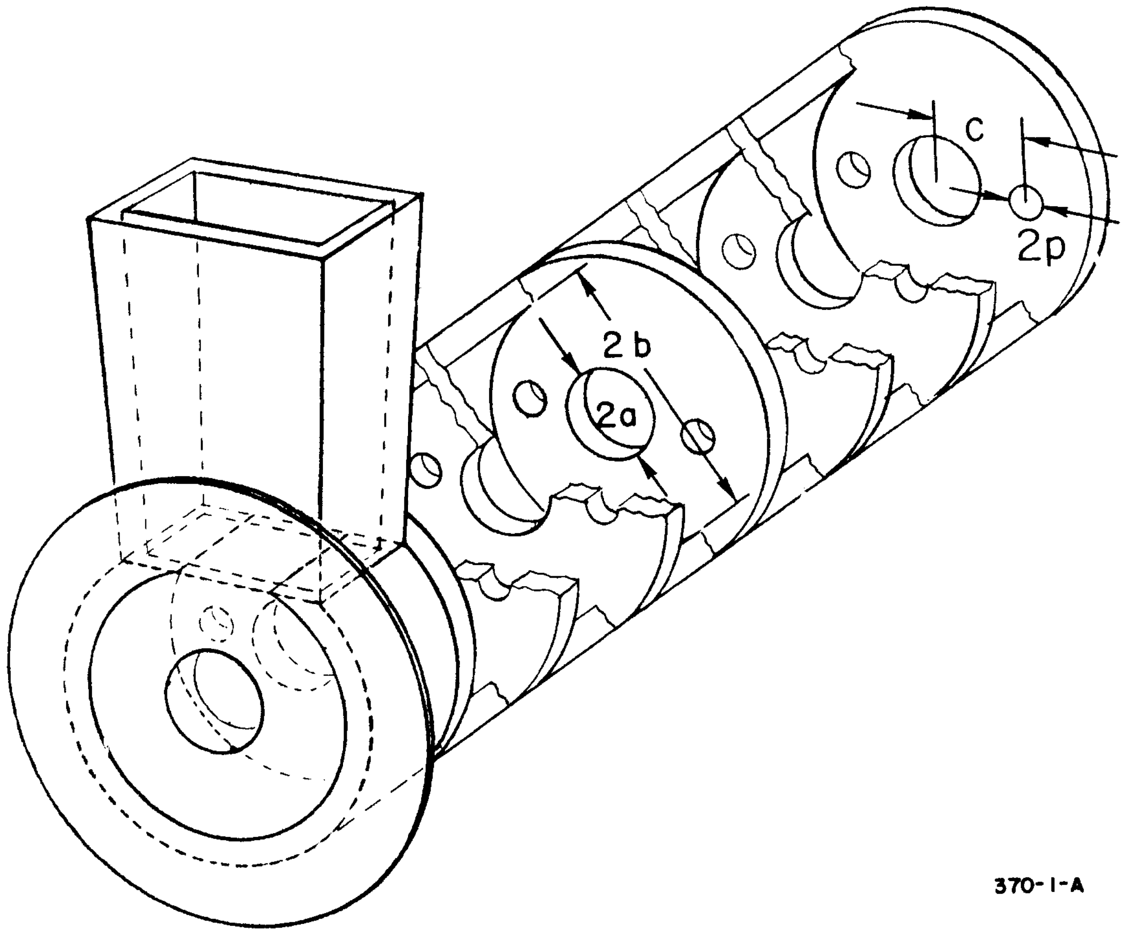

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FIG. 1

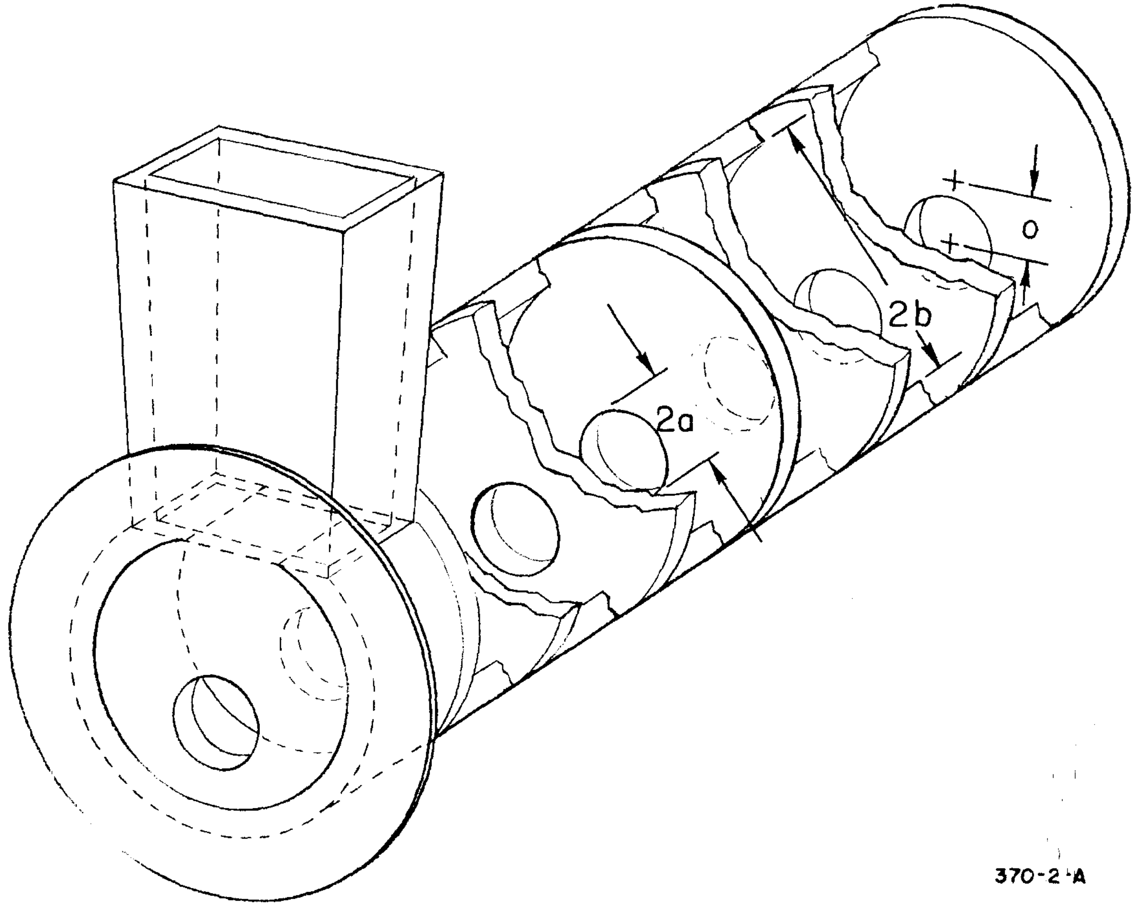

FIG. 2

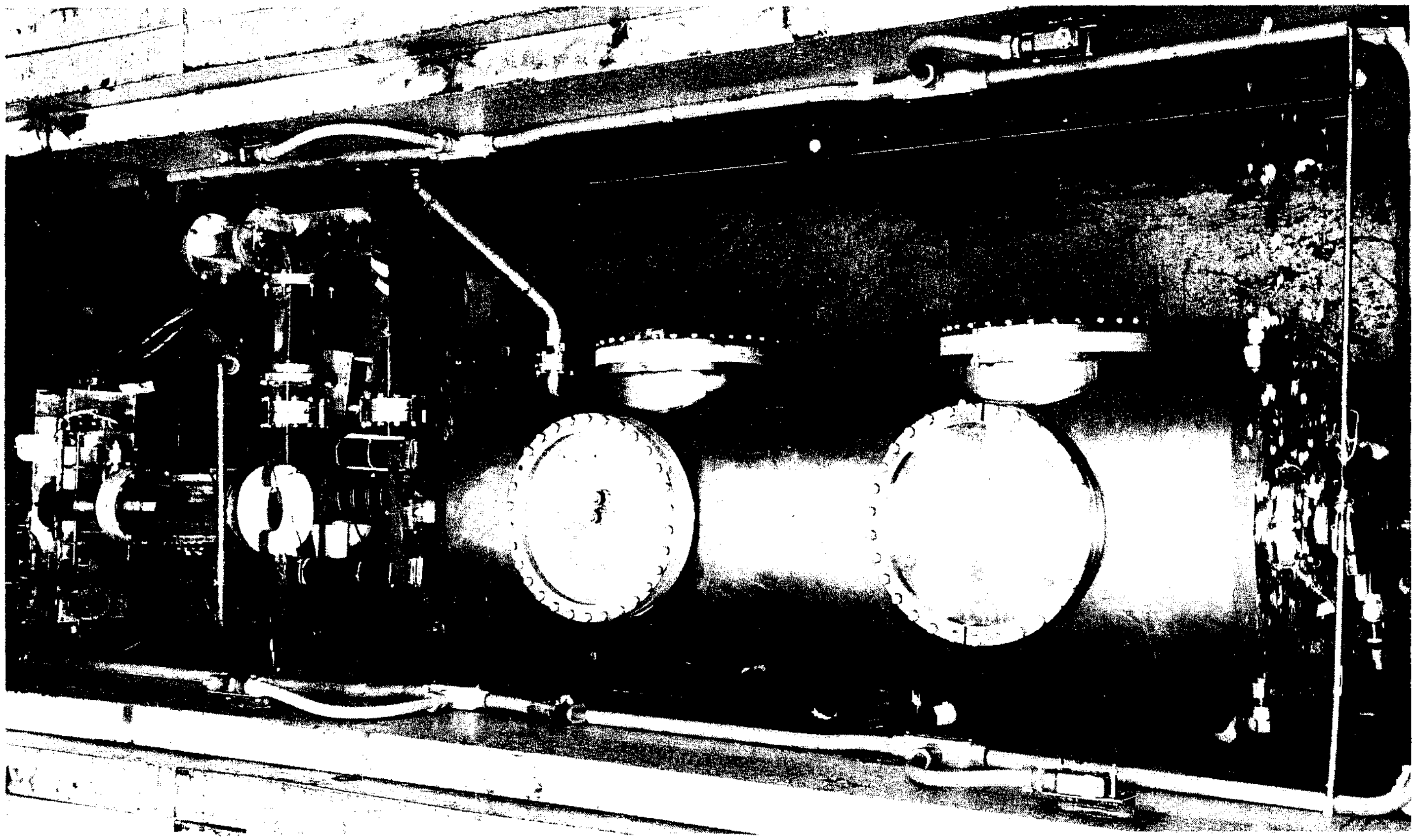

FIG. 3

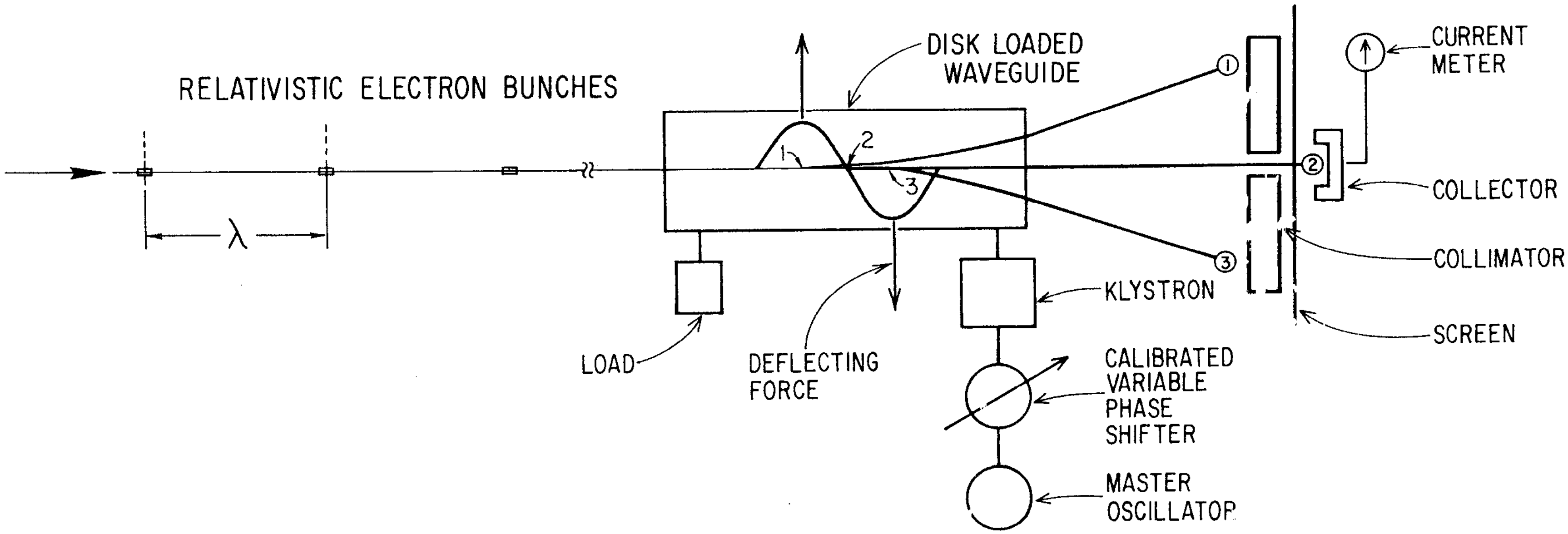
RELATIVISTIC ELECTRON BUNCHES
λ
DISK LOADED WAVEGUIDE
1
2
3
CURRENT METER
COLLECTOR
COLLIMATOR
KLYSTRON
SCREEN
LOAD
DEFLECTING FORCE
CALIBRATED VARIABLE PHASE SHIFTER
MASTER OSCILLATOR

FIG. 4

67-7-8

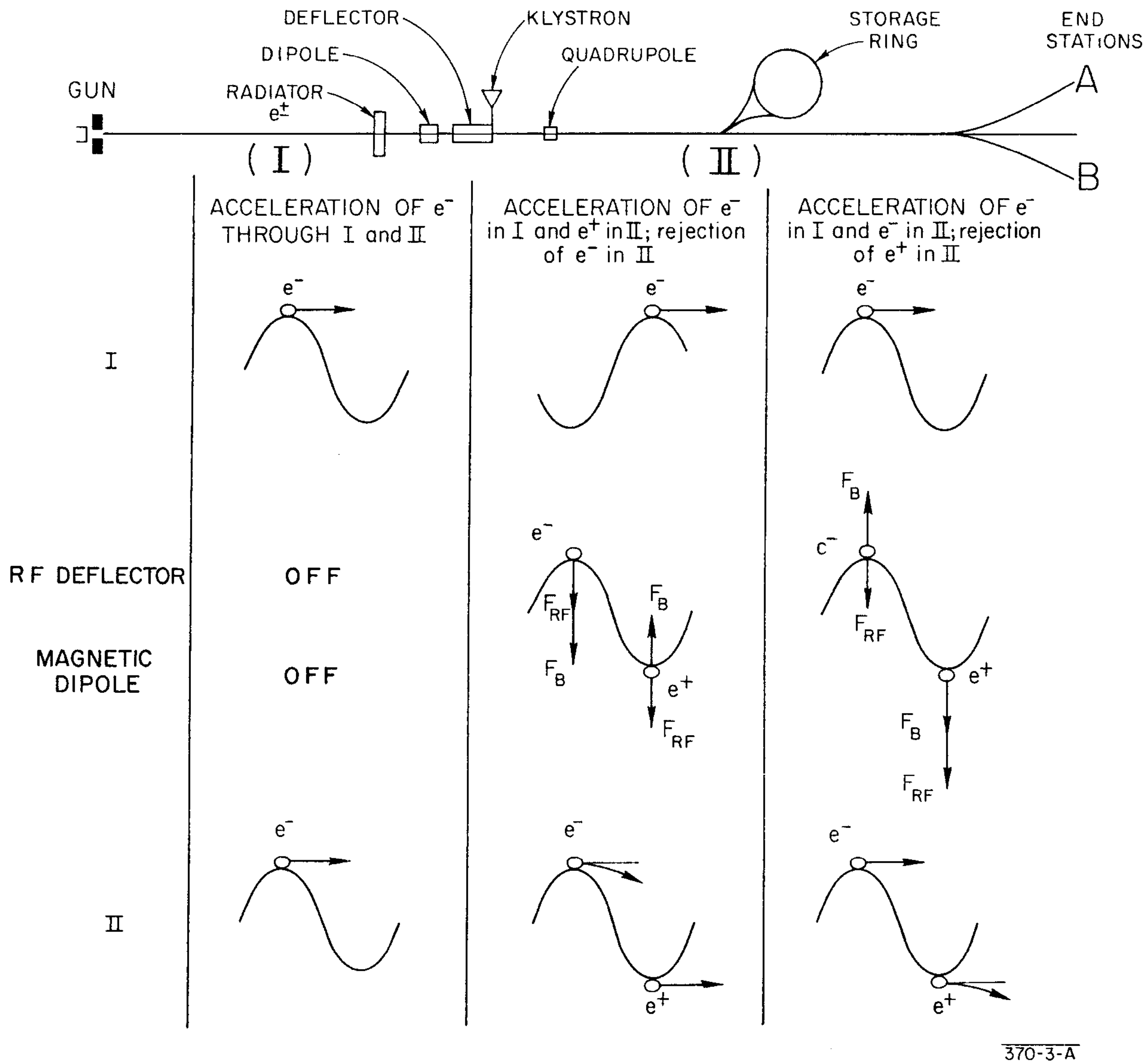
GUN
RADIATOR
e±
DIPOLE
DEFLECTOR
KLYSTRON
QUADRUPOLE
STORAGE RING
END STATIONS
A
B
(I)
(II)
ACCELERATION OF e⁻ THROUGH I and II
ACCELERATION OF e⁻ in I and e⁺ in II; rejection of e⁻ in II
ACCELERATION OF e⁻ in I and e⁻ in II; rejection of e⁺ in II
I
RF DEFLECTOR
MAGNETIC DIPOLE
II
OFF
OFF
e⁻
e⁺
F_B
F_RF
370-3-A

FIG. 5