DESIGN AND APPLICATIONS OF R.F. DEFLECTING STRUCTURES AT SLAC *

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(Presented by G.A. Loew)

I. INTRODUCTION

This paper summarizes the work done at SLAC on r.f. deflecting structures since the 1963 Dubna Conference (1, 2, 3). Because there is no plan to have an r.f. separated beam available immediately upon turn-on o fthe 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 r.f. 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 r.f.-separated beams are extremely low. Using the definition of transverse shunt impendance per unit length defined by

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

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

$$p_\perp c = q\sqrt{2Il}\,\frac{1 - e^{-Il}}{Il}\,\sqrt{P_o l_T} \qquad [2]$$

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 " r.f. 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 l for LOLA III comes very close to the optimum of 1.26 which maximizes the function of I l 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 l, yields a better deflection than LOLA II. In addition, the larger aperture (2a) provides a better acceptance. Because the acceptance varies as the deflecting

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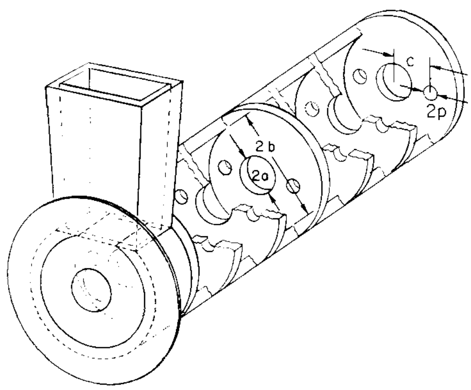

Fig. 1 - The « TM_{11}-type » deflecting structure (LOLA).

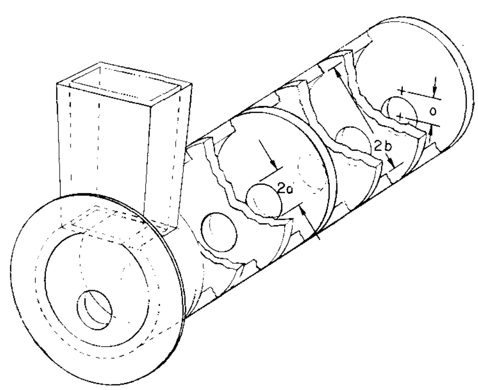

Fig. 2 - The « TM_{01}-type » deflecting structure (LOLITA).

field an 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

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	—	2π/3	2π/3	2π/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	7.5598
Beam aperture diameter (cm)	2a	4.064	4.732	2.324
Beam aperture offset (cm)	o	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)	Il	0.331	1.0371	1.0542
$(1-e^{-Il})\sqrt{2Il}/Il$	—	0.670	0.894	0.895
Predicted deflection (MeV/$\sqrt{MW}$)	$p_\perp c/\sqrt{P_o}$	4.60	5.29	7.02

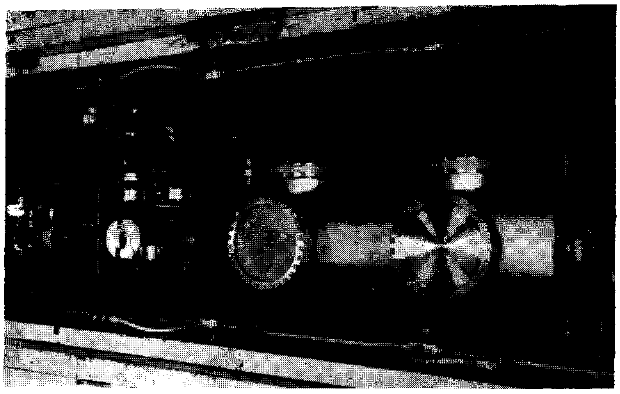

Fig. 3 - Experimental set-up showing deflecotr, momentum spectrometer, and evacuated tank with end plate to measure beam deflection.

is negative. The transverse shunt impedance is about twice that obtained for LOLA III for approximately the same value of I *l*. 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 r.f. separators, this property added to the lower acceptance may be a serious

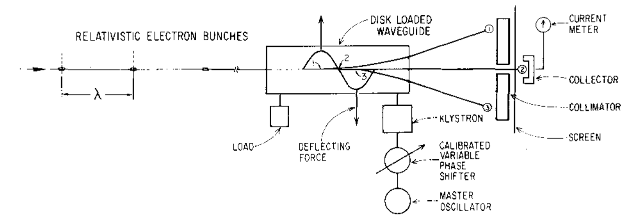

Fig. 4 - Deflector used as bunch-width analyzer.

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 tests cell. The value of the fundamental space harmonic is 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

Fig. 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

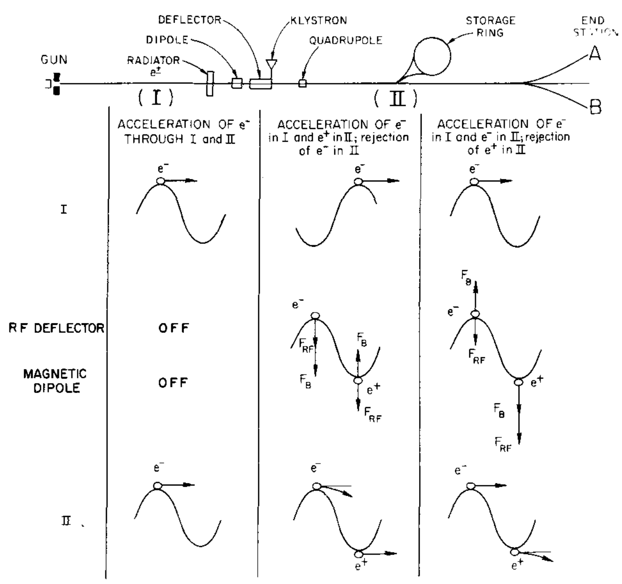

Fig. 5 - The three modes of operation of the electron-positron deflecting system.

by a steel plate, whereas electrons in position 2 remain undeflected and are collected. The device can be calibrated by varying the input r.f. 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 r.f. 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 r.f. 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 r.f. deflector. Depending on the combinations of r.f. 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 dimension of LOLA II. It will be supplied with 0.2 MW of peak power to produce a transverse momentum of 0.4 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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DISCUSSION

MULLETT: Is the perturbation of the TM_{01} mode large so as to produce negative group velocity and hence a transverse deflection?

LOEW: Indeed, the iris offset is a large perturbation of the TM_{01} mode. For a given offset, the structure is cut-off. Beyond this offset, the structure becomes of the backward-wave type. This corresponds to the case where the coupling from one cavity to the next becomes predominantly magnetic rather than electric.

MONTAGUE: I think that if you devide your waveguide "LOLA" along the median plane and distort the two semi-circular halves suitably you have essentially two "LOLITAS". In LOLA, the deflection force is proportional to grad E_z and therefore there is an accelerating force one side of the axis and a decelerating force the other side. This is compatible with the properties of "LOLITA". This accelerating force has been discussed in CERN in connection with the analysis of the 10 GeV/c K^- bubble chamber photos. In principle it is possible for the two halves of the separated beam, split by the beam stopper, to have slightly different momenta; in practice the effect is small and can be neglected.

LOEW: I still believe there is a basic difference between the TM_{01} and the TM_{11} structures since the cut-off frequencies and therefore the cross-sectional dimensions are different.

SAXON: In the TM_{01} mode with offset iris holes, how constant are the deflecting and accelerating field across the aperture?

LOEW: Although we do not yet have measurements of beam aberrations, one microwave measurements seem to indicate that this TM_{01} structure is also aberration-free.

COURANT: It would seem to me that quite generally, regardless of the details of the r.f. structure, Hamiltonian beam dynamics requires that a device which produces a phase-dependent transverse deflection must also produce an acceleration dependent an transverse position.
LOEW: Yes.

LAPOSTOLLE: In addition to B. Montague's remark. I should like to notice that this description of LOLITA as a half LOLA results in a twice as large shunt impedance (same field for half flux of power) in reasonable agreement with experiments.

RADIO-FREQUENCY PARTICLE SEPARATION USING PRIMARY BEAM MODULATION

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1. INTRODUCTION

In January of this year the CERN radio-frequency separator (1) came into full operation in the 02 beam (2) (3); by April it had successfully completed three runs, during which a total of over 200'000 photos of 10 GeV/c K^- were taken in the 1m52 British Hydrogen Bubble Chamber.

The long shut-down of the PS this summer has been used to make a number of improvements to the r.f. separator. This autumn, operation will start again in a new beam, called U1, which will serve the CERN 2-metre Bubble Chamber. The U1 beam will use an external target in conjunction with a fast-ejected primary beam from the CPS.

One of the practical problems associated with high-energy separated beams from proton synchrotrons is the long flight path required to carry out momentum selection and mass separation sequentially. R.f. separators in particular make heavy demands in this direction, partly because of the high momenta for which they are most interesting and partly because of the need for an efficient final momentum selection after mass separation.

The necessity for re-defining momentum just before the bubble chamber arises mainly from the relatively large acceptance of r.f. separated beams compared with those of electrostatic separators, which makes for greater transmission of unwanted background. In particular there is a substantial contribution of muons resulting from pion decay; such muons are emitted at angles small enough to remain within the acceptance of the beam channel but not so small as to continue along the trajectories of their parent pions to hit the beam stopper. A narrow momentum acceptance near the end of the beam can do much to reduce this muon contamination.

When the 02 beam operated during the first half of 1965, practical limitations on flight path length and layout limited the resolution of the final momentum analyser, resulting typically in a muon flux of 30-40% of the total flux in the bubble chamber. Although, again due to lack of space and bending angle, the U1 beam will have even less momentum selection at the end, other factors in the beam design are expected to reduce the muon flux in the bubble chamber substantially below that of the 02.

Nevertheless, reduction in length between target and beam stopper would permit a further

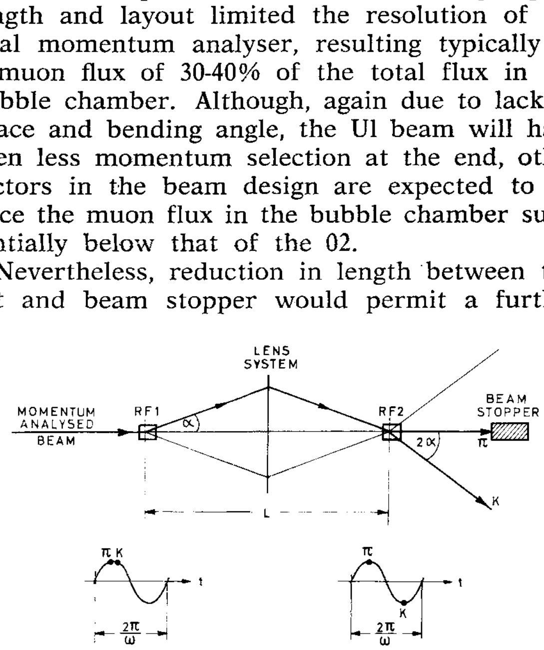

Fig. 1 - Principle of CERN r.f. separator.

reduction in muon contamination, not only because of the extra length available for final momentum selection, but also because of the shorter flight path fo rpion decay. The r.f. separation scheme proposed in this paper should make possible a useful saving in length by arranging that one section of the beam fulfils two functions simultaneously. The method is dependent on ha-