THE BROOKHAVEN RADIOFREQUENCY BEAM SEPARATOR *

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(Presented by J.P. Blewett)

I. INTRODUCTION

The r.f. beam separator proposed by Panofsky (1) and elaborated by Schnell (2) appeared to have some practical advantages when compared with the separation schemes conceived and studied by Blewett (3, 6) and Robertson (7, 9), and the investigation of Panofsky's separation method was started by the authors in 1961 at Bookhaven (10). The beam optics for this separator was studied at Yale by a group under Sandweiss (11, 12). Our r.f. beam separator is now essentially completed and will be installed in the so-called beam No. 4 between section I-10 of the AGS and the 80-inch bubble chamber during an AGS shutdown in October 1965 This paper is only intended as a summary of the more important features of the r.f. beam separator whereas details my be found in the references cited.

II. PRINCIPLES OF OPERATION

The separator analyzes the different masses of the particle species in a momentum analyzed beam with the help of two r.f. deflecting fields as follows. The beam, imaged into deflector # 1 experiences a vertical angular deflection $\hat{\theta} \exp(j\omega t)$. After traversing a drift space of length L, the particles receive a second deflection which is phased so that for unwanted particles the first deflection is cancelled out. Due to their different time of flight, wanted particles receive, in general, a net deflection and will, at least in part, pass a beam stopper, which on the other hand intercepts all of the unwanted particles. The separator stage starts at the « mass-slit » which defines the angular divergence of the beam in the deflector. It ends at the beam stopper, where angular deflections in the deflectors are reconverted into positions. The basic properties of the separator are summarized in Table I. The beam stopper will be wider than required by the mass slit image to accomodate chromatic aberrations, phase and amplitude errors of deflections, nonisochronous transmission in the inter deflec-

TABLE I

Properties of the r.f. beam separator

Total length	129 m
Deflector distance L	40 m
Intrinsic deflector acceptance Δ	120×10^{-6} cm^2 sterad
Momentum bit $\Delta p/p$	$\approx 1\%$
Inherent total angular spread of beam (beam optics)	$\leq 1.2 \times 10^{-3}$ rad (adjustable)
Peak deflection per deflector $\hat{\theta}$ ($p_T = 18$ MeV/c)	$\geq 1.0 \times 10^{-3}$ rad
Beam stopper size (muon background)	$\geq 2 \times 10^{-3}$ rad (adjustable)
Loss in beam stopper (beam stopper size)	$\geq 34\%$ (variable)

TABLE II

Operating momenta and deflection efficiency for beams with two-contaminant rejection

The condition for two-contaminant rejection is given by $\tau_{U1} - \tau_{U2} = 2 m \pi$, with m = 1, 2, 3, ..., provided that the deflection efficiency $\varepsilon_W = \psi/2\hat{\theta}$ of wanted particles is sufficient. We define the phase slip of one particle as $\tau = \frac{1}{2} k L (c m_o/p)^2 + \tau_o$, where τ_o = r.f. phase difference between deflectors, k = wave number in free space, L = deflector distance, m_o = rest mass, and p = momentum. θ is the peak deflection in each deflector (1 mrad at BNL), and $\psi = 2 \hat{\theta} \sin \tau/2$ the total deflection of a particle after passing both deflectors. $X = (p_o/p)^2$ where the design momentum $p_o = c^2 (m^2_{oK} - m^2_{o\pi}) L/\lambda_o = 9.245$ GeV/c for the BNL separator with L = 40 m and $\lambda_o = 10.5$ cm.

Beam	m	X	p (GeV/c)	τ_{WU}	ε_W
K	1	0.521	12.81	1.637	0.730
K	2	1.043	9.05	3.277	0.998
K	3	1.564	7.39	4.913	0.633
π	1	0.705	11.01	2.215	0.894
π	2	1.410	7.79	4.430	0.800
$\bar{p}$	$\tau_{p\pi} = \pi$	0.261	18.11	$\tau_K = 0.820$	$\varepsilon_K = 0.399$

* Work performed under the auspices of the U.S. Atomic Energy Commission

tor drift space, and in order to intercept and degrade beam like μ-mesons. This last requirement will be the main determining factor for the width of the beam stopper.

III. OPERATING MOMENTA AND PARTICLE FLUXES

π^- beams are possible without separation. π^+ beam require the removal of protons. $K^\pm$ and $\bar{p}$ beams require the rejection of two species of U particles and operation will be possible at certain selected momenta only (11). The operating momenta for two-contaminant rejection are listed in Table II (13). It is anticipated to use the r.f. beam separator with a fast ejected beam (14, 15). This is necessary for two reasons: the particle bursts of 2.2 μs are well matched to the 5 μs r.f. pulses from the klystrons and the external target allows the utilization of the high fluxs of a zero degree secondary beam. In fact, the extraction of a single bunch will be tried. This would considerably alleviate the requirements on phase jitter and amplitude ripple during one r.f. pulse. An estimate of secondary particles (13) indicates that the full machine intensity may be required for the $\bar{p}$ experiment; all others can be carried out with one bunch extraction.

IV. THE DEFLECTOR

For proper operation, the r.f. beam separator described above requires deflectors which are

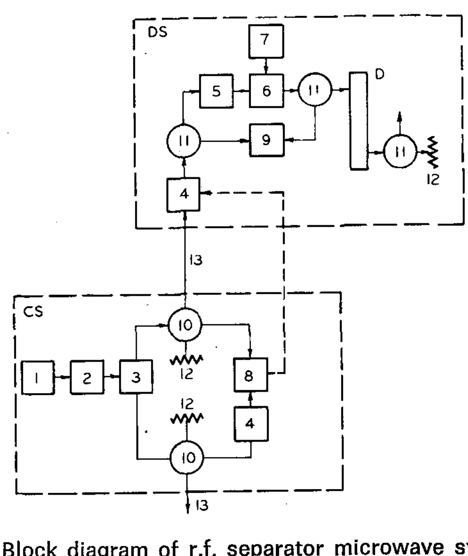

Fig. 1 - Block diagram of r.f. separator microwave system. D. Deflector; CS. Central control station; DS. Deflector station; 1. Phase locked source; 2. TWT amplifier; 3. Power splitter T; 4. Phase shifter; 5. Pulsed triode amplifier; 6. Klystron; 7. Modulator, 8. CW phase servo; 9. Pulsed phase meter; 10. Four port circulator; 11. Directional coupler; 12. Dry load; 13. Coax cable of 30 m length.

capable of imparting a transverse momentum $P_T > 18$ MeV/c to traversing ultrarelativistic particles. Furthermore, the deflections should be independent of initial position or angle, i.e., an aberrationfree deflection is desirable. An iris-loaded structure operating in a backward wave HEM_{11} deflecting mode was selected and our investigations showed that both conditions are satisfied (16). Using the deflector parameters listed in Table III and Table IV, it may easily be verified that klystron pulses $\hat{P} \geq 14$ MW should give particle deflections of $\geq$ 1 mrad peak per deflector over the momentum range of interest. The deflectors were tested to operate at 18 MW levels without electrical breakdown, so that a comfortable safety margin in deflection is provided.

TABLE III

Properties of Iris-Loaded deflector

Design wavelength	$\lambda_o = 10.495$ cm
Design frequency	$f_o = 2856.451$ MHz
Anticipated operating frequency	$f_{op} = 2856.17$ MHz
Phase shift per cell	$\Phi = \pi/2$
Pitch	w = 2.624 cm
Iris thickness	w-d = 5.25 mm
Aperture	2a = 48.13 mm
Outer diameter	2b = 116.71 mm
Length	$l = 117 + 2$ cells ≈ 3.07 m
	$R/Q = 1.41$ kΩ/m
Quality factor	Q = 8700
Shunt impedance	R = 12.3 MΩ/m
Group velocity	$v_g/c = -0.0204$
Attenuation parameter	$\alpha l \approx 0.5$ Np
Coupler	VSWR ≤ 1.1
Filling time	$t_f \approx 0.5$ μs

TABLE IV

Cold measurements of deflectors

The frequency $f_{\pi/2}$ is quoted for 25°C and in vacuum. The quality factor is calculated according to

$$Q = \omega l / 2 v_g \, \alpha l,$$

where $|v_g/c| = 0.0204$ and $l/\lambda_o = 29.25$ was taken.

Defletcor	$f_{\pi/2}$(MHz)	αl	Q	VSWR	$\Delta\Phi_{RMS}$
No. 1	2856.17	0.477	9450	1.03	1.6°
No. 2	2856.45	0.550	8200	1.07	3.5°
No. 3	2855.88	0.490	9200	1.20*	4.7°

* Coupler mismatch has to be improved.

V. THE MICROWAVE SYSTEM

The objective of the microwave system is to generate r.f. pulses of correct frequency (2856.17 Mc), amplitude (14 MW), phase and duration (4.5 μs), in each deflector. The residual deflection of unwanted particles, $\Delta\psi_U$, is in first approximation given by $\Delta\psi^2_U = (\hat{\theta}\,\Delta\tau)^2 + (\Delta\theta_1 - \Delta\theta_2)^2$ were $\Delta\tau =$ phase error between cavities and $\Delta\theta_1$, $\Delta\theta_2 =$ error in deflection in first and second deflector. The tolerances will strongly depend on the choice of mass slit and beam stopper size. Design specifications are $\Delta\tau < 10°$ and $(\Delta\theta_1 - \Delta\theta_2)/\hat{\theta} < 6\%$. The blok diagram of the microwave system for the Brookhaven r.f. beam separator is sown in Fig. 1. From measurements it follows that errors in deflections will be negligible. The phase difference between deflectors will be caused by temperature drift in the coax cables, by the phase changes in the high power klystron (RCA 8568), and to a smaller degree by the pulsed triode amplifier (6442). Slow phase changes of the TWT amplifier (RCA 4054V1) occur before the power-splitter and are inconsequential. The phase servo will measure and compensate any steady-state phase difference which may exist at the cable ends driving the deflectors. Phase noise was minimized by use of a phase-locked r.f. source (17). The phase shifter at the central control station allows to adjust the required initial phase difference between deflectors. The complete system was thoroughly tested and its performance was judged entirely satisfactory for its use in an r.f. beam separator (18).

Acknowledgements

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DISCUSSION

MINTEN: How do you count particles in a burst of 2 μ sec?

BLEWETT J. P.: The detector will be the 80" liquid hydrogen bubble chamber.

SEMENYUSHKIN: Which is the phase stability in r.f. separators and which is the phase control for work r.f. separator?

BLEWETT J. P.: The phase error between the two deflectors will not be appreciably greater than 5°.

MARTIN J. H.: What limits the angle of deflection available in the separator? Is it power, voltage breakdown, or what?

BLEWETT J. P.: The deflectors are not limited by breakdown. The maximum deflection is set by apertures in the system.

VALDNER: What is the quality of the beam? (how many particles of other type per 1000 particles?). In the calculations of the quality of the beam have you considered the background due to the particles decay in the separator?

BLEWETT J. P.: The antiproton beam will include about 20 antiprotons per 10^{12} protons on target. Expected contamination of this beam will be primarily muons.