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OPERATION OF ARGONNE NATIONAL LABORATORY'S RF PARTICLE SEPARATOR IN THE TRAVELLING WAVE MODE*

A. Moretti and P. F. Schultz
Argonne National Laboratory
Argonne, Illinois

Summary

Argonne's two RF deflector separated beam line has been operated in the travelling wave mode. It has produced a good yield 50% pure $\overline{p}$ beam at 4.08 GeV/c. The operating frequency is lowered to make the phase velocity of the RF separator synchronous with the wanted particle. Results for $\overline{p}$ beams at 2.57, 4.08 and 5.77 GeV/c are presented. In addition, the operation of the travelling wave separator in the "non-conventional" manner, i.e., phase velocity synchronous with unwanted particle, is described.

Introduction

Argonne's RF separated beam line, Beam 10, utilizes two 3.57 m long copper s-band iris-loaded circular waveguide deflecting structures.[1] The structures are operated in the HEM_{11} $2\pi/3$ deflecting mode[2] with a phase velocity of c at 2856.2 MHz. The structures can be operated at a phase velocity smaller than c by simply changing the RF frequency. In our case, the deflecting structure supports a backward wave in its HEM_{11} passband, i.e., negative group velocity; therefore, the phase velocity can be reduced by slightly lowering the operating frequency. The RF separator then may be operated in the travelling wave mode.[3]

To produce separated beams at low momentum, the phase velocity is adjusted to be synchronous with the velocity of the wanted particles. They, therefore, receive large angular deflection while passing through the deflectors. The angular deflection is transformed by the beam optics into a large vertical displacement at the beam stopper plane. The unwanted particles being nonsynchronous undergo large phase slip while passing through the deflectors. They receive little angular deflection and, therefore, not enough displacement to clear the beam stopper. The beam stopper size can then be adjusted so that a large fraction of the wanted particles clear the stopper, while intercepting a large fraction of the unwanted particles. In addition, the phasing between the separators can be adjusted to further minimize the deflection of the unwanted particles at a cost, however, of some deflection of the wanted particle.

RF Separator Principles

A particle travelling synchronously through the RF separator will experience an EM field which appears static to it. In this case the field, HEM_{11} deflecting mode will impart energy to the particle in the transverse direction given by

$$P_T c = \frac{\left(e\, 2\alpha R L^2 P_o\right)^{1/2} \left(1 - e^{-\alpha L}\right)}{\alpha L} \cos(2\pi f t) \qquad (1)$$

where e is the charge of an electron, α is the attenuation factor of the field, R is the shunt impedance of the RF deflector defined as square of the energy gained in transverse direction per unit length to the power lost per unit length, L is the length of RF deflector, P_o is the power, f is the RF frequency and t is the time.

The maximum deflection given to nonsynchronous (unwanted) particles while travelling through one deflector can be shown to be given by[3]

$$D_{nsyn} = \frac{\sin(\psi/2)}{\psi/2} D_{syn} . \qquad (2)$$

where ψ is the total phase slip in radians between the EM wave and nonsynchronous particle, and D_{syn} is the maximum deflection given the synchronous particle.

$$\psi = 2\pi fL/c\left(1/\beta_1 - 1/\beta_2\right) \qquad (3)$$

where the β's are the relative velocity of the particles.

It can be shown from Eqs. (2) and (3) that for large phase slips ψ the D_{nsyn} is much smaller then D_{syn}. In fact, for wanted $\overline{p}$'s below 3GeV/c, $|D_{nsyn}| < |D_{syn}|/4$. The unwanted particles essentially pass through undeflected. In our case, since we have two RF deflectors separated by a drift length of 31.25 m, the ratio of nonsynchronous to synchronous particle deflections is further reduced over certain momentum bands, this will occur in momentum regions where there is $(2n \pm 1)\pi$ phase shifts over the drift length between the wanted and unwanted particles. At low momentum this occurs quite frequently.

The method described above for producing RF separated beams is often referred to as the conventional travelling wave mode. The wanted particles are made synchronous with the HEM_{11} wave and are given enough deflection to clear a beam stopper situated along the beam axis. However, for beams with only one appreciable contaminating particle, a second method of separation is possible, the "so called" non-conventional travelling wave mode. In this method, the contaminating (unwanted) particle is made synchronous with the travelling HEM_{11} deflecting mode. It, therefore, receives a large angular deflection while passing through the first RF separator. A stopper converse to the conventional stopper, i.e., hole along the axis, can be placed between the first and second RF separator to intercept the particles of large deflection. The remaining undeflected unwanted particles can then be deflected by the second RF deflector and intercepted by a second downstream converse stopper. The wanted particle being nonsynchronous is undeflected and, therefore, passes on through and separation is accomplished.

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Beam Optics, Instrumentation and Tuning

Secondary particles are produced at 0^o in the extracted proton beam of the ZGS.[4] After the preseparation momentum analysis ($\Delta p/p \sim \pm 1\%$) the beam is restored parallel to the initial extracted proton beam. The separation stage then extends from the vertical angle collimator through the two cavities and to the beam stopper where the unwanted particles are removed. The target is focused vertically and horizontally in both RF deflectors with unity angular magnification between them. Angles of particles at the second RF deflector are converted to vertical positions at the beam stopper. For optimum transmission of wanted particles the deflection given by each separator should be the same as the angular spread set by the angle collimator and the beam stopper size is then made large enough to intercept the unwanted particles.

A collimator immediately following the beam stopper redefines the image for the post-separation momentum analysis. This analysis is done at a collimator following the final bend. The collimator, set at $\Delta p/p \sim \pm 1\%$, has the low momentum jaw magnetized to 15 kG to sweep the muons, which have lost momentum in the beam stopper, away from the bubble chamber. The final stage also focuses the beam vertically and spreads it horizontally at the bubble chamber entrance window.

The beam stopper height and all collimator settings are remotely controlled. Beam profiles at the several horizontal and vertical foci are observed using 24 wire-2 mm spacing proportional wire chambers operating with either integrating or digital readout electronics, depending upon the counting rates at the chambers. There is also a 96 wire-2 mm spacing proportional chamber in front of the beam stopper. This chamber is used for matching deflections of the two deflectors and choosing the proper phase to achieve cancellation of the unwanted particles. Provision is also made for using scintillation counters at various places in the beam for measuring fluxes and particularly after the final momentum collimator where a gas Cerenkov counter is located.

A tuning matrix[5] is used to determine quadrúpole gradient changes necessary to move individual foci relative to the various detectors in order to determine quadupole gradients for optimum beam transmission and purity.

Results

Before proceeding with the results, a series of photographs of the beam profile will be presented demonstrating the operation of the travelling wave separator. All photographs are of positive tuning beams taken directly from the operating log book. They are photographs of the oscilloscope reading of the 96 wire proportional chamber in front of the beam stopper. The large discontinuous steps are due to malfunctioning wires. In addition, the beam was tuned by simply scaling the magnet settings from the values for a "good" tune at 6.5 GeV/c. The RF frequency as determined from the dispersion curve was set to the nearest crystal reference frequency to obtain a phase velocity nearly synchronous with the wanted particle. No frequency tuning was done to maximize the deflection of wanted particles.

Figure 1 shows the beam profile for a positive beam at 2.57 GeV/c with no RF power into the RF separators. One can see that the beam is all bunched in the center as it should be with no deflection. The height of the profile is proportioned to the number of particles counted while the width (inscribed number) is about 10 times the RF deflection in mrad, that is, 0.1 mrad corresponds to 1 wire spacing. Figure 2 depicts the beam profile with a power of 500 kW in RF separator #1 (RF1) and zero power in RF2. Now we see that the π's are still bunched in the center. They receive little deflection. In contrast, the p's receive large deflections and are spread out away from the center. An almost identical photograph was obtained by operating RF1 with zero power and RF2 with 500 kW. Figure 3 demonstrates the effect of operating with RF1 = RF2 = 500 kW and with an RF phase set so as to add the wanted particle deflections. The protons are given large deflections and unfortunately, from a pictorial point of view, large enough to reach unsensitive regions of the wire chamber. The π's can be seen still bunched in the center. Figure 4, 4.08 GeV/c is interesting in that it shows that as the momentum is raised, the π's which correspond to the two centered peaks begin to receive some deflection. However, the p's, the two end peaks, are receiving much larger deflections because they undergo less phase slip. Finally, Fig. 5, demonstrates the operation of the travelling wave separator in the "nonconventional" travelling wave mode. The beam is at 1.5 GeV/c. However, the frequency was raised to be synchronous with the π's. The p's occur in the center of the beam, in this case, because they undergo a large phase slip. The π's are spread out to large deflections. Only one separator was powered.

Table I lists the actual measured $\bar{p}$ flux and purity for each momentum per 10^{11} protons at 12.3 GeV/c incident on a production target of 6 mm x 5 mm x 30 mm beryllium. We wish to emphasize that the tune was merely scaled down from 6.5 GeV/c value with no attempt at fine tuning. Beam calculations show that higher purities of 60 and 70% are possible at 2.57 and 4.08 GeV/c respectively. At 5.77 we have almost reached the limit of 36% purity.

Table I

Momentum GeV/c	$\bar{p}$ Flux	Purity ($\bar{p}$/all)
2.57	2	0.25
4.08	4.5	0.50
5.77	1.5	0.33

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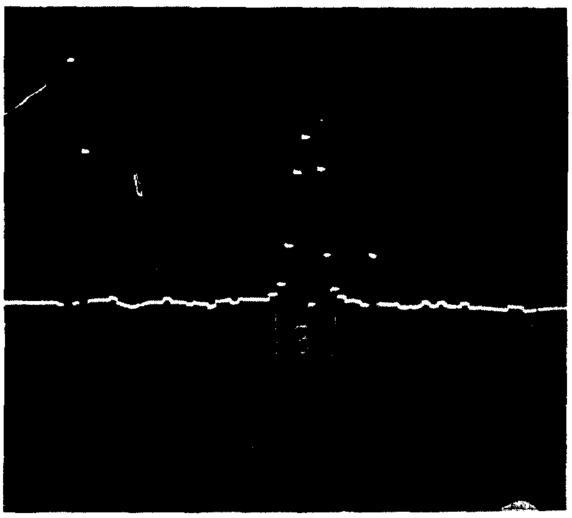

Fig. 1 2.57 GeV/c positive Beam, Zero RF Power

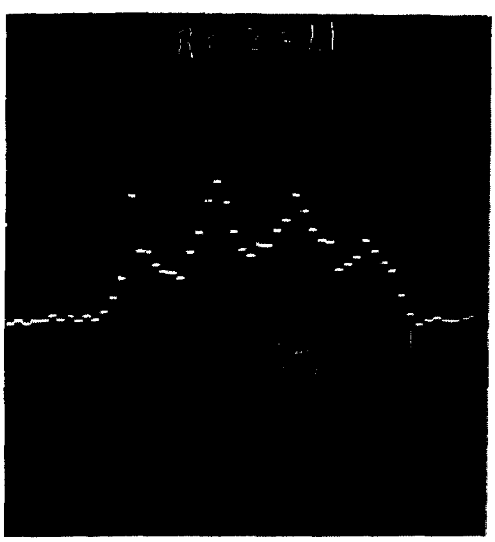

Fig. 4 4.08 GeV/c Beam RF1 = 0, RF2 = 1.1MW

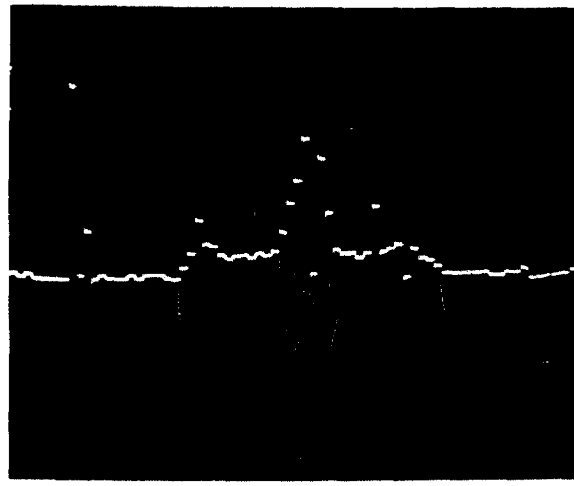

Fig. 2 2.57 GeV/c Beam RF1 = 500 kW, RF2 = 0, conventional travelling wave mode.

Fig. 3 2.57 GeV/c Beam RF1 = RF2 = 500 kW

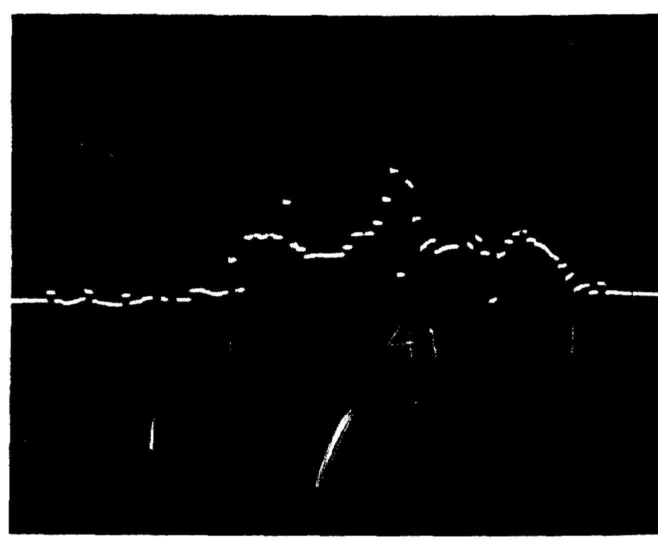

Fig. 5 1.5 GeV/c Beam RF1 = 500 kW, RF2 = 0, non-conventional travelling wave mode.