# USE OF DIELECTRIC LOADED WAVEGUIDES FOR RF PARTICLE SEPARATION AT NAL

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## ABSTRACT

It has been shown by Dawson and Kustom that a transverse deflecting mode can be propagated down a dielectric-loaded smooth-bore waveguide. This paper investigates the application of such deflectors to NAL beams. It is pointed out that substantial power economies appear feasible and that such deflectors may well allow CW operation with presently available power tubes.

## I. INTRODUCTION

Secondary beams from the NAL 200-BeV accelerator are confidently expected to be sufficiently intense so that counter spark-chamber experiments will require physical purification of the beam for efficient operation. As is well known, these beams must be capable of operating with duty factors of ~0.3. Straightforward scaling[1] of existing rf separators yields designs that are very likely capable of short-pulse operation at NAL, but fall considerably short of the long-pulse requirement. Specifically, cw power sources are not available, and if they were, the power dissipation in the deflector would present severe thermal and mechanical problems.

A possible solution has been suggested by H. Foelsche[2] which involves using a sequence of 10 iris-loaded deflectors, properly phased so that they present an equivalent single deflector of 10 times the length of one unit. It is easy to see that for the same total power the "10-fold deflector" provides $\sqrt{10} = 3.16$ times the deflection of a single deflector.

Another solution, of course, lies in the development of high power-density, superconducting deflectors. Although promising, this development continues to present many substantial technical difficulties.

It is the purpose of this paper to present another solution to the high-energy, long-pulse, rf-separator problem. In particular, it is proposed to use a dielectric-loaded waveguide which propagates a transverse deflecting mode with $v_{phase} \approx c$. Because the (rf) attenuation length of such a guide is much longer than for an iris-loaded structure, the deflector length can be correspondingly much longer. Since the deflection is proportional to the length, substantial power economies are effected.

## II. PROPERTIES OF THE DIELECTRIC-LOADED WAVEGUIDE

It has been shown,[3] both theoretically and experimentally, that a rectangular waveguide, coated on two faces with dielectric, can support a propagating deflecting wave with $v_{phase} = c$. For a considerable latitude of dimension, the deflecting mode [TE(0, 1)] is the lowest-frequency propagating mode. The structure is illustrated in Fig. 1.

The general property of greatest interest for the deflecting wave in a dielectric-loaded guide is the long attenuation length for the rf power. It is this feature which permits the use of long and hence power-efficient structures. The phase velocity $v_p$ of the deflecting wave can be adjusted ($v_p \sim 0.9c$ to c) by varying the frequency of the input rf power.

J. W. Dawson and R. L. Kustom of Argonne National Laboratory are currently designing a dielectric-loaded deflector for a low-energy $K^-$ beam which will operate at a frequency of 1.42 GHz. They have very kindly scaled their design to 10 GHz and calculated the parameters listed in Table I. It is worth noting that one can anticipate substantial improvement from a design optimized for 10 GHz operation. It thus appears conservative to use the parameters of Table I in the subsequent sections of this report.

Table I. Properties of a 10 GHz Dielectric-Loaded Deflector.

| | |
|---|---|
| Rf attenuation length (1/e) | 62 meters |
| Size of good-field region (± 15%) | 1 cm × 1 cm |
| Transverse momentum = $0.227 \sqrt{\frac{P_{(kw)}}{250}}$ | MeV/c/meter |

The dimensions of the structure are shown in Fig. 2. The dielectric used is BeO with a dielectric constant of about 6.0.

As an example we calculate the power required to give a 5 MeV/c transverse impulse. We assume a structure of 31 meters length ($\alpha \ell = 0.5$ as is typical practice with iris-loaded deflectors).

$$5 = 0.227 \sqrt{\frac{P}{250}} \times 31 \ .$$

Therefore, $$P = 126 \text{ kW} \ .$$

We can compare this with the power required to achieve a 5 MeV/c impulse in a typical iris-loaded structure, again with $\alpha\ell = 0.5$. We know[2] that here $\ell = 65$ cm and for this length

$$P_T = 18 \times 0.003\ P\ (\mathrm{MW})\ .$$

Therefore for $\quad P_T = 5$ MeV/c, $P = 2.57$ MW.

Thus, the dielectric-loaded structure is about a factor of 20 more efficient in the use of rf power.

We discuss briefly the required tolerances in the construction of a dielectric-loaded deflector. Essentially, the structure must propagate the deflecting wave at a phase velocity which is sufficiently well defined that the distinction between the velocities of the wanted and unwanted particles is not lost. An accurate calculation of the required tolerances has not been made, but an approximate argument is given below.

We assume the relationship between phase velocity and frequency for the mode of interest to be the same as for an "ordinary" TE or TM mode in a guide filled uniformly with a dielectric with an "average" dielectric constant.

From Fig. 2 and recalling $\epsilon = 6.0$ for the dielectric, the "average" dielectric constant, $\bar{\epsilon}$, is:

$$\bar{\epsilon} = \frac{2 \times 6.0 + 10 \times 1.0}{12} = 1.83\ .$$

For the TE (TM) waves, we have

$$\frac{v_p}{c} = \frac{1}{\sqrt{\bar{\epsilon}}}\ \frac{1}{\sqrt{1 - (w_\lambda / w)^2}}\ ,$$

where $w_\lambda$ = cutoff frequency, $w$ = operating frequency.

If we set $v_p = c$, $w = 8$ GHz, $w_\lambda = 5.39$ GHz. Using the above we easily see

$$\frac{dv_p}{c} = \frac{0.74}{\left[1 - (w_\lambda / w)^2\right]^{3/2}}\ (w_\lambda / w)^2\ \frac{dw_\lambda}{w_\lambda}\ ,$$

or

$$\frac{dv_p}{c} = 0.80 \frac{dw_\lambda}{w_\lambda} .$$

The most critical dimension is the width, a (the 3 cm dimension if Fig. 2), and we also have

$$\frac{dw_\lambda}{w_\lambda} = \frac{da}{a} .$$

Let the difference in velocity between the wanted and unwanted particles be $\Delta\beta$, and let us set the condition that $dv_p/c$ be $\lesssim 0.1\Delta\beta$. Then

$$0.1\Delta\beta \gtrsim 0.80 \frac{da}{a}$$

or

$$\frac{da}{a} \lesssim 0.125\Delta\beta .$$

As an example consider 40 BeV/c K, $\pi$ separation. Here $\Delta\beta = 0.72 \times 10^{-4}$ and $da/a \lesssim 0.9 \times 10^{-5}$.

In actual practice this tolerance can probably be relaxed by about a factor of 4 because 4 separate deflectors (each about 25 meters) would probably be used for a 40 BeV/c beam and errors in $v_p$ can be partially compensated by phase adjustment at the feed points. This is elaborated in Sec. III.

## III. SYNCHRONOUS SEPARATORS

At momenta up to ~40-50 BeV/c the length of a power-efficient dielectric deflector (i.e. with $\alpha\ell \sim 0.5$) is an appreciable fraction of the length required to slip phase by $\sim\pi$ radians between beam components at 8 KMC. This suggests the use of a synchronous separator in which $v_p$ is matched to $v_w$, the velocity of the wanted particles and they receive the maximum deflection.

The principal advantage of the synchronous separator is its wide momentum bandwidth. Unlike the usual two "point" deflector rf-separator systems, the synchronous separator does not involve precise cancellation of deflections given to unwanted particles. Thus it does not operate only at "special" momenta for which the cancellation is effective for two contaminants simultaneously. It is, in fact, for this reason that "point" deflector systems are now often made with three deflectors.

Figure 3 illustrates the principle of the synchronous separator. Because the unwanted particles slip phase with respect to the deflecting wave, they receive a smaller average deflection than the wanted particles. Figure 3 illustrates the "worst" case for the unwanted particles. Since we always assume a beam which is unbunched in time, we must reject those wanted particles which have received a deflection less than the maximum deflection of the unwanted particles. This gives rise to the so-called "stopper loss" of wanted particles. Table II lists the stopper loss of wanted particles for various phase slips $\phi$ for the unwanted.

Table II. Stopper Transmission for a Synchronous Separator.

| $\phi$, phase slip between wanted and unwanted, (radians) | Fraction of wanted particles transmitted around stopper, (%) |
|---|---|
| $0.25\ \pi$ | 6.66 |
| $0.50\ \pi$ | 28.9 |
| $0.75\ \pi$ | 42.6 |
| $1.00\ \pi$ | 56.0 |

Thus for phase slips $\phi \gtrsim 0.3\,\pi$, the synchronous separator has a stopper transmission greater than 10% which we regard as acceptable.

As an example of the use of the dielectric-loaded deflector in a synchronous separator, we now consider the application to the 20-40 BeV/c (for $K^{\pm}$ mesons) rf-separated beam designed by H. Foelsche.[4] In fact, we simply replace the ~110 meters between rf-1 and rf-3 by a 100-meter channel of a synchronous separator.

This is not exactly what one would do for an optimum beam design but is a reasonable approximation for our present purposes. If we choose 4 25-meter sections, each will have $\alpha \ell = 0.4$, and the deflecting field at the end will be ~67% of the field at the beginning. The average field is 82.5% of field at entrance or equivalently the effective deflecting power is 68% of the injected power.

The beam of Ref. 4 uses 3 point deflectors of 5 MeV/c each. We know that when a 3-deflector system is used with cancellation for the unwanted particles, the maximum deflection of the wanted is twice that of a single deflector. In this case, $2 \times 5 = 10$ MeV/c. Thus for equivalent operation, the 100-meter deflector must provide 10 MeV/c of transverse deflection. We note that Foelsche assumes 50% stopper transmission and that for a synchronous separator, the stopper transmission varies from 20% at 40 BeV/c (K's) to 80.5% at 20 BeV/c (K's).

We now calculate the required power. Using Table I and the above considerations, we calculate the average power flowing in the 100-meter structure.

$$10 = 0.227\ \sqrt{\frac{\overline{P}}{250}} \times 100,$$

therefore, $\overline{P} = 48.5$ kW.

Thus recalling that $\overline{P} = 0.68\ P_{inc}$, we find that each of the 25-meter sections must be fed by 71.5 kW. This is well within the scope of presently available power klystrons at 8 GHz and the total power of $4 \times 71.5 = 285$ kW is clearly low enough to allow cw operation.

The long (100-m) synchronous separator must be surrounded by a strong-focusing channel to keep the beam in the deflector. For the application described above, this channel can be rather modest (~10 quadrupoles) but has not been studied in detail.

The application of the synchronous separator to a very intense separated beam has been studied by T. Murphy[5] with considerable attention to the strong-focusing channel.

It is perhaps worth noting that the intensity of the Ref. 4 beam is not limited by separator function for most of its range but rather by the front end which was designed to be compatible with a large number of other beams in the second target area.

## IV. USE OF A DIELECTRIC-LOADED DEFLECTOR AS A "POINT" DEFLECTOR

As the momentum of the beam to be separated increases, the deflector length required for "adequate" transverse deflection becomes much less than the length required for $\sim\pi$ radians phase slip between wanted and unwanted particles. This arises, of course, from the constancy of the transverse momentum. It is in this case that separated "point" deflectors comprise the most effective rf separation system.

We consider briefly the application to the beam of Ref. 1. Here, we choose as our "point" deflector one 31-meter section ($\alpha\ell = 0.5$) of dielectric-loaded deflector. As in Sec. III, we calculate the required power input to achieve the 5 MeV/c deflection assumed in Ref. 1. We find

$$P_{inc} = 200 \text{ kW},$$

giving a total rf power (3-"point" deflectors) of 600 kW, again, well within the scope of presently available tubes at 8 GHz.

## V. HYBRID SYSTEMS

It seems plausible that some energy regions will be most efficiently covered by separator systems that combine features of the synchronous and "point" approaches, that is, "long" sections separated by significant drift spaces. Time does not permit a study of these systems here, but it is recommended that careful study be given them as it seems likely that substantial economies might be realized.

## VI. SUMMARY

The use of dielectric-loaded waveguides appears to offer large power economies compared to iris-loaded deflectors for the energy regions of interest at NAL.

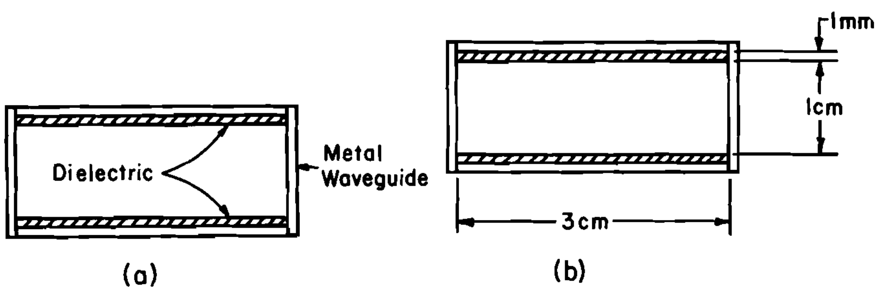
## REFERENCES


[1]See, for example, the analysis given by J. Lach, "A High Energy RF Separated Beam for the Proposed 200-BeV Accelerator," in 200-BeV Accelerator: Studies on Experimental Use, Vol. I, 1964-65, UCRL-16830, CCID-10184, p. 190.

[2]H. Foelsche, "A Normal RF Separator with 33% Duty Cycle," National Accelerator Laboratory 1969 Summer Study Report SS-13, Vol. I.

[3]J. W. Dawson and R. L. Kustom, "A Single Section Traveling Wave Particle Separator," Argonne National Laboratory, Internal Report JWD/RLK-1, June 17, 1968; also C. P. M. Chang, J. W. Dawson, R. L. Kustom 1969 Particle Accelerator Conference IEEE Trans. Nucl. Sci. NS-16, 3 (1969).

[5]C. T. Murphy et al., Twenty-Five Foot Bubble Chamber Film Format and Film Analysis Costs, National Accelerator Laboratory 1969 Summer Study Report SS-147, Vol. II.


Figs. 1a and b. Location and dimensions of dielectric loading in waveguide.

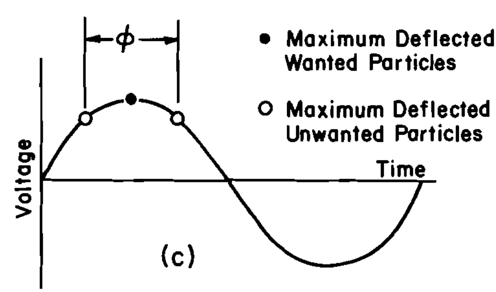



Fig. 1c. Phase relation between unwanted and wanted particles.