A NORMAL RF SEPARATOR WITH 33% DUTY CYCLE

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ABSTRACT

The paper gives an analysis of the parameters of an rf separator of long duty cycle employing normally conducting copper structures, operating at a frequency of 8 GHz. A comparison with an equivalent superconducting device is given. It is concluded that the normal separator is a technically feasible option. It would, however, become obsolete if and when the superconducting equivalent becomes operational at these high operating frequencies. The normal device would be quite useful in the energy region around 30 GeV as a stopgap solution in case the superconducting one gets delayed.

There is interest in having at least a modest enriched beam of K-mesons and antiprotons with essentially continuous duty cycle available at NAL in 1972. A superconducting rf separator would provide the preferred technical solution, but a high operating frequency of ~ 8 GHz is essential for the energy regions of interest at NAL. Efforts are underway at several laboratories (e.g., Stanford, Karlsruhe, Brookhaven) to achieve operable superconducting rf devices at operating frequencies between 1 and 3 GHz in the next few years, and eventually with the necessary stimulus from NAL, higher frequency devices will evolve.

The purpose of this note is to analyze a conventional option for the contingency that superconducting devices will be delayed: to employ normally conducting rf deflectors at X-band frequencies (say 8 GHz, wavelength 3.75 cm). This option has one and only one advantage: the probability for its success at an early date (given the same will) is in its favor, and its feasibility can be established quickly at a small fraction (< 10%) of the final system cost. On the other hand, it will be painfully obsolete as soon--or as late--as the superconducting device becomes practical. It suffices for beams of lower energy (say 30 BeV/c K's) but one should not contemplate its use at the ultimately available energies (~ 100 BeV). The main problem, on which a modest amount of laboratory testing would still be required, is not the availability of rf power, but its dissipation in the structure without detriment to the mechanical tolerances.

Some Reminders

The basic component in a conventional radiofrequency separator is an iris-loaded cylindrical waveguide. Such structures support a traveling wave deflecting field which imparts a transverse deflection on a particle passing in synchronism with it. A continuous beam would be made to describe an angular oscillation pattern, for example in the vertical plane. The oscillations imposed by several such structures, placed at certain distances along the beam, would interfere in a phase relationship which depends on the particle drift time between deflectors, hence on particle velocity. This velocity-dependent interference of angular oscillations is employed for separation of particles.

The waveguide is a periodic structure (see Fig. 1). In order to meet the boundary conditions on the electromagnetic fields, it has to support a mixture of space harmonics (propagating at different "phase velocities"), the fundamental of which will be the desired deflecting mode.* By proper choice of dimensions, this fundamental can be made to propagate at the velocity of light, and its relative size can be made as large as possible compared to the others.

In the conventional deflector, the electric field attenuates as it passes through the deflector due to dissipation losses in the walls. The "quality factor" Q of the structure measures the energy that can be stored in the field in units of the energy loss per cycle in the walls. As the power propagates along the guide at the "group velocity" V_g, it gets dissipated at a rate 2α [or with a power attenuation length $(1/2\alpha)$] and

$$2\alpha = \frac{\omega}{QV_g} \ \mathrm{cm}^{-1}, \tag{1}$$

ω being the angular frequency.

The maximum transverse momentum imparted to a beam particle (the amplitude of the angular oscillation induced on a passing beam) is given in terms of the equivalent deflecting field E_0 (at the rf input end) by

$$\frac{P_{\perp}c}{e} = E_0\ell \left(\frac{1-e^{-\alpha\ell}}{\alpha\ell}\right) \tag{2}$$

for a structure of length ℓ. The electric field E_0 is related to the required power P (at the input end) by

$$E_0^{\,2} = PZ, \tag{3}$$

where, finally, the impedance Z is obtained by space harmonic analysis. These relations will be useful for scaling from one wavelength to another.

One more important quantity is the sensitivity of the "phase velocity" of the

*For conventional TE or TM modes propagating at the velocity of light, electric and magnetic forces on a synchronous particle would cancel.

deflecting wave to small changes of frequency f, or equivalently, its sensitivity to changes of deflector dimensions. If this wave "runs away" from the particle by a phase u over the length of the deflector, the oscillation amplitude will be reduced by $(\sin u/2)/(u/2)$ and at a sufficiently large phase slip u (say 360°), the deflector would become ineffective. One may easily show that

$$\Delta u = 2\pi \cdot \frac{\ell}{\lambda} \cdot \frac{1}{V_g/c} \cdot \frac{\Delta f}{f}. \qquad (4)$$

The group velocity V_g enters critically into the deflector design, and its value is essentially determined by the diameter a of the iris hole.[1,2] For these structures, it is a small fraction of the velocity of light (0.01-0.04 c). The choice of group velocity influences such critical parameters as:

1. The size of the deflecting field E_0 for a given amount of power.
2. The sensitivity of the structure to electrical breakdown.
3. The attenuation length $1/\alpha$ [Eq. (1)].
4. The sensitivity of the structure to mechanical tolerances [Eq. (4)].

The best iris opening for a wide variety of designs is about 0.4-0.5λ. This is for deflectors about one or two attenuation lengths long ($\alpha\ell \sim 1$). For example, the BNL structure[1] (λ = 10.5 cm) has $\alpha\ell$ = 0.5, it is 3 meters long, it has a group velocity of V_g = -0.02c (backward wave), a $Q \approx 10{,}000$, and it provides a transverse momentum of 18 MeV/c for an input power 12 MW, i.e.,

$$p_\perp \approx 18 \text{ MeV/c} \sqrt{\frac{P}{12\,\text{MW}}} \quad (\text{BNL}, \ell = 3\,\text{m}, \lambda = 10.5\,\text{cm}).$$

An X-Band Separator

Let us scale the BNL design (λ = 10.5 cm) to a wavelength of λ = 3.75 cm to get a first approximation to a deflector for NAL. What would be its power requirement for a given transverse momentum? Let the basic cell dimensions be scaled down as λ. The power required to maintain E_0 scales as λ^2 (an elementary consequence of Poynting's theorem, i.e., $E_0^2/P = Z \sim \lambda^{-2}$). The quality factor Q scales as $\lambda^{1/2}$, hence from Eq. (1)

$$\ell \sim \lambda^{3/2} \quad (\text{if } \alpha\ell \text{ remains same}).$$

Unfortunately, this shrinkage of length (down to ℓ = 0.65 m at X-band) would require that more power would have to be dissipated in a shorter structure to maintain the same transverse momentum: from Eq. (2) and (3)

$$p_\perp \sim \sqrt{P\lambda}\,.$$

To solve this problem one has to (a) be more modest in the $p_\perp$ requirement,

(b) split the available power P into n parts (P/n) and distribute it into n structures each of length ℓ = 0.65 m dumping each unused fraction at the end of a unit. Each of the n units would contribute $p_\perp/n \sim \sqrt{P\lambda/n}$, and together they would give (if properly phased to add) $p_\perp \sim \sqrt{nP\lambda}$ per deflector of n units. For a given $p_\perp$, distributing the power into n structures saves a factor of n in power and a factor n^2 in power dissipation per unit length. As power dissipation is the main problem in a normal continuous duty cycle deflector, one uses for each deflector as many units of length ℓ = 0.65 m as is reasonably consistent with the beam acceptance to be accommodated in the deflector.

Power Requirements

Let each deflector be made from n = 10 units (ℓ = 0.65 m each) for a total length of ~6.5 m. Assume that three such deflectors are required in the rf beam. Let each of the deflectors be supplied by a total of P = 0.25 megawatts rf power (one tenth of this into each unit and dumped separately at the end of each unit). Scaling from the Brookhaven design as outlined above:

$$p_\perp = 18 \text{ MeV/c} \cdot \sqrt{10 \cdot \frac{0.25}{12} \cdot \frac{3.75}{10.5}}$$

$p_\perp$ = 5 MeV/c (λ = 3.75 cm, 10 × 0.65 meters long). This is useful for a separated beam in the lower energy regions of the NAL accelerator. About 0.16 MW of rf power would be dissipated in the deflector, the remainder would go into dummy loads. The klystrons to provide such power with a continuous duty cycle are available off the shelf (Varian VA 879, 100 kW, or VA 949, 250 kW). These klystrons are about 40% efficient, hence each deflector would require a 600 kW dc power supply.

A separator with three deflectors of this design, operating at a 33% duty cycle would require on the average 600 kW at the dc power supply (1,800 kilowatts peak), of which about 160 kilowatts average rf power will be dissipated in three structures (90 kilowatts in the 30 dummy loads). This amounts to 8 kilowatts average dissipation per meter of deflector, which is manageable.

Dissipation and Tolerances

The power can be purchased, the dissipation is manageable, but there remains a problem of the tolerances under these dissipation loads. The problem of tolerance to temperature change is one order of magnitude less severe than has been generally realized, and this is a result of splitting the deflector into 10 separately fed units. If the deflectors were one unit of 6.5 meter length, this problem would indeed be intolerable. If the temperature of such a device changed by only 1° C, the particle would fall behind (or ahead of) the wave by a phase u = 54°/°C, and the resultant angular oscillation of the beam would have an amplitude $(\sin u/2)/(u/2)$ and a phase change of $(u/2) = 27°/°C$. This would be unbearable if there occurred a transient temperature change of several degrees during pulsing at a 33% duty cycle. However, with ten separately-fed units, the particle will find itself back in phase after passing through each tenth of the deflector and the phase slip Δu will be reduced by a factor of ten to about 5° per °C. Fundamentally the problem of tolerances can be regarded as solved.

Comparison With Superconducting Deflectors

If the deflector were made superconducting, it would be used as a cavity not as a waveguide. Assuming, conservatively, an improvement in Q by a factor of 10^5 (at 1.8°K) over the BNL structure and scaling the BNL geometry to X-band (scaling $Q \sim \lambda^2$ for superconducting rf devices) one would get a Q of 10^8 and a peak power dissipation of

$$P_d \approx 11 \text{ watts, per 6.5 meter long structure}$$

for $$P_\perp = 5 \text{ MeV/c}.$$

Assuming a 33% duty cycle for three deflectors and refrigeration at 7% of Carnot efficiency at 1.8°K, one would need

$$P \approx 27 \text{ kW average hot refrigerator power}$$

ignoring lead losses. The Stanford refrigerator will handle 300 watts of dissipation (it costs ≈ $0.5 M). The power estimate is conservative: one eventually expects to reach $Q \approx 10^9$, in which case one would need only one tenth of the above power, plus whatever is needed to cool the leads and supports. Ultimately the superconducting separator can be pushed to provide much higher transverse momenta, as would be required for separation in the 100-GeV region. The required power would scale as $p_\perp^2$. Also the deflectors could be made shorter than 6.5 meters, but the required power would scale inversely proportional to length. Even if the deflectors were only 2 m long (three times above power required), the peak magnetic fields associated with achieving $p_\perp = 5$ MeV/c (~ 350 G) would be well below the critical fields already established in the lab (≳ 1000 G).[3]

Summary

This note defines realistic parameters of an rf separator, using normally conducting copper structures, operating at a 33% duty cycle at X-band (8 GHz). This device could be used in an rf separated beam of moderate energy (~ 30 BeV/c K-mesons) essentially at the start of experimental operations in 1972.

Each deflector would be about 6.5 meters long, composed of 10 separately powered subunits properly phased to add deflections. This splitting is a natural feature of a conventional X-band deflector because the power attenuation length for a reasonably optimized geometry becomes quite short (~ 0.65 m). It results (a) in a crucial power economy, (b) in a reduction of the power dissipation per unit length to manageable levels, and (c) it reduces the fundamental problem of mechanical structure tolerances (sensitivity to temperature changes) by an order of magnitude. Each deflector (3 required) would require a klystron dc power supply of 600 kilowatts peak, 200 kilowatts average. These conclusions appear to make the normal X-band separator a technically feasible option.

This does not mean that it is a technically, aesthetically or even economically preferred device. It will be a useful device which, however, will become obsolete when a superconducting X-band separator becomes available. Superconducting separators have more ultimate potential, and in a beam line full of superconducting magnets, the power supply for the normal deflector will look quite odd.

REFERENCES

[1] H. Hahn and H. J. Halama, Rev. Sci. Instr. 36, 1788 (1965). This paper contains further references.

[2] P. Bernard, H. Lengeler, and V. Vaghin, CERN 68-30, July 1968. A very useful summary report.

[3] Stanford results, private communication via H. Hahn (BNL).

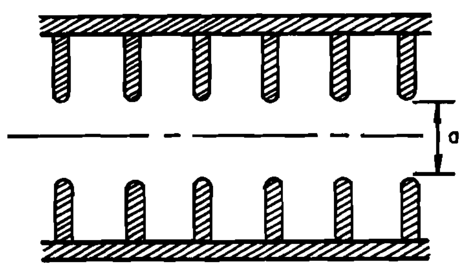

Fig. 1. Iris-loaded waveguide section.