PERFORMANCE OF THE CEA LOW-BETA BYPASS

R. Averill, A. Hofmann, R. Little, H. Mieras, J. Paterson, K. Strauch, G-A. Voss, H. Winick

CEA, Harvard University and Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

Abstract

The effects of non-linear resonances on the operation of the low-beta bypass have been investigated. Effects of satellite stop bands have been made manageable by reducing the chromaticity to a value near zero using 30 sextupole magnets distributed around the ring. Non-linear fields in critical quadrupoles of the bypass reduce the effective aperture of the system to below the physical value. Satisfactory operation has been achieved with β_h = 7 cm and β_v = 22 cm, and further improvements in magnetic field quality should permit operation at even lower values of β. The beam size at the interaction point is measured by passing a fiber through the stored beam and observing the resulting bremsstrahlung.

Introduction

The low-beta bypass was added to the CEA ring structure as an essential part of the colliding beam program. It is required to give an interaction point for the e^+e^- beams where both amplitude function and momentum vector have small values, and to have an interaction region around which there is adequate space for experiments. The design of the bypass and the associated switching system are described in references 1, 2, and 3.

The performance of this structure has been studied for different tunes, characterized by different values of β at the interaction point and the neighboring lenses, and for different ν-values. See Figs. 1 and 2. The limits of performance are determined by non-linear fields which give non-linear resonances and restricted apertures for betatron oscillations.

Non-Linear Resonances

Figure 3 shows the variation of beam lifetime as a function of the horizontal and vertical ν-values around a typical working point. These resonances have been studied

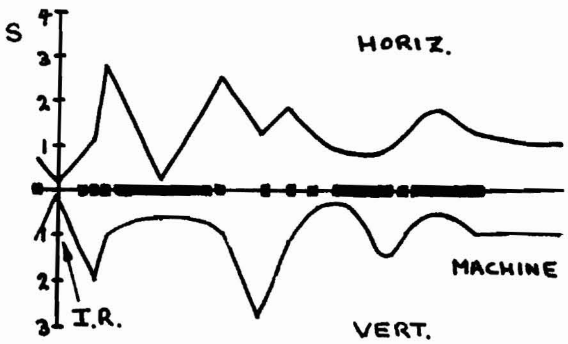


Fig. 1. Relative beam size through one-half of the bypass. Tune II.
At interaction region S_h = 0.25 (β_h = 45 cm)
S_v = 0.17 (β_v = 20 cm)

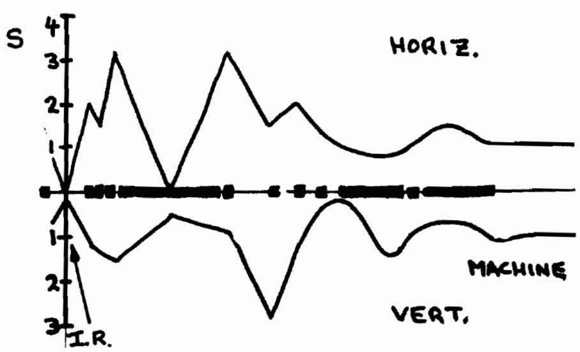


Fig. 2. Relative beam size through one-half of the bypass. Tune VI.
At interaction region S_h = 0.098 (β_h = 7.3 cm)
S_v = 0.17 (β_v = 20 cm)

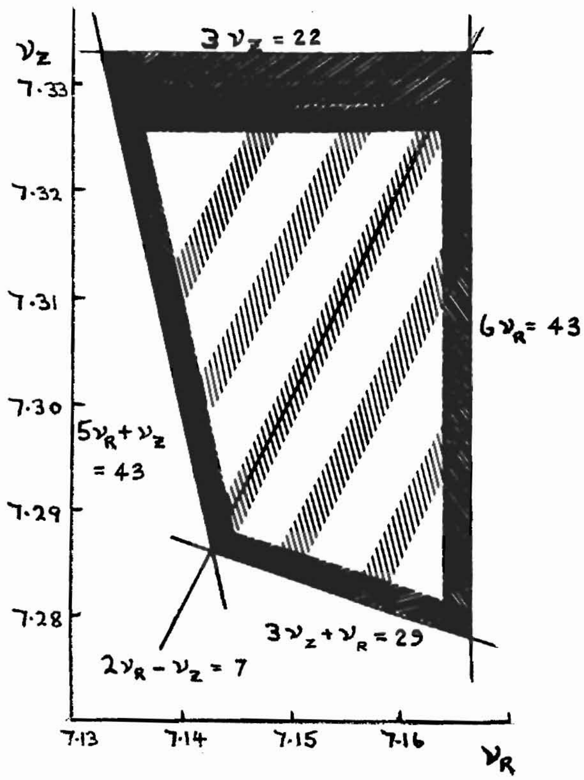


Fig. 3. A section of a resonance diagram around a typical working point. The dark areas indicate the half width of the resonance lines where the beam lifetime is greatly reduced. The lightly shaded bands are a difference resonance and satellites of it. In these regions the vertical beam size is increased but the beam lifetime is not significantly affected.

and identified and we find almost all possible sum and difference lines up to the 7th order; i.e. when $n\nu_r \pm m\nu_z$ = integer we find lines for $n+m \leq 7$. The strength of a resonance, as measured by its effect on beam lifetime, in general decreases with increasing order and sum resonances are somewhat more important than difference resonances.

At the beginning of 1971 we had a situation where there were many resonances which were not identified and the narrow spacing between them represented a severe limitation on performance. These resonances had a periodic structure which was dependent on the rf accelerating voltage and indicated that they were satellites or sidebands of major linear or non-linear resonances. The number of such resonances is approximately proportional to the chromaticity $\Delta\nu/(\Delta p/p)$. We were limited in the application of the bypass sextupoles to control chromaticity by the fact that they were not adequately distributed in betatron phase angle. We therefore designed and installed a system of 30 sextupole magnets distributed around the accelerator ring. With this system the chromaticity of the machine plus bypass can be adjusted to near zero and we have greatly reduced the effect of these satellite resonances.

Figure 3 shows a typical point in the tune diagram as we are presently operating the bypass and it can be seen that we have ranges of 0.005 in ν-value where the lifetime is constant and the beam size small. This requires the current in certain critical quadrupoles to be stable to within .05% and the machine energy as determined by the main ring magnets to be stable within .03%.

Limitations of Available Aperture

The measured lifetime of a beam and the range available for closed orbit distortions show that the aperture available for betatron oscillations is considerably less than the physical aperture. The physical aperture is more than twice as large as the ±6 std. of the natural beam size required for long lifetime. When we attempted to change the bypass tune to give a smaller beam size at the interaction region (compare Figs. 1 and 2), it became clear that we were limited in available aperture where the beam size was largest, i.e. in the horizontal plane where β_h is large. This effect is due to non-linear fields in the quadrupoles but it is more complex than the simple $\Delta\nu$ of a particle with a large betatron oscillation moving on to one of the measured resonance lines. In fact the aperture available for oscillations is relatively independent of the exact ν-value.

To understand the relative importance of non-linear fields at various locations in the bypass, one must take account of the possible strength of such a field and the beam size at that point. Let us describe a field as a multipole expansion along an x-axis normal to the beam.

$$B = a_0 + a_1x^1 + a_2x^2 + \ldots\ldots a_nx^n$$

so that the coefficients a_1, a_2, etc. give the strength of the quadrupole, sextupole, etc. field components. It is convenient to relate everything to a point away from the low β insertion and we choose a machine straight section where $\beta_h = \beta_v = 7.4$ meters and is independent of the bypass tune. Then comparing the effect on a particle of multipole fields at points of different β we derive

$$a_n\, x_0^{n-1}\, S^{n+1} = \text{constant}$$

where x_0 is the particle amplitude in a straight section and S is the relative beam size between the point in question and a straight section, i.e. $S = (\beta/\beta_{ss})^{\frac{1}{2}}$. The constant is defined by the maximum allowable value at which a multipole field leads to resonant growth of a particle amplitude. The value of this constant (hereafter called C_n) is probably different for different multipoles and dependent on their distribution. Thus we can write the stability condition

$$a_n\, x_0^{n-1}\, S^{n+1} \leq C_n$$

This expression has proved to be very useful in understanding the non-linear effects in the bypass. It gave a reasonable description of the behavior of the bypass, i.e. lifetime and available apertures, as a function of tune on the assumption that the dominant effect was the 12-pole field in the quadrupoles with the largest S. For example, the ratio of the largest S between tunes VI and II (Figs. 2 and 1) is 1.2 and therefore the maximum allowable amplitude is reduced by a factor of

$$(1.2)^{(n+1)/(n-1)}$$

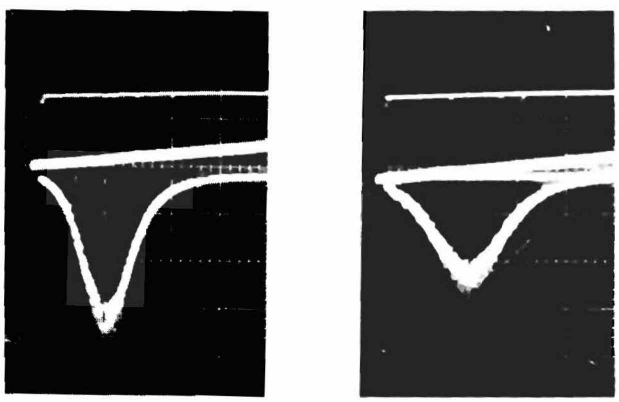
or 1.3. The 12-pole content would have to be reduced by a factor of S^{n+1} or approximately 3 to maintain the same effective aperture or lifetime. Indeed, tune VI gave unacceptable performance until two quadrupoles at locations of large S were replaced by ones with a larger bore and less 12-pole field. In addition pole face windings were added to further reduce the 12- and 20-pole fields. As the horizontal beam size is proportional to the energy E, the tolerances should decrease like E^{n-1}. The performance of the bypass at different energies is consistent with this behavior.

At the present time we have satisfactory operation at an energy of 2 GeV with an S_h at the interaction region of 0.098 (β_h = 7 cm) and S_h in the quadrupoles of 3.2 (β_h = 74 m). The β_v at the interaction region is 22 cm (S_v = .173). We found that to maintain an aperture of ±1.3 cm at 2 GeV in a quadrupole where the β = 74 m, the error fields, e.g. the 12- and 20-pole fields, had to be less than 10^{-5} of the quadrupole field within this aperture. This number is probably very dependent on the total non-linear field content and its distribution throughout the machine plus bypass.

Beam Size at the Interaction Region

The beam size at the interaction point is determined by many factors including β function, horizontal to vertical coupling from rotated elements, asymmetries in the focusing properties of the bypass, non-linear resonances and beam-beam focusing. One can estimate beam dimensions from observations of synchrotron light emitted by the beam where it is large and/or from measurements of the luminosity with colliding beams. Both of these techniques are indirect and not very accurate. In order to achieve a better understanding of the low-β bypass we felt that a more direct measurement was necessary.

Although several exotic techniques were suggested, we found that passing a thin fiber through the beam at a known velocity and recording the bremsstrahlung radiation from this target, is a satisfactory technique. A 7-μ carbon filament is mounted on the end of a lever arm inside the vacuum system in such a way that motion of the arm moves the fiber through the beam. The velocity of the fiber is measured externally where the arm is pneumatically driven. The bremsstrahlung from the fiber is picked up 10 meters downstream on spill counters (see Fig. 4). The fiber moves in such a way as to give a vertical scan of the beam and the mechanism allows ±10° of rotation to enable one to measure the horizontal beam size. The velocity of the fiber is typically 50 cm/s and it therefore scans through a beam ≤ 0.1 mm high in ≤ 200 μs. The bremsstrahlung from 7-μ carbon in this process gives a beam loss of only a few percent. The increase in beam size during the scan can be seen from the asymmetry of spill in Fig. 4 but the leading edge gives a good measurement of the half height of the beam.



(a) (b)

Fig. 4. Spill from 7-μ fiber passing vertically through an e^+ beam at the interaction region. Sweep speed is 100 μs/cm and calibration is .025 mm per horizontal division. (a) Beam height is ±.02 mm. (b) Beam enlarged by weak nonlinear resonance to ±.03 mm.

This system has been extremely useful in increasing the understanding of the bypass. It was used to check the rotational alignment of the high-β quadrupoles and it indicated that there were non-linear resonances which could increase the beam size significantly without an apparent effect on the lifetime of the beam (Fig. 4). It has also shown that the vertical height of the beam is intensity-dependent. The vertical beam height has been measured to be typically of the order of 0.05 mm with a β_v of 20 cm; this corresponds to a horizontal to vertical aspect ratio of 10:1 at a point where $\beta_h = \beta_v$.

References

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3) J. M. Paterson, "Performance of the CEA Colliding Beam Facility", Proceedings of the 1971 Particle Accelerator Conference, Chicago, Illinois, U.S.A., IEEE Trans. on Nucl. Sci. NS 18-3, 196 (1971).