CON 90-2
January 10, 1990
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Magnetic Separation of Multiple Bunch Beams

Introduction

Unequal energy beams have separated closed orbits wherever the dispersion in a lattice is finite. The orbits coincide where there is zero dispersion. Since the momentum compaction is typically greater than zero, the high energy beam will have a longer path than the low energy beam. The path lengths can be made equal by separating the beams into distinct guide fields for some fraction of the circumference of the ring. The path length difference of the transfer lines must be sufficient to guarantee equal revolution times for both beams on the separated orbits. A CESR lattice has been generated that has a uniform dispersion everywhere outside the L0 interaction region. It can accomodate as many as 32 bunches in each beam if the energies of the beams are $\frac{E_{\pm}-E_0}{E_0} \sim \pm 0.009$. The separated beams share the vacuum chamber south of Q44. North of Q44 the beams are steered via a septum into separate guide fields. A magnetic layout of the "path length bypass" and the high and low energy lattice is presented.

A sextupole distribution that preserves equal tunes,chromaticicities, β^*, and that is consistent with collisions at L0 is described. Distributions compatible with zero and nonzero dispersion at the interaction point are presented. The solution for nonzero dispersion is characterized by energy monochromatization. The deviation of the sextupole strengths from uniformity is not severe.

Linear Lattice

A typical lattice in which beams with a small energy difference are separated everywhere but in the L0 interaction region is shown in Figure 1.

The displacement of the beams from the central trajectory is equal to the dispersion times the energy offset. The number of bunches that can be accomodated is limited by the distance from the IR to the point at which there is finite dispersion. Dispersion is generated by bends so the number of bunches is determined by the space from the IP to the first bend. Note that unlike multiple bunch operation with electrostatically separated beams, there is no relationship between the number of bunches and the horizontal tune. In the lattice that is shown the soft bend is placed immediately beyond Q2 and is followed by a hard bend. The details of the layout of magnetic elements is appended. Two additional quadrupole magnets are added in order to manipulate the betatron phase. The reconfigured machine can accomodate up to 32 bunches in each beam if the energies of the two beams are $\pm\delta_E = \frac{\Delta E}{E} = \pm 0.009$. The energy difference is chosen to yield separation of the bunches at each of the parasitic crossing points and to keep the beams inside the CESR aperture south of Q44. The closed orbits for electrons and positrons in a lattice that includes sextupoles is shown in Figure 2.

The practicality of such a layout is determined by detector background considerations. The existing CESR layout of bending magnets in the vicinity of the L0 interaction region is compatible with ~ 14 bunches per beam. Because the horizontal phase advance and the number of bunches are independent, there is a soft limit on the number of bunches in any particular layout. For example, increasing the number of bunches by one moves the first parasitic crossing slightly closer to the IP to a point of slightly less dispersion and less separation. The separation at the remaining crossing points is not diluted. It is an experimental question to determine the consequences of a single very close encounter.

Of course in any guide field with linear focusing elements (including longitudinal focusing) there is a a unique closed orbit and unique energy associated with that closed orbit. Since our beams have slightly different energies they must at some point be separated into distinct guide fields. In the part of the guide field that is common to both beams the path length for the high

Fig. 1. The lattice can accomodate as many as 32 bunches per beam with $\delta_{\pm} = \pm 0.009$.

Fig. 2. The closed orbits are separated from the first parasitic crossing outside the IR north to Q44. In the vicinity of Q44 the separation is sufficient to insert a septum magnet and steer the beams into the appropriate path length bypass. North of Q44 the beams travel through different guide fields.

energy beam will be greater than that of the low energy beam by

$$\delta l = \delta_E \int_{Q44E}^{Q44W} \eta(s) ds$$

where Q44E and Q44W indicate the start and end points(clockwise) of the shared guide field. Since roughly 90% of the guide field is shared we have that

$$\delta l \sim \frac{\delta E}{E} \alpha_p C$$

where α_p is the momentum compaction and C the machine circumference. For the lattice in question $\delta l \sim 17cm$.

The strategy is to separate the beams north of Q44 into distinct guide fields. The low energy bypass is 17cm longer than the high energy bypass so that the revolution time for both beams is identical. The dispersion is high near Q44(see Figure 1.) so the beams can be steered by a septum magnet into their respective bypass. A schematic of the bypass is shown in Figures 3.

Complete lattices have been designed for both the high energy and low energy bypass. The bends are arranged to yield the appropriate difference in path length. The quadrupoles south of Q44 are common to both high and low energy optics. The quadrupoles in each of the legs of the bypass are independent. The relevant global parameters (emittances and energy loss) are essentially the same for both optics. The displacement of the beams from the machine centerline at the septum is $\pm(8\sigma_h + 15mm)$. There is a similar clearance of displaced beams from vacuum chamber walls throughout the shared part of the ring. The clearances are similar to those in CESR with electrostatic separation.

Sextupole Lattice

The constraints on the sextupole lattice are somewhat more severe than in a machine in which both beams have the same energy. Both beams must have equal tunes and positive chromaticity. In addition we require that the high and low energy beams have equal β^*, identical closed orbits in the interaction region, and equal but opposite dispersions. In summary, the constraints on the sextupole distribution include:

$$\nu_{v/h}(\delta_E) = \nu_{v/h}(-\delta_E)$$

$$\frac{\partial \nu}{\partial \delta}|_{\delta_E} = \frac{\partial \nu}{\partial \delta}|_{-\delta_E} \sim 1$$

$$\beta^*_{v/h}(\delta_E) = \beta^*_{v/h}(-\delta_E)$$

$$x_0(\delta_E) = x_0(-\delta_E)$$

$$\eta(\delta_E) = -\eta(-\delta_E) = 0.$$

$\delta = \frac{E-E_0}{E_0}$, where E is the particle energy and E_0 the nominal energy of the lattice. $\delta_E = \frac{\Delta E}{E_0}$ and $\pm\Delta E$ the deviation of the average energy of the high and low energy beams respectively. It is by no means obvious that a practical distribution that satisfies the above exists. A fitting program designed to find such a distribution has been developed .[1] It is based on an evaluation of the

Fig. 3. In the view of the entire ring the low energy bypass is barely visible as a concave bump at L3. In the expanded view the bending radii of the low energy transfer line bends are indicated.

relevant parameters with the Dimat tracking code. For a given sextupole distribution the closed orbit and its transfer matrix are computed at each of four distinct energies $-\delta_0 \pm \epsilon$, and $\delta_0 \pm \epsilon$. Tunes and $\beta's$ are derived from the transfer matrix. Chromaticities for high and low energy beams as well as dispersions are computed. Minop is used to manipulate the distribution. In addition to the contraints on the optical parameters the weighted sum of sextupole strengths $\sum s_i^2(\beta_i^v\beta_i^h)^{\frac{3}{2}}$ is constrained in order to minimize the amplitude dependent tune shift.

1. Zero Dispersion Distribution

Indeed it is not difficult to realize practical distributions. The characteristics associated with a zero dispersion solution are indicated in Figures 4.

Note in particular the energy dependence of the tunes. The desired chromaticity and central value are achieved at the nominal operating energies of $\delta_E = \pm 0.009$. Keep in mind that small adjustments in the linear and nonlinear optics can be accomplished independently for each beam within the path length bypass. It is not necessary that all tuning be through a manipulation of the sextupole lattice. A histogram of the sextupole strengths is shown in Figure 5 and the strengths of the corresponding two family distribution is indicated.

Fig. 5. The sextupole distribution yields the energy dependencies shown in Figure 4. The strengths of a two family distribution with similar chormaticity are indicated.

Fig. 4. The tunes and β^* are computed with respect to the closed orbits for each of the energy points. x_0 is the horizontal coordinate of the closed orbit at the IP.

2. Nonzero Dispersion Distribution

One might be inclined to believe that in a machine in which a small energy difference is used to separate the beams that a nonzero $\eta*$ would be intolerable. But this is not so. A sextupole distribution has been designed with the dispersion at the IP constrained so that

$$\eta(\delta_0) = -\eta(-\delta_0) = 30cm.$$

Its characteristics are summarized in Figure 6.

There is an effective monochromatization by virtue of the equal but opposite dispersions.

Operation with magnetically separated beams

The implementation of the $\pm 0.9\%$ solution requires the installation of a section of arc from Q44E through Q44W including 8-10 quadrupoles and about 6-8 bending magnets. In addition the vacuum chamber just south of Q44 would need to be enlarged to accept the increasing displacement of the beams and septum magnets designed and installed. Advantages of the scheme include:

1. Multiple bunch operation without electrostatic separators. At present the luminosity limit is perceived to be imposed by the separators. While the septum magnets are likely to present an impedance similar to that of the separators, they are not simultaneously reguired to hold a high DC voltage.
2. ~ 30 bunches per beam
3. The horizontal tune and the number of bunches is independent. The lattice described above with an integer tune of 11 can accomodate from 1 to 32 bunches per beam. Because horizontal phase advance and the spacing of the bunch crossings is independent, long range beam-beam effects tend to average to zero rather than accumulate.[2]
4. Equal but opposite dispersions yield energy monochromatization thus reducing the center of mass energy spread. (A significant narrowing of the energy spread only occurs if $\sqrt{\beta^* \epsilon} \ll \eta^* \frac{\sigma_E}{E}$).
5. ?Luminosity in excess of $10^{33} cm^{-2} s^{-1}$.

Fig. 6. The energy dependencies are for a sextupole distribution that generates $\eta^*_\pm = \pm 30cm$. Both beams are displaced in the same direction with respect to the on energy point.

1. Beam beam effects for unequal energy beams

The possibilty that the beam beam effect is significantly altered in a machine with small energy assymetry remains to be explored. The energy difference $E_{high} - E_{low} \sim 30\sigma_E \sim 95MeV$. The difference in damping times is about 1% and small adjustments can be made independently to damping times and emittances if wigglers are added in the bypass. The linear beam beam tune shift is equalized by a beam current assymetry inversely proportional to the energy assymetry. The corresponding difference in beam currents is negligibly small in practical operation.

REFERENCES

1. The development of the code owes much to the efforts of A. Bhagwati.
2. R. Littauer, CON89-11