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On the Multiturn Injection of High-Power Beams into an Accumulator Ring *

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ABSTRACT

The usual methods of multiturn injection result in substantial loss which is not acceptable with a high-Power beam. A method first proposed in 1973 [1] is here improved and applied to both the injection of protons and charge-exchange injection. Changes with respect to the original method avoid tunes close to an integer resonance and provide for the necessary tune shift through space-charge forces and nonlinearities in either the pulsed equilibrium-orbit-bump magnets or in fixed octupole magnets. When applied to charge-exchange injection, the method drastically reduces heating and damage to the stripper while providing systematically for the dilution of transverse phase space that is necessary for the intended application--that of injection of 660 turns of a 1.1 GeV, 100 mA beam.

Introduction

The normal methods of multiturn injection of protons as applied to a synchrotron yield optimal beam brightness at the expense of very large losses. The use of charge-exchange injection allows the beam brightness to be greatly increased and at the same time minimizes beam losses. However, when applied to beams of high power such as the proposed KFA-KFK spallation neutron source accumulator ring (where a 100 mA beam of 1.1 GeV protons is to be stored for a period of 500 microseconds with the cycle repeated at 100 Hz--5.5 MegaWatts), the fraction lost must be reduced drastically compared to conventional proton injection. Such power applied to a thin carbon stripping foil is expected to result in very frequent failure of the foil. Moreover, it is not desirable to increase the beam brightness over that of the linac lest the space-charge-induced tune shifts become excessive.

The proposal to inject along a spiral in one of the transverse phase spaces provides a means of injecting protons with very little dilution and very little loss. When applied to charge-exchange injection, the same considerations mean that each injected ion will pass through the stripping medium only a few times, thus significantly increasing the lifetime of the foil.

The method requires that the equilibrium orbit be shifted in proportion to the square root of the turn number; this results in a constant rate of generation of phase area to be filled. For protons, the tune **must** shift in inverse proportion to the square root of the turn number. For charge-exchange injection, this dependence need not be attained as ions may return to the phase area occupied by the foil in a subsequent turn without being lost. To achieve this tune shift may require large changes in the currents in the tuning quadrupoles. G. Schaffer of KFK has suggested that the quadrupoles could be part of a biased resonant circuit operating at some harmonic of the ring cycle, thereby closely approximating the desired tune program.

Because the amplitude is proportional to the square root of the turn number, the desired tune shift may also be approximated by means of fixed octupole magnets. Finally, the space-charge-induced tune shifts can be made to be about the correct magnitude.

When first proposed by the author in 1973 in conjunction with injection requirements of the Los Alamos proton storage ring, the method was visualized as the sequential placing of phase ellipses along a single logarithmic spiral in phase space; this meant that the tune must asymptotically approach an integral resonance. However, the ellipses may be placed along a multiarmed spiral. For example, if the tune asymptotically approaches 3.2, the injection will be along a spiral of five arms. The total tune shift is reduced in inverse proportion to the number of arms. Moreover, the number of turns that can be injected increases with the number of arms.

Geometry

We can restrict our discussion to a simplified representation upon making the transformations: $\frac{x}{\sqrt{\beta}} \to x\ ;\ \frac{\alpha x}{\sqrt{\beta}} + x'\sqrt{\beta} \to x'$.

The acceptance ellipse at the point of injection is transformed into a circle, and all motion for subsequent turns is represented by circular arcs--of angle $2\pi\nu$ per turn. The septum (protons) is represented by a vertical line (of finite width). For charge-exchange injection, the region to the right of the line representing the septum corresponds to the phase area occupied by the stripping foil. In the remainder of the discussion, we freely pass back and forth from proton injection to charge-exchange injection.

At the start of injection, the equilibrium orbit is tangent to this line and moves to the left in proportion to the square root of the turn number. The injected beam is represented by an upright ellipse that is, in general, injected at a slightly inward angle with respect to the equilibrium orbit. This is shown in Fig. 1 on the next page.

Let W be the emittance of the injected beam and let c be the dilution factor (c=1 is no dilution, but the fitting of the ellipse into the partial acceptance generated during the turn prevents c from exceeding about 0.8 without causing overlapping with earlier turns). Then the equilibrium orbit is to move according to:

$$R_{eq} = \sqrt{\frac{W}{c\pi}}\sqrt{N}$$

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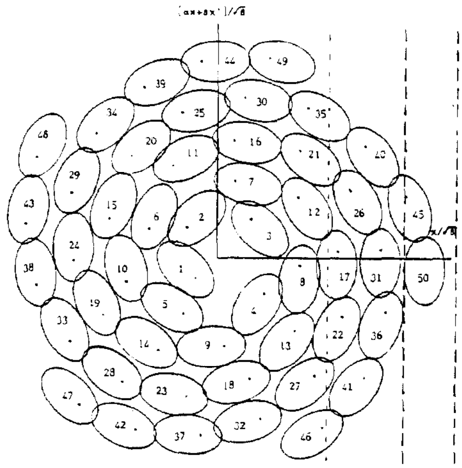

Fig. 1. Representation of the Injection Process.

The condition that ellipses be adjacent after m turns is: $\nu = \nu_0 + \frac{R_{eq}}{\pi m \bar{x} c N}$

where m is the number of arms, x is the half-width of the injected ellipse in the transformed phase space, and N is the turn number. We see immediately that the tune shift is reduced by injecting along more arms, and it is also reduced for the injection of an ellipse with narrow divergence.

In order to miss the septum (protons) or not to pass through the foil a second time (charge-exchange) m turns later, it is necessary to use the other plane by injecting above the equilibrium orbit. After a great many turns, as the curvature of the spiral is reduced sufficiently, it is possible for this to occur at the (pXm)th turn following injection for N $>$ Nmax where Nmax $\sim \left\{ 2\sqrt{\frac{c}{\beta_e^3}} + \frac{1}{2}\frac{p m}{\sqrt{\beta_e c}} \right\}^2 ; \; \beta_e = \frac{\bar{x}}{\bar{x}'}$.

Here again we see the advantage of multiple arms and injecting with an ellipse of narrow divergence. By increasing the displacement in the other plane and by judiciously choosing the tune in the other plane, it is possible to miss the septum or foil at not only the mth turn, but the (2m)th, the (3m)th ...

To inject a great many turns, it is is seen to be advantageous to increase the displacement in the other plane of the septum or foil as the injection proceeds. By doing this, we can greatly reduce the likelihood that an injected particle will return to the region of the septum or foil in a subsequent turn. This suggests injecting in this manner in both planes simultaneously. To accomplish this, it is necessary only that the equilibrium-orbit-bump magnets be adjacent to the injection point and rotated so deflection occurs in both planes. The magnet configuration thus resembles a rotated "wiggler" magnet. It is necessary then to control the tunes in both planes.

Injection performed in this manner yields a uniform distribution of charge density in both transverse phase planes, and it yields the "waterbag distribution" of dePackh [2] and Ehrman [3] which Sacherer [4] has shown yields nonlinearities in tune shift that are much smaller than those obtained with a Gaussian distribution.

References

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