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A LOW ENERGY CURRENT ACCUMULATOR FOR HIGH-ENERGY PROTON RINGS*

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SUMMARY

Building current in high-energy p-p colliding beam machines is most appropriately done in a low-energy (small circumference) current accumulator. Three significant factors favor such a procedure: First, large rings tend to be susceptible to unstable longitudinal density oscillations. These can be avoided by pumping up the beam in the accumulator. When the current stack is injected into the storage ring, potentially harmful instability is essentially neutralized. Second, high-field magnets characteristic of future high energy proton rings are designed with superconducting coils within the iron magnetic shield. This means coil construction and placement errors propagate rapidly within the beam aperture. An intermediate "stacking ring" allows the minimum use of the superconducting ring aperture. Finally, the coils are vulnerable to radiation heating and possible magnet quenching. By minimizing beam manipulation in the superconducting environment and using only the central portion of the beam aperture, coil vulnerability can be put at a minimum.

I. INTRODUCTION

We present arguments which tend toward the conclusion that to achieve both high currents and high energy for a colliding beam complex the preferred procedure is to divide the functions in a manner opposite to what has previously been considered best. Rather than accelerate small currents in a "fast" cycling accelerator and stack current in a storage ring at high energy it is proposed that it is better to do the reverse: stack current at moderate energy, transfer the high current to a pair of storage accelerators and slowly raise the stack to the desired high energy. In other words, accepting the fact that the functions of stacking and accelerating are performed optimally in separate rings, we suggest that stacking and accelerating be used in preference to accelerating and stacking.[1-6]

There are three significant factors favoring the suggested procedure. First and foremost is the fact that stacking current in a high energy, that is, large circumference storage ring is such that the beam during the stacking process is exceptionally vulnerable to unstable density oscillations caused by induced electromagnetic fields resulting from the interaction of the beam with the surrounding uneven metallic chamber.[1-6] This point is discussed in section II. The second factor relates to the fact that high-field magnets characteristic of future high-energy proton storage rings are designed with superconducting coils within the magnetic iron shield. This implies that coil construction and placement errors propagate rapidly within the magnet aperture. It is therefore appropriate to minimize the beam occupation within that aperture. The use of an intermediate separate stacking ring accomplishes this and allows a minimum use of the superconducting ring aperture. Arguments connected with random field errors[7] are presented in section III. Finally, a third factor favoring a stack-accelerate procedure is that the potential for irradiating the superconducting coils due to lost protons from the beam[8] is minimized. By performing minimal beam manipulation in the superconducting environment and utilizing only the central portion of the magnet aperture, the coil vulnerability to radiation heating can be put at a minimum and therefore possible quenching of magnets as well as damage to the coils can perhaps be avoided. Details pertaining to beam manipulation is given in section IV.

II. LONGITUDINAL INSTABILITY

The stacking procedure which provides the optimal beam characteristics for use in colliding proton beams is the momentum stacking method.[9] However, it has been shown at the ISR that the injected pulses are susceptible to what has become referred to as the longitudinal "microwave" instability.[10,11] Another term applied has been the single bunch "fast" instability.[12] Two major features of this instability are its universality and the difficulty of containing it by hardware control. It is present in standard accelerators such as the PS, the SPS and the FNAL machines and electron storage rings such as SPEAR, as well as the ISR. The only clear way of avoiding the instability is through beam design and this, as we will see, is the essence of our proposal to use a separate accumulator ring.

The theory of the "microwave" instability has been given much attention,[12] and although the specific nature of the forces causing it and the details of the dynamic mechanism are not certain, there appears little doubt that beams are self-stabilizing through frequency spread and that this fact can be expressed in a relatively simple manner. If Z_n is the impedance characterizing the beam induced field for a particular mode n, then the beam is stable provided[12,13]

$$|Z_n/n| < \tfrac{1}{2}(\Delta p/I)(\Delta f/f) \quad , \qquad (1)$$

where $(\Delta p/p)$ is the relative momentum spread, I is the beam current, $\Delta f/f = \eta(\Delta p/p)$ is the relative beam frequency spread, and η is the frequency slip factor, $\eta = -(p/f)\,\partial f/\partial p = (1/\gamma_{tr}^2 - 1/\gamma^2)$, with γ_{tr} and γ the transition energy and beam energy in proton rest energy units. The frequency of the instability, f_{INST} is related to n by $f_{INST} = nf$. It has been demonstrated that for the "fast" or "microwave" instability we can apply formula (1) to both coasting and bunched beams. However, to apply it to bunched beams, we interpret I and $\Delta p/p$ as peak values within the bunch.[10-12,14]

In order to see the advantage of using a small circumference stacking ring, we consider a simplified but not unrealistic situation. Since a storage ring performance is connected with the essentially invariant density $I/\Delta p$, we take this to be a constant for purposes of comparison. Thus, assuming that the frequency of the instability, f_{INST}, remains the same (i.e., that the chamber discontinuities tend to be similar for different machines), then a measure of how vulnerable a given machine is to these "fast" instabilities is the quantity

$$K = \Delta f/f = \eta(\Delta p/p) \quad . \qquad (2)$$

The larger the value of K, the less susceptible the design. Let us compare K for the two alternate possibilities: 1) stacking in a 200-400 GeV storage ring, or 2) stacking in a 30-60 GeV storage ring

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followed by transfer to a 200-400 GeV storage ring.[15]

The presence of the factor $(\Delta p/p)$ in the figure of merit, K, is at the essence of our suggestion. FOR A GIVEN DENSITY, if $(\Delta p/p)$ is very large, the beam will tend to be stable. Thus, a beam already stacked to high current, that is, one which has a relatively large $(\Delta p/p)$, will not be sensitive to instability. Remember we are considering stacks composed of perhaps 100-200 pulses.[15]

Therefore, the relevant comparison from the point of view of the longitudinal instability is that between K for the injected bunches in the high-energy storage ring on the one hand and in the low-energy stacking ring on the other. Let us refer to them by using the subscripts H and L respectively. We want to compare $K_H = \eta_H(\Delta p/p)_H$ and $K_L = \eta_L(\Delta p/p)_L$. Roughly speaking, $\eta \propto 1/\gamma_{tr}^2$ or since $\gamma_{tr} \propto \nu$ (the horizontal tune) and $\nu \propto C$ (the circumference), then we have $\eta \propto 1/C^2$. Actually, in practical machines, the dependence of η on C is somewhat less if operation is not close to transition and we should take, for example, $\eta \propto 1/C^{3/2}$. Also, since Δp remains essentially invariant, $\Delta p/p \propto 1/C$, roughly. Therefore, we obtain $K \propto 1/C^{5/2}$, or

$$K_L/K_H = (C_H/C_L)^{5/2} \quad . \qquad (3)$$

Now, since the circumference of the high-energy ring (200-400 GeV) is about 4-5 times larger than that of the stacking ring (30-60 GeV), we obtain $(K_L/K_H) \approx$ 30-60. This would mean the vulnerability to "fast" longitudinal instability is not far from 2 orders of magnitude worse for the case of accelerate-stack as compared to stack-accelerate. This is an impressive result.

Of course, what this really means is that in order to make stacking at high energy viable, some sacrifices in performance and machine design must be made. Thus, we might consider allowing Δp to increase, say proportional to p. This, of course, reduces the current density by a significant amount. In rings designed with long experimental insertions and rather small momentum apertures,[16] such a procedure is limited without reducing the flexibility in the insertion design and thereby the performance. By doing this, we can see that the relation between K_H and K_L becomes

$$K_L/K_H = (C_H/C_L)^{\frac{1}{2}} \quad , \qquad (4)$$

or $(K_L/K_H) \approx 2$, which is a significant gain. However, to avoid the reduced performance inherent in this procedure, the only thing left at our disposal is control of the impedance itself. Discontinuities in the vacuum chamber must either be substantially limited in number or somehow made invisible to high frequency fields. This is difficult, indeed, because of 1) the need for discontinuities in designing the many systems needed for machine operation, such as vacuum system, electron clearing system, and others, including the system of experiments; and 2) the fact that the frequency region and range for the instability is not well known.

In comparing injection into a large storage ring and into a stacking ring at the same energy and keeping the density, $I/\Delta p$, fixed, we obtain a relationship intermediate to Eqs. (3) and (4):

$$K_L/K_H = (C_H/C_L)^2 \quad . \qquad (5)$$

We have here used the faster variation of η with C ($\eta \propto 1/C^2$) to take account of the fact that "low" energy stacking in a large storage ring probably implies injection near the transition energy. Another way of expressing Eq. (5) is that for the same figure of merit, $K_L = K_H$, the impedance in the large storage ring must be smaller than the impedance of the stacking ring by a factor

$$(Z/n)_L/(Z/n)_H = \eta_L/\eta_H \approx (C_H C_L)^2 \quad . \qquad (6)$$

"L" is about a factor 16-25 better. Of course, we could alternatively increase the momentum spread in the large storage ring relative to the stacking ring. However, this again would reduce the performance of the colliding beam facility and in this instance would also require an increased aperture since the spatial aperture required is directly related to the amount of momentum aperture needed through the lattice dispersion function.

III. RANDOM FIELD ERRORS DUE TO SUPERCONDUCTING MAGNET COILS

The presence of current carrying coils just outside the beam aperture in superconducting magnets has the effect of making the magnetic field within the aperture sensitive to random coil positioning, constructional and support errors.[7] The immediate consequence is the creation of field multipole components at the magnet center which are strong functions of the radial distance to the coils. Furthermore, for orbits off the magnet center, the multipoles become amplified, with the amplification increasing rapidly as the coils are approached.

In high current pp colliding beam machines,[15] a substantial fraction of the magnet aperture must be used if the storage ring is also to be used for stacking the high current. In particular, during the stacking process, the injected orbit is appreciably off the magnet center and particles on this orbit must traverse paths lying close to the error source. In this instance, the amplification effect could be very significant.

Specifically, the amplification factor for off-center orbits is the ratio of multipole components off and on center and is a function only of the ratio of the displacement of the off-center orbit, x_0, to the coil radius, R_c. Introducing the coil aperture parameter, $t = x_0/R_c$, the amplification factor for a multipole of order m, r_m, is a function of t alone. Note: m = 0 corresponds to the amplification of the dipole term. Using a model of cos θ current distribution created approximately by a series of current carrying coil blocks held in place in a circular bore tube, it can be shown that the amplification factor $r_m(t)$ can be written approximately in the form[7]

$$r_m(t) = 0.7/(1 - t)^{m+3/2} \quad . \qquad (7)$$

We plot in Fig. 1 r_m as a function of t for the first

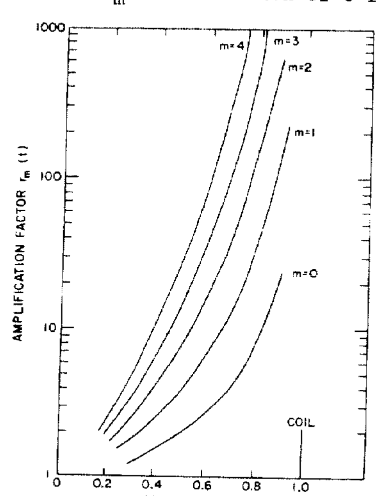

Fig. 1. Multipole variation across the magnet aperture. $r_m(t)$ is the amplification factor for the m^{th} multipole (m = 0 corresponds to the dipole case). t represents the orbit location within the magnet coil aperture. t = 1 corresponds to the orbit being at the coil block radius.

five multipoles. As can be seen, for higher multipoles, the amplification extends further into the central portion of the aperture. For example, the sextupole error is amplified by about a factor of 10 at a point 40% from the coil radius. The decapole term is amplified by a factor 1000 at the 60% point.

Thus, in attempting to stack beam in a ring composed of superconducting magnets, particles on the injected orbit become particularly susceptible to coil errors. For a given magnet aperture, the injection of a full stack in the center of the aperture would mean a significant improvement. One could imagine keeping the beam within a region, $t < 10\%$, if stacking were not required.

On the other hand, the stacking of beam in a conventional magnet intermediate current accumulator is not subject to this effect. In designing such a ring, where the magnetic field is determined essentially by the iron shape, errors can be made much smaller. Also, the amplification effect is essentially nonexistent since the coils do not enter in shaping the field to any significant degree. Thus, the amplification effect is peculiar to the superconducting magnet design. Since the use of a stacking ring greatly limits the amount of beam occupation within the superconducting magnet aperture, the advantage of using such a procedure is obvious.

IV. BEAM MANIPULATION

In future high field machines, the beam will undoubtedly have to be designed so as to be compatible with a superconducting environment. We must be concerned with the possibility of magnet quenches and coil damage in general due to the radiation heating of the superconducting coils, resulting ultimately from protons lost from the beam.[8,15] It seems clear that an optimum design of a p-p colliding beam complex from this point of view is one which minimizes the amount of protons lost within the superconducting environment. This is in essence equivalent to minimizing the amount of beam manipulation.

In this respect, there are three clear advantages to using an intermediate stacking ring as we have been suggesting. First, the momentum stacking process is intrinsically lossy in the following sense: The procedure one follows is to create a dilute stack initially to maintain longitudinal instability. As the stack is "pumped up" to maximize density, there must be continual scraping of beam tails. One might expect that ~ 50% of the particles injected will have to be removed and are therefore potential hazards to the superconducting coils. The actual amount of particles that must be scraped from the beam is difficult to determine. The value ~ 50% is taken from the experience with stacking at the ISR. It is not inconceivable that for larger machines, where susceptibility of the beam to longitudinal instability is substantially higher than at the ISR, the total percentage of loss will in fact be higher. A second related point is that during the creation of the stack, particles occupy an appreciable fraction of the coil aperture. Since particles tend to spend time close to the coils, losses and the consequent heating is more probable than if particles simply occupied the central region. Finally, a third point relates to beam rebunching. In the case where the beams are to be accelerated in the large storage rings, after stacking, they must be rebunched. This process also causes direct loss and momentum dilution, the latter probably requiring scraping, which means further particle loss and further increased danger of radiation heating.

If stacking is performed at moderate energy in a conventional magnet ring, particle loss per se is not of major significance. Momentum density can be made maximal by continued "pumping" of beam into the stack. Luminosity can be improved by decreasing the beam height, of course, at the expense of momentum dilution. This requires more "scraping and pumping." Finally, to overcome the rebunching loss, a little extra current could be stacked in the accumulator so that after rebunching, and taking into account the resulting loss and scraping (to keep the momentum density high), the desired current density in the storage ring is obtained.

Thus, with all the beam manipulation, stacking scraping and rebunching performed in the conventional stacking ring, the beams transferred to the storage accelerators should have minimal beam loss.

V. CONCLUSIONS

Because, 1) large rings tend to be vulnerable to longitudinal instability, 2) superconducting coils introduce large magnetic field errors away from the magnet center, and 3) appreciable beam manipulation in a superconducting environment is hazardous due to radiation heating of the coils, we conclude that building current for high-energy p-p colliding beam machines is most appropriately done in a low-energy (small circumference) intermediate stacking ring.

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15. See, e.g., "ISABELLE - A Proposal for Construction of a Proton-Proton Storage Accelerator Facility," BNL Report, to be published (1977).
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17. There are other minor advantages arising from the presence in the complex of an intermediate stacking ring. For example, the physical separation of the complicated stacking process from the colliding beam center affords obvious advantages in the areas of facility operation and construction as well as in the area of machine studies. The high current ring, while not being used for stacking the storage accelerators, could also be used in conjunction with other projects such as study of $\bar{p}$ cooling or the production and accumulation of $\bar{p}$ beams.