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ACCELERATOR DEPARTMENT
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LOW ENERGY STACKING RING FOR HIGH ENERGY STORAGE ACCELERATORS

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ABSTRACT

The use of a stacking ring at low energy to achieve high currents in high energy accelerators is proposed. This technique circumvents the high frequency longitudinal instability of the injected bunches, which otherwise tends to result in the large circumference machines required for high energy proton storage. A practical example of a stacking ring, using small gap, conventional, room temperature magnets, and suited to the ISABELLE storage accelerators is presented. Placed in the AGS tunnel, this ring could also be used as a "physics stretcher". The small gap property, tending to minimize power consumption and cost, also introduces strong image space charge fields. This was looked into, and it is concluded that currents even as high as 10 A could be accumulated in such a stacking ring. Aside from the primary reason for the stacking ring, some other benefits for the ISABELLE project are discussed. Some implications for storage ring stacking in general are also included.

1. INTRODUCTION

Recent analysis of low current longitudinal instabilities of bunched beams at both the PS(1) and the ISR(2) at CERN has led to new insight on the design of high energy storage rings. The basic characteristics of these instabilities is that they are single bunch instabilities induced by longitudinal fields oscillating at very high frequencies (in the GHz region for the CERN machines). Although the single bunch nature of the instability was at first surprising, the high frequency characteristic allowed an interesting interpretation. If parts of the bunch are sufficiently locally unstable then the growth of the instability could procede fast enough to avoid the characteristic stability of disturbances averaged over a bunch synchrotron period.

From this notion, it follows that one might attempt to explain the instability of the bunches in terms of the well known coasting beam theory applied to local regions of the bunch. This was done and substantial agreement between observation and theory was realized.

Thus, a tentative theory is available and can be extrapolated to storage ring designs. The conclusion is simple: high circumference, small aperture machines are relatively more sensitive to the introduction of proton bunches. This can be arrived at from the following three facts: (1) such machine designs tend to have much higher transition energies; (2) the stability of the bunches for a given current density and momentum spread depends on the frequency spread in the bunch; and (3) a higher transition energy means a lower frequency spread.

A means of completely circumventing the bunch instability and still attaining high current at high energy is proposed here: Stack high current at low energy in a small circumference stacking ring; transfer the bunches, which, if enough current was stacked, will now have enough momentum spread in the larger ring to cancel the effect of the larger transition energy, i.e. there will now be sufficient frequency spread; and finally, accelerate to final energy in the storage accelerator.

In section 2, we discuss the stacking strategy for high energy storage rings in a little more detail. In section 3, we suggest a practical stacking ring for the ISA storage accelerators, and in section 4 we draw some conclusions with regard to the ISABELLE proposal.

2. STACKING STRATEGY

The stability criterion for coasting beams or, as we have previously indicated, for local bunch conditions in the case of high frequency, fast growth disturbances, can be written(3)

$$\left|\frac{Z}{n}\right| < \left(\frac{\Delta p}{I}\right)\left(\frac{\Delta f}{f}\right) \quad , \tag{1}$$

where I is the current in amps, Δp is the spread in beam momentum in eV, f is the beam central frequency, Δf is the beam frequency spread, and Z is the longitudinal impedance inducing the instability at frequency

$$f_{INST} = nf_{rev} \quad . \tag{2}$$

That is, n is the mode number for the instability, defined as the ratio of the instability frequency to the revolution frequency. The impedance limit is therefore simply the relative frequency spread divided by the longitudinal current density, $I/\Delta p$.

The performance of a storage ring is dependent on the ratio $(I/\Delta p)$, which is essentially independent of energy. For the purposes of comparison of different situations, it is not necessary to consider this factor. Thus to achieve a given performance, the total high frequency ring impedance of a given design, i.e. $|Z/n|$, must be less than some constant times the relative frequency spread. This means that the question of stability can be reduced to an understanding of what determines the relative frequency spread.

The relative frequency spread is connected to the relative momentum spread by

$$\frac{\Delta f}{f} = \eta\left(\frac{\Delta p}{p}\right) , \qquad (3)$$

where η is a function of the energy of the particle, γ, and the transition energy of the ring, γ_t, by

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} , \qquad (4)$$

assuming the particle has energy above the transition energy (i.e. $\gamma > \gamma_t$).

As rings increase in size to accomodate higher energy particles, their transition energy increases. Since $\gamma_t \sim \nu$, the ring tune, we see that, for example, at the ISR, $\gamma_t \sim 8$, while new storage ring designs with their much larger circumferences will have $\gamma_t \sim 25$-50. Another way of seeing this trend is to notice that

$$\frac{1}{\gamma_t^2} \propto \frac{< X_p >}{C} , \qquad (5)$$

or, η is essentially proportional to the dispersion function divided by the circumference. This means that η can be increased only at the expense of aperture or by decreasing the circumference (i.e. decreasing the top energy or decreasing the straight section length for experimental needs). In any case, it is clear that in the new high energy storage rings, η cannot be much different than a factor of 10 to 40 smaller as compared to the ISR.

The evaluation of the situation seems clear. The four apparent alternatives are as follows:

1. Control high frequency impedances better than the ISR by a factor of, say, 10 to 40. This could mean a strict if not unacceptable limitation on the flexibility with regard to vacuum chamber construction for machine functions, such as electrodes or scrapers, as well as for experimental purposes in the collision and detector regions.

2. For a given injected bunch, attempt to develop a new form of stacking rf system so as to increase the local momentum spread, $\Delta p/p$.

3. Reduce the performance potential (i.e. luminosity) by decreasing the density $I/\Delta p$. If I is kept constant, the increase in Δp will also increase the frequency spread, giving a quadratic increase of the impedance limit.

4. Increase $\Delta p/p$, but keep the density constant. This keeps the performance potential unchanged. However, it requires that more current per bunch be injected. The question then is, how do we get more current per bunch?

The first three alternatives seem either undesirable (1 and 3) or technologically uncertain (2). The 4th alternative seems simple and attractive. It appears especially suitable to a design such as ISABELLE(4), using the small stacking ring scenario given in the previous section: simply stack in the small circumference stacking ring, transfer and accelerate. We will consider a practical suggestion for a small stacking ring which can be used in conjunction with the proposed ISA storage accelerators in the next section.

3. PRACTICAL STACKING RING FOR ISABELLE

The proposed ISABELLE has a circumference of 3000 m., almost four times that of the AGS. Its transition energy is 21.6 (in proton mass units). For injection into ISABELLE at 29.4 GeV, $\eta_{ISA} = 1.129 \times 10^{-3}$. A stacking ring in the AGS tunnel designed with $\gamma_t = 8.0$ would lead to $\eta_{SR} = 14.6 \times 10^{-3}$, a factor of 12.9 larger.

It turns out that a conventional room temperature magnet system already suggested as a "physics stretcher" for the AGS(5) of modest cost and low power consumption would be suitable for a stacking ring as well. The cost and power consumption are extrapolations from the original magnet design put forward as a conventional, room temperature option in the ISABELLE design study of 1974.(6)

Of course a stacking ring is not a stretcher. The cost would certainly be higher owing primarily to the need in the former case (1) for an ultra high vacuum, in the region of 10^{-9} to 10^{-11} torr, depending on the required storage lifetime, and (2) for a stacking rf system and probably a different rf system for synchronous bunch transfer to ISABELLE.

The main property of the magnet system, the one which ultimately gives it its low cost, low power consumption property is the small magnet gap, on the order of 1 inch. This implies an inner chamber height on the order of 2 cm. Thus, the main question to be asked is to what extent the space charge image force arising from the nearby chamber limits the stacked current. We recall that the main conclusion of the ISABELLE study of 1974 was that small gap magnets, used in that design study to limit power consumption, are not suitable for high current storage accelerators with top energy 200 GeV. The current limit was about 1A. Now, why should we expect our stacking ring to do better, say 10A? We will see that the current limit for the stacking ring is even larger than this value, the main reason being that the strength of the space charge effect for equal magnet gaps is proportional to $R^{5/2}/\nu$, which is about 30 times larger for the 200 GeV storage ring as compared to the stacking ring in the AGS tunnel we are suggesting.

The current limit due to the space charge image force induced by the vacuum chamber can be expressed in terms of the spread in tune required for Landau damping of the transverse resistive wall instability. Large spreads must be avoided because if too large, particles near the edge would be subjected to the influence of non-linear resonances. If we take a conservative value for the total tune spread of $\delta\nu \approx 0.02$, we obtain a conservative current limit.

An expression for the current limit in terms of a given $\delta\nu$ can be written,$^{(7,8)}$

$$I \lesssim \frac{e\nu\gamma h^3(\delta_\nu)}{4r_pR^{5/2}} \left(\frac{c|k-\nu|}{2\epsilon_o\rho}\right)^{1/2} \frac{1}{f(a/h)} , \tag{6}$$

where I is the beam current, in A,

R is the average radius of the ring,

r_p is the classical proton radius, $= 1.54 \times 10^{-18}$m,

ν is the vertical tune,

γ is the beam energy in proton mass units,

h is the chamber 1/2-height,

ρ is the chamber resistivity, in ohm-m ,

k is the mode number for the dominant unstable ,
dipole mode ($f_{dipole} = f_{rev}\,|k - \nu|$),

c is the velocity of light, = 3.0×10^8 m/sec ,

ϵ_o is the free space dielectric constant, = $10^{-9}/36\pi$ sec/ohm-m,

a is the beam ½ - width,

e is the electric charge, = 1.602×10^{-19} Coulombs,

and f is a form-factor derived in Ref. (7) and plotted more conveniently for our purpose for the case of a parallel plate geometry in Ref. (8), (chamber width large compared to chamber height), which is appropriate to our situation. Taking $\nu = 8.2$, $k = 9$ (lowest mode), $\gamma = 31.4$, $h = 1$ cm., $\delta\nu = 0.02$, $R = 128$ m, $\rho = 4 \times 10^{-8}$ ohm-m (using an aluminum vacuum chamber), $a = 2$ cm, and from the plot in Ref. (8), $f(2) \approx 0.5$, we compute for a conservative current limit, $I < 26.6$ A.

In order to compensate for the incoherent image tune shift, specifically the component which causes a variation across the beam, octupoles and perhaps higher order multipoles will be required. This working line shaping is necessary to avert the Brickwall Effect.(9) An estimate of the multipoles required can be deduced from the tune shift and its variation across the beam. The former is roughly given by (10)

$$\Delta \nu_{im} \approx \frac{\pi^2 I r_p R^2}{48 e c \nu \gamma h^2} , \qquad (7)$$

where we have included a factor of 1/2 to take account of the charge spread in the wide ribbon beam. The spread of image tune shifts for a beam twice as wide as the vacuum chamber height is about 0.6 this value; i.e. in our case,(11)

$$\delta(\Delta\nu_{im}) \approx 0.6\ \Delta\nu_{im} . \qquad (8)$$

For a 10A beam, $\Delta\nu_{im} \approx 0.04$ and $\delta(\Delta\nu_{im}) \approx 0.024$, from which the required multipole strengths can be estimated.

4. CONCLUSIONS

We have suggested the use of a stacking ring at low energy to achieve high currents in high energy storage accelerators.[13] This technique circumvents the high frequency longitudinal instability of the injected bunches which otherwise tends to occur in the large circumference machines required for high energy proton storage. A practical example suited to the ISABELLE project was presented. In particular, the use of small gap, conventional, room temperature magnets within the AGS tunnel was considered. The small gap characteristic is a magnet property which minimizes both power consumption and capital cost. The impact of this small gap design on space charge effects was also discussed and it was concluded that a current even as high as 10A could be accumulated in the stacking ring.

Aside from the primary reason for the stacking ring emphasized in the previous paragraph, there are other benefits to be gained. Of course, the stacking ring could be used as a stretcher for physics as already pointed out elsewhere. We can enumerate some other advantages, specifically for ISABELLE.

1. The stacking ring could eliminate completely the need for stacking in ISABELLE (except of course the stacking required for filling the ISA circumference, which is about 4 times the stacking ring circumference). This means that substantial proton losses, which seem difficult to prevent when stacking, could be avoided, thus significantly alleviating the quench tendency of the superconducting coils of the ISABELLE magnets which are directly vulnerable to the radiation heating from lost protons.(12)

2. The stacking ring could be built well in advance of ISABELLE. The complex stacking process could be studied and optimized. The high current proton beam could thereby be ready when ISABELLE is completed, thus greatly improving the possibility for experiments soon after ISABELLE comes on the air.

3. The stacking ring would require the creation of teams for construction and operation of various machine functions. Thus, the stacking ring rf and vacuum teams for example could be immediately expanded to include the needs of ISABELLE. This allows experienced working groups to be available to ISABELLE right from the beginning. These groups will have had invaluable experience in the handling of high current stored beams, in their control and dumping, by the time ISABELLE's superconducting environment becomes an added factor.

4. Since the voltage reduction during the stacking process must procede to a minimum whose value is proportional to η, the mean voltage is generally smaller in the larger rings. Thus, the estimated time of the stacking process would tend to be substantially higher in the large circumference storage accelerators as compared to the small circumference stacking ring. The implication of this fact for ISABELLE has more significance than merely the stacking time. For, since the stacking ring would be less sensitive to the stacking time, the AGS could be operated at lower intensity to optimize for maximum transverse phase space density. This optimizes the luminosity, which for a given stacked current, depends inversely on the beam height. It should be kept in mind that decreasing the current per stacked pulse (while keeping the density $I/\Delta p$ constant) would place a more stringent condition on the maximum allowable high frequency impedance in the stacking ring. The point is that since the η factor is so much larger in the stacking ring than in the storage rings, there is just that much more freedom to optimize for the peak transverse density with an intermediate accumulator ring.

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13. After completion of this manuscript, it was brought to the attention of the author that during private discussions within the rf and acceleration working group at the BNL summer study, 1975, the possibility of using an intermediate storage ring for the ISA was mentioned, although not pursued further.