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HIGH FREQUENCY BUNCHES FOR PROTON-PROTON STORAGE ACCELERATORS*

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Summary

In the post-ISR period of high energy proton-proton colliding beams, it may be necessary to reconsider the high current, continuous beam approach as a practical operating procedure. An alternative for achieving both high level performance and operational simplicity is through the use of high frequency bunches. A scheme that could be used in operating the ISABELLE facility is outlined. High-luminosity is obtained with low average current and tight bunching. The bunched mode is natural for achieving flexibility in energy variation. With sufficiently high bunch frequency, the total number of events per colliding bunch can be kept down to a value on the order of unity. The advantages of bunched operation cover the areas of current accumulation, beam loss, aperture utilization, beam handling (e.g., debunching, rebunching, and beam extraction) and synchrotron radiation. Other relevant topics are stability against growing coherent beam oscillations, the beam-beam interaction, and the rf heating induced in the vacuum chamber.

I. INTRODUCTION

The ISABELLE Storage Accelerator, as presently planned, will operate in a way essentially analogous to the CERN ISR. Continuous beams of protons will be made to collide. However, to achieve the larger energy range (30 to 400 GeV), ISABELLE has chosen the conventional "synchronous" or bunched method of acceleration, rather than the phase displacement technique developed at the CERN ISR to cover the more limited energy range, from 26 to 31 GeV. The result of this choice is that the beam must alter its form, from bunched at injection, to dc in stacking, to bunched for acceleration, to dc for collisions. These added beam manipulations contribute to a variety of complications, for example, to an increase in aperture requirement with an accompanying increase in beam loss. Such considerations lead us to inquire about the performance possibilities of operating ISABELLE with a bunch structure which is maintained in the stacking, acceleration, and collision phases.

II. THE AGS INJECTOR

In discussing the use of a proton-proton storage accelerator with many colliding bunches, we will assume that we are given the basic design of the superconducting proton rings as described in the ISABELLE proposal.[1] However, to obtain many bunches, we shall adopt the boxcar stacking scheme initially proposed by R. Chasman.[2] Thus, we envision the AGS accelerator operating on a harmonic number of one injecting a single bunch at a time, of about 3.5×10^{12} protons, into one of 57 buckets of an ISABELLE ring. The total time required to fill both storage rings is then about 12 minutes. In Table I, we have listed the parameters for the AGS serving as such an injector. The beam characteristics for injection from the 200 MeV Linac, for passage through the transition energy, and for acceleration to a high energy of 29.4 GeV are presented.

Before transfer to ISABELLE, the bunch must be shortened to fit the 4.5 MHz ISABELLE buckets. To do this, the 12th harmonic (4.5 MHz) AGS rf system is used. With a voltage of 420 kV, a length of 15 m for the bunch is obtained, acceptable for transfer. The corresponding fractional momentum spread that must be accommodated in the transfer line and in the ISABELLE rings is 6×10^{-3}.

Table 1 AGS Beam Parameters

Circumference of AGS	807.1 m
Linac kinetic energy	200 MeV
Harmonic number	1
Longitudinal phase space area	6.2 eV sec
Number of protons per turn	3.5×10^{12}
Normalized betatron emittance	$10 \pi\ 10^{-6}$ rad m
Accelerating voltage	50 kV
Rate of acceleration	7.8 GeV/sec
Total energy at transition	8 GeV
Peak momentum spread at transition	6×10^{-3}
Bunch length at transition	27.8 m
Momentum aperture at transition	2.2 cm
Ratio of space charge force constant to rf force constant at transition	0.5
High energy	29.4 GeV
Full momentum spread	1.7×10^{-3}
Bunch length at high energy	48.5 m
Harmonic No. (matched transfer to ISA)	12
Matching voltage	420 kV

III. BEAM STACKING, ACCELERATION, AND STORAGE IN ISABELLE

Each of the bunches prepared in the AGS will be injected one at a time into the aperture of the rings. This will necessitate a fast full-aperture kicker and will place the 57 bunches into the center of the 8 cm aperture. A sketch of the extent occupied by the beam is illustrated in Figure 1. This is compared with the present ISABELLE injection aperture,[1] sketched also in Figure 1.

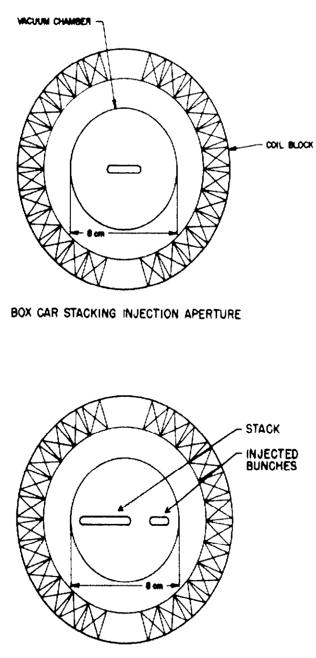

Figure 1. Injection aperture utilization.

It is clear that such a central positioning will minimize the possibility of beam loss and, thereby, also minimize the possibility of a quench occurring in the surrounding superconducting magnetic elements. During the boxcar stacking of the machine, the rf voltages in

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the two rings will have a relative phase such that the bunches in the two rings pass through the intersection regions at different times. This "noncollision" geometry, see Figure 2, will be maintained during the subsequent acceleration of the beams to the energy level specified by the experimenters.

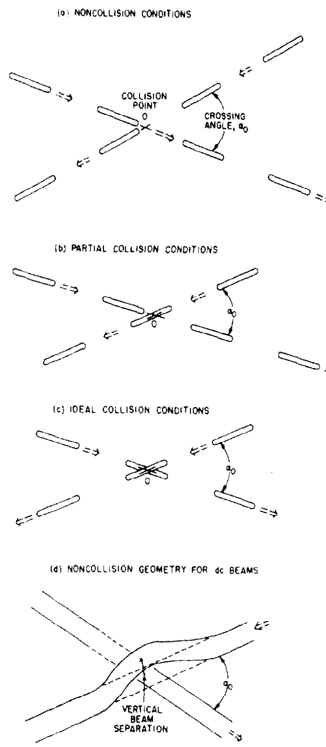

Figure 2. Collision geometry.

At this point, the bunches would slowly be brought into collision by phasing the rf. Magnetic corrections can be introduced as the beam-beam effects slowly appear. Such an adiabatic procedure cannot be applied when dc beams are separated vertically, Figure 2. Experience at SPEAR with vertically separated beams shows that the beams must be brought into collisions rapidly, in a few turns. In Table II we present the beam parameters typical of the bunch mode of operation in ISABELLE. For an average current of 2.5 A and a vertical beta function of 4 m at the interacting points, we observe that the average luminosity is 5×10^{31} cm^{-2}sec^{-1} at low energy and 1.8×10^{32} cm^{-2}sec^{-1} at 400 GeV. The luminosity per bunch collision at the higher energy is 4.2×10^{25} cm^{-2}. This gives a total event rate of about 2 per bunch collision, assuming a total cross section of 50 mb. Corresponding to these luminosities, the beam-beam tune shift strength parameters are about 8×10^{-3} and 2×10^{-3}.

When operating with bunches in a storage accelerator, it is important to consider the heating of the chamber due to the circulating wall currents. For the copper clad stainless chamber to be used inISABELLE, the heat that must flow in the copper sleeving, away from the center of the superconducting magnet, is about 0.6 Wm^{-1}, and the expected temperature rise is only 19°C.

Although there are many advantages to operating ISABELLE with high frequency, the basic vulnerability of the ISABELLE design to the vertical resistive wall instability remains. For the parameters introduced in section 3, the direct space charge tune shift, $(\Delta\nu)_{sc}$ ~ 0.03. A rough estimate of the threshold for the

Table II ISABELLE Bunch Beam Parameters

Circumference of ISABELLE	3834	m
Injection energy	29.4	GeV
Max. Full beam width (Inj.)	23	mm
Max. Full beam height	9	mm
Number of bunches	57	
rf frequency (57th harmonic)	4.457	mHz
Number of protons per bunch	3.5×10^{12}	
Average current	2.5	A
Length of each bunch (50 nsec)	15	m
Separation of bunches (224 nsec)	67.3	m
Top energy	400	GeV
Crossing angle	10	mrad
Vertical beta function at crossing	4	m
Horizontal beta function at crossing	30	m
rms height at crossing (400 GeV)	0.12	mm
Bunching factor	0.22	
Lum./bunch collision (400 GeV)	4.2×10^{25}cm^{-2}	
Total event rate (σ_T = 25 mb)	2/bunch coll.	
Average luminosity (400 GeV)	1.8×10^{32}	
Beam-Beam tune shift (400 GeV)	2×10^{-3}cm^{-2}sec^{-1}	
Betatron tune values $\nu_V \simeq \nu_H$	22.6	
Gamma at transition	19.1	
Injection voltage	270	kV
Momentum spread at injection	6×10^{-3}	
Peak current	11	A
Microwave impedance limit (Inj.)	62	Ω
High energy voltage	31	kV
Momentum spread at 400 GeV	4×10^{-4}	
Microwave impedance limit (400 GeV)	7	Ω
Synchrotron frequency at injection	29	Hz
Synchrotron frequency at 400 GeV	3.5	Hz

coherent rigid bunch instability is found by requiring a tune spread in the bunch, $(\delta\nu)$ spread $\sim (\Delta\nu)_{sc}$. A more detailed computation suggests that a spread equal to twice the shift is needed. Thus, to obtain stability by Landau damping, we need a tune spread of ~ 0.06. This is not a satisfactory solution since a working line of this magnitude may be limited by nonlinear resonances. Another approach is to use a direct feedback system to control the incipient oscillation. A "single bunch system" is already required to correct injection errors and this, therefore, seems a natural approach. For our case, the growth period far from threshold is $\tau_g \approx 5$ msec at injection. The most severe requirement on the feedback system comes from the injection error, where the damping time should be sufficiently less than the e-folding growth rate, i.e., $t_d \leqslant 1$ msec. Under colliding beam conditions, this constraint is considerably eased and one can tolerate a damping time which is at least a few e-folding growth periods, since any signal must arise from beam noise. For high energy operation, since the growth period is proportional to the energy, the requirement on the feedback system speed is further reduced by an order of magnitude. It is interesting that for single bunch operation, the bunch is stable against the resistive wall rigid bunch instability since the betatron tune has been chosen to be above the ½-integer.[4] When beams collide horizontally, the weak-strong beam-beam force only has a vertical component. This lack of a horizontal component of net force holds true whether the colliding beams are dc or bunched. The difference is that in the bunched case there is a modulation of the magnitude of the force at twice the synchrotron frequency (see Figure 2). One of the questions encountered in assessing the feasibility of bunched beam operation is what effect this force modulation will have on the beam lifetime and perhaps on the luminosity lifetime as well. Although this is an important consideration, one should keep in mind when contrasting performance between dc and high frequency bunch operation, that the latter has a significantly reduced accumulation period, 15 minutes compared with a few hours. Thus, the acceptable effective lifetime could in many experiments be lower in the bunched mode.

IV. OPERATIONAL CHARACTERISTICS

It is fair to say that the operational aspects of ISABELLE with many bunches should be straight forward. Except for periods of actual interaction of the beams, all operations will be similar to those of a conventional proton accelerator. In Table III we present a list of a number of features characterizing the bunched mode of operation.

Table III Aspects of Bunched Beam Operation

1. Injection. Fast boxcar stacking carried out from AGS. Stacking time ≃ 12 minutes for two rings.
2. Aperture Utilization. Inject bunches into center of chamber, minimizing beam loss and radiation background. Beam is kept in center of magnetic aperture.
3. Beam Position Observation. Bunches always observed on conventional PUE's.
4. Collision Control. Bunches brought into collision slowly by changing relative rf phase. Control magnetic corrections during this operation. Vertical beam separation not required. Luminosity control by varying bunch length and by phasing bunches.
5. Ejection. Normal ejection made by bringing beams out of collision, decelerating to low energy and extracting bunches. Emergency ejection made at high energy with some missing bunches.
6. Electron Clearing of Beam. Self clearing due to bunch structure. No e-p instability.
7. Background Measurement. Measure beam gas background with beams not colliding, without vertical displacement. Measure with unequal number of bunches in two rings, e.g., for effects of distant crossings.
8. Energy Cycling. Cycle energy of one or both rings, slowly and by a small amount, while colliding with other beam. Threshold behavior can be studied.
9. Synchrotron Radiation Correction. At 400 GeV, a proton loses 0.2 GeV per hour. This loss is automatically corrected for by the rf.

A particular feature of the bunched mode is the availability of a variety of operating cycles. Some of these are illustrated in Figure 3.

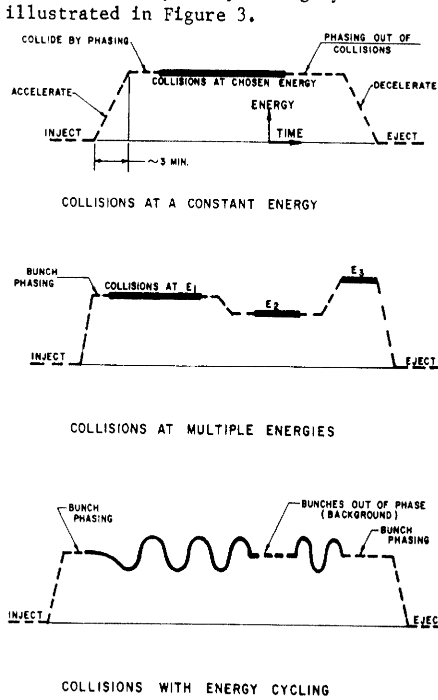

Figure 3. Energy Cycles for Bunched Beam Operation.

It is of interest to point out that in this bunched mode of operation, the average luminosity is linear in the number of circulating bunches. This means that operation with a small number of bunches, which could be desirable in the early ISABELLE experimental phase, would still give a respectable luminosity even with a relatively low current. For example, with three bunches per beam, that is an average current of only 0.13 A, the luminosity at 400 GeV is about 10^{31} $cm^{-1}sec^{-1}$.

V. HIGHER ENERGY EXTENSION

Another aspect of operating ISABELLE in a high frequency, bunched mode is the straight forward extrapolation of the operating procedure to higher energies. ISABELLE then plays an ideal role as an injector in the higher energy facility. The high density bunches would be conveyed through the 400 GeV machine, on a single or multiple basis, and then injected into the larger machine. Achieving good beam control and high luminosity would then follow the pattern set in ISABELLE. An illustration of a system with ISABELLE serving as an injector into a 2 TeV on 2 TeV Super ISABELLE is shown on the BNL site in Figure 4. We have considered a similar arrangement at 1.2 TeV per beam in a previous publication.[5]

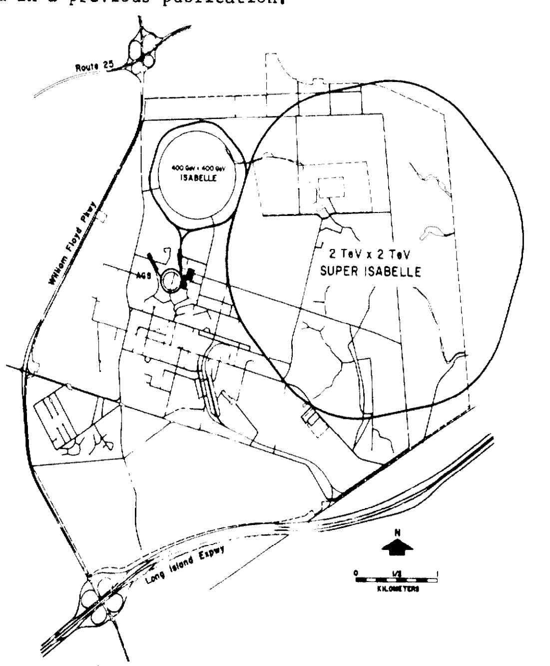

Figure 4. 2 TeV on 2 TeV ISABELLE Extension on Brookhaven Site.

Acknowledgments

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References

1. ISABELLE - A Proton-Proton Colliding Beam Facility, BNL 50718 (1978).
2. R. Chasman, BNL Report, CRISP 72-94 (1972).
3. E.D. Courant, et al., "Enhanced Resistive Wall Instability For Off-Centered Beams", this conference.
4. E.D. Courant and A.M. Sessler, Rev. Sci. Instrum. 37, 1579 (1966).
5. J. Claus, et al., Proc. Xth International Conference on High Energy Accelerators, Serpukhov, USSR, 484 (1977).