BNL 18313

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

CRISP 73-20

ACCELERATOR DEPARTMENT
Informal Report

24,491

BUNCHED BEAM INTERSECTING STORAGE ACCELERATORS
FOR PROTON-PROTON COLLISIONS

M. Month
October 24, 1973

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ABSTRACT

A pair of intersecting storage accelerators is proposed. Using bunched beams colliding head-on, a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ per collision region can be obtained with an average current of 0.7 A (corresponding to ~ 10 A peak current). The mechanism for obtaining collisions is simply to transfer the bunched AGS beam to the matched ISA rings, accelerate the beams in the ISA rings to their final energy and collide them. The requirements on the AGS beam are: transverse emittance, $\epsilon \approx 2.5 \times 10^{-6} \text{ rad-m}$ at an energy of 30 GeV (note that phase space area = $\pi\epsilon$); longitudinal emittance, $\Delta \approx 1.0 \text{ eV-sec/bunch}$; and intensity $\approx 10^{13}$ protons per pulse. These are values that are well within the range of the existing AGS. If the ISA is chosen to have a circumference three times that of the AGS, then with a filling factor of 48% (i.e. in order to accommodate injection, fast protective extraction into dumps, rf requirements, vacuum equipment and experimental areas), an energy of 200 GeV can be achieved with 35 kG magnetic fields. This means superconducting magnets. If another AGS circumference is added (i.e. 800 m with a 67% filling factor), an energy of 165 GeV can be obtained with a field of 20 kG. That is, if $R_{\text{ISA}} = 4R_{\text{AGS}}$, then with normal 20 kG magnets, a top energy of 165 GeV can be reached. A total magnet aperture of 5 cm seems reasonable, although a magnet gap of about 4 cm in the case of normal magnets, where only the vertical dimension is relevant, is acceptable. The rf system, which would be used for matching, acceleration, and storage, would have a frequency of 13 MHz and operate at a voltage of 50 kV/turn peak. Acceleration could be accomplished in less than 1 minute, and rf power consumption would be less than 1 MW. To obtain sufficient beam lifetime and sufficiently low background for experiments, an average pressure at least as low as 10^{-9} torr is recommended. It should be kept in mind that with the simplicity of beam transfer and stacking, and with the speed of the acceleration process, dumping and refilling should not be a major operation and could be performed in about 1 min. It is thus conceivable that the device could be operated in 1 hour

cycles. The interaction of the beam with itself, with the other beam and with the surrounding environment is considered. Discussed at various places are: (1) Incoherent space charge tune shifts; (2) Bunched beam transverse resistive wall effect; (3) Head-tail effect; (4) The interaction of the bunched beam with the rf cavity; (5) Proton interaction with electrons produced by ionization of the residual gas; (6) Diffusion from intrabeam scattering; (7) Beam gas interaction; and (8) Beam-beam interaction. Design parameters are chosen so as to negate any potential beam blowup from these phenomena.

1. Introduction

We propose a pair of intersecting storage accelerators. With bunched beams colliding head-on and an average current of 0.7 A (corresponding to ~ 10 A peak current), we obtain a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. The energy that can be achieved is determined by the circumference and magnetic field chosen. For a circumference three times the AGS, that is $C_{\text{ISA}} = 2422 \text{ m}$, we can reach 200 GeV with 35 kG magnets. Because of space requirements for injection, for fast protective extraction into dumps, for rf and vacuum equipment and for experimental layout, the bending magnet filling factor used was 48%. The 35 kG magnetic field means the use of superconducting magnets. If, however, we add an AGS circumference ($C_{\text{AGS}} = 807 \text{ m}$), we can use a filling factor of 67% for the added length. This allows us to reach an energy of 165 GeV with 20 kG magnets. That is, if $C_{\text{ISA}} = 4C_{\text{AGS}}$, then normal 20 kG magnets result in a top energy of 165 GeV.

The mechanism for obtaining collisions is simply to transfer the bunched AGS beam to the matched ISA rings, accelerate the beams in the ISA rings to their final energy and collide them. The two rings are conceived as two identical rings separated vertically by 0.5 m (beam to beam).¹ The collisions will take place in four areas and the beams are brought together by vertical bending magnets. The requirements on the AGS beam are: transverse emittance, $\epsilon \approx 2.5 \times 10^{-6} \text{ rad-m}$ at an energy of 30 GeV (note that transverse phase space area = $\pi\epsilon$); longitudinal emittance, $\Lambda \approx 1.0 \text{ eV-sec per bunch}$; and AGS intensity $\approx 10^{13}$ protons per pulse. These are values that are well within the range of the existing AGS.²

A total magnet aperture of about 5 cm seems reasonable, taking into account beam size, closed orbit errors, sagitta and some uncertainty. In the case of normal magnets, where only the vertical dimension is relevant, a magnet gap of $\sim 4 \text{ cm}$ is acceptable.

The beam will interact with the residual gas in the vacuum chamber. To obtain sufficient beam lifetime for performance, to avoid harmful radiation in magnets and equipment, and to have a sufficiently low background for experiments, an average pressure at least as low as 10^{-9} torr is recommended.

The rf system is used for matching the bunches from the AGS, accelerating the beam to its final energy, and for storing the beam for collisions. We suggest a frequency of ~ 13 MHz, corresponding to a harmonic number $h = 108$, and a voltage $V = 50$ kV/turn peak. With 3 consecutive AGS pulses injected, there are 36 bunches in each ISA ring. The harmonic number of $3 \times 36 = 108$ is chosen so as to reduce the voltage (since $V \propto 1/h$) required and so reduce the power consumption. With such a system, acceleration could be accomplished in less than 1 minute, and rf power consumption would be less than 1 MW. For the case when $C_{ISA} = 4C_{AGS}$, there would be 48 bunches and the frequency would be 17 MHz (corresponding to a harmonic number $h = 144$). For the same voltage of 50 kV, the acceleration time is unchanged and the power consumption remains below 1 MW.

The effect limiting the luminosity is the beam-beam interaction. The beam loss is due to a blowup of the beam due to the highly nonlinear beam-beam interaction. A measure of the limitation is the linear beam-beam tune shift.³ In effect, the beam lifetime is a function of the linear tune shift (or, strength of the beam-beam interaction). Thus, by insisting that the beam-beam tune shift remain below a certain limit $(\Delta\nu)_{bb}$, we are essentially requiring a certain lifetime against this effect. Again here, beam loss not only affects performance, but induces radiation in magnets and equipment, and creates background in experimental areas. Taking this into consideration, we adopt a beam-beam limit $(\Delta\nu)_{bb} = 0.005$, which presumably corresponds to a lifetime of many hours. It should be kept in mind, however, that since there is substantially no stacking, and acceleration is performed in less than 1 min, dumping and refilling should not be a major operation and could be performed in about 1 min. Thus, although we are designing for a lifetime of many hours, it is not inconceivable to operate such a device for as little as 1 hour, then dump and refill, and so on. The loss in performance (assuming that only minor adjustments will be needed to take account of pulses from linac to AGS to ISA not being exactly repetitive) should be inconsequential.

Our choice of tune is ~ 20.25 , which means that at the injection energy of 30 GeV, the beam is sufficiently above transition ($E_t \sim \nu \sim 20$ GeV) to avoid blowup associated with the crossing of transition. However, as we will see, the performance of the device we are proposing is not too

sensitive to longitudinal parameters and some longitudinal beam blowup is tolerable. If therefore, there were reason to operate at a higher tune, say $\nu \sim 40$ or 50 , we could alter our design to accommodate this. This means that transition would be crossed in accelerating from 30 GeV to the final energy; but, as we have indicated, our basic design should be able to accommodate the transition crossing.

The tune spread (due to momentum spread) is $\delta\nu \approx 10^{-2}$. This appears to provide sufficient Landau damping to prevent any coherent transverse instability.⁴ However, the chromaticity ($\xi = p\delta\nu/\delta p$) must be as large as 1 in magnitude. The point here is that to counter head-tail effects,⁵ we require that the chromaticity be positive, while naturally the chromaticity produced by the lattice is negative. Sextupoles must be used to change the sign of the chromaticity, and, if coils are added to the main lattice quadrupoles to produce the required sextupole fields, we estimate that the needed fields at the coils are about 0.5 kG (at 2.5 cm from the center where the field is zero). The transverse resistive wall instability and the head-tail effect are considered more fully in Section 7, along with brief discussions of incoherent space-charge tune shifts,⁶ diffusion from intrabeam scattering,⁷ and the interaction of beam protons with electrons produced by the ionization of the residual gas.⁸ Relevant ISA parameters, such as chromaticity, tune spread, and residual gas pressure, are chosen so as to negate any potential beam blowup from these phenomena.

In Section 2, we discuss the collision parameters, and, in particular, we compute luminosity estimates. In Section 3, we give details of the lattice and specifically, we discuss the layout of the experimental insertions. Beam transfer, acceleration, and storage are considered in Section 4, while short sections are devoted to magnet aperture (Section 5) and vacuum requirements (Section 6).⁹ Background to experimental events arising from scattering of protons off the residual gas is also discussed in Section 6.¹⁰

In Table I, we provide a list of basic parameters that are developed over the length of this paper.

TABLE I Parameters for Bunched Beam ISA

Final Energy (GeV)	200	100	165
Luminosity ($\text{cm}^{-2} \text{sec}^{-1}$)	1.2×10^{32}	0.6×10^{32}	0.6×10^{32}
Beam-Beam Tune Shift	-0.005		
Average Radius (m)	385.5		514.0
Bending Radius (m)	187.2		280.6
Magnetic Field (kG)	35.6	17.8	19.6
Bending Magnet Length (m) [no.]	3.5 [336]		3.8 [464]
Experimental Insertion Length (m) [no.]	160 [4]		
Multipurpose Insertion Length (m) [no.]	100 [4]		
Lattice FODO Cell Length (m) [no.]	21.6 [64]		22.8 [96]
Symmetry	4		
Average ISA Current (A)	0.72		
Peak ISA Current (A)	10.9		
Kicker Rise Time (μsec) [Inj, Ej]	0.22		
f_{rf} (frequency, MHz)	13.4		
V_{rf} (Peak voltage/turn, kV)	48.5		
Bunching Factor (length/separation)	0.066 (15 to 1)		
Acceleration Time (min)	< 1		
RF Power Consumption (MW)	< 1		
Magnet Aperture or Gap (Total, cm)	5	4	4
Residual Gas Pressure (torr)	10^{-9}		
Desired Beam Lifetime (hours)	$\geq 2-4$		
Tune	20.25		
β_{max} (m)	40		
$\frac{1}{2}$ Beam Size (Vertical, 30 GeV, cm)	1		
$\frac{1}{2}$ Beam Size (Horizontal, 30 GeV, cm)	1.2		
Total Momentum Spread (Final Energy)	4.2×10^{-4}	7.1×10^{-4}	4.9×10^{-4}
Total Bunch Length (m)	4.5	5.4	4.7
β_0 (m, collision point)	5		
Chromaticity ($\xi = \text{pdv}/\text{vdp}$)	+1		
Tune Spread	9×10^{-3}	1.4×10^{-2}	1×10^{-2}
AGS Intensity (protons per pulse)	1.2×10^{13}		
AGS Longitudinal Emittance (eV-sec/bunch)	1.0		
AGS Transverse Emittance (A/n, 30 GeV, rad-m)	2.5×10^{-6}		

2. Collision Characteristics and Luminosity

Let us assume 200 GeV protons in a superconducting ring, that is, a circumference, $C = 3 \times C_{\text{AGS}}$. For 100 GeV protons, in a ring with normal magnets, we simply use the fact that, other things kept equal, the luminosity is directly proportional to the energy when in the beam-beam limited condition. Further we assume that bunches are transferred directly from the AGS and collide head-on. Then, for uniform density beams (both transverse and longitudinal), the luminosity per bunch is¹¹

$$L/\text{Bunch} = \frac{cN^2}{C\epsilon \ell_p} \tan^{-1} \frac{\ell_p}{2\beta_0} \quad (2.1)$$

where N = number of protons per bunch,

ϵ = transverse emittance (assume, $\epsilon_H = \epsilon_V$),

ℓ_p = total bunch length, and

β_0 = value of β at the collision center.

If

$$\beta_0 > \frac{1}{2}\ell_p, \quad L/\text{bunch} \approx \frac{cN^2}{2C\epsilon \beta_0} \quad (2.2)$$

The limiting beam-beam tune shift in this simple case is¹¹

$$\Delta\nu = - \frac{r_p}{4\gamma} \frac{N}{\epsilon} \quad (2.3)$$

where γ = the proton energy in mass units,

r_p = classical proton radius ($= 1.54 \times 10^{-18}$ m).

Thus, the tune shift is a limit on the transverse brightness, N/ϵ .

With a beam-beam limit

$$(\Delta\nu)_{bb} = - 0.005 \quad (2.4)$$

then,

$$\frac{N}{\epsilon} = \frac{4\gamma |\Delta\nu|_{bb}}{r_p} = 2.6 \times 10^{18} \text{ m}^{-1} \quad (2.5)$$

From (2.2), using $C = 2400$ m, $c = 3 \times 10^8$ m/sec,

$$L/\text{bunch} = 1.62 \times 10^{19} \frac{N}{\beta_0} (\text{cm}^{-2} \text{ sec}^{-1}) \quad (2.6)$$

If we now assume that we can have 10^{12} protons per bunch, then the emittance, ϵ , from (2.5) is

$$\epsilon = 0.4 \times 10^{-6} \text{ m-rad (at 200 GeV)} \quad (2.7)$$

while the luminosity is

$$L/\text{bunch} = 1.6 \times 10^{31} / \beta_0 \text{ (cm}^{-2} \text{ sec}^{-1}) \text{ ,} \quad (2.8)$$

with β_0 in m.

Now, if we use 3 AGS pulses to fill each ring, then we have a total of 36 bunches, and the total luminosity per collision region is

$$L = L/\text{bunch} \times \text{no. of bunches} = 5.8 \times 10^{32} / \beta_0 \text{ .} \quad (2.9)$$

Thus, for bunch lengths, l_p , of about 1-2 m, we can reduce β_0 to about 2 m and obtain

$$L \approx 3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1} \text{ .}$$

Conservatively, we can choose $\beta_0 \approx 5\text{-}6$ m, giving

$$L \approx 10^{32} \text{ cm}^{-2} \text{ sec}^{-1} \text{ .}$$

In this case the luminosity is insensitive to bunch lengths up to about 10 m.

3. General Characteristics of the Lattice

Consider a lattice with a geometric symmetry of four, as follows:¹
 4 experimental matched insertions (E) of total length 160 m each; 4 matched insertions (I) with free space provided for use in injection, fast protective extraction, and for rf devices, each of total length 100 m; and 64 FODO type cells (N) each of length 21.6 m. The general arrangement is shown schematically in Fig. 1. The total circumference is $4 \times 160 + 4 \times 100 + 64 \times 21.6 = 2422.4$ m, which is $3\times$ the AGS circumference.

The normal cell, pictured schematically in Fig. 2, has four 3.5 m bending magnets (B), two 1.3 m quadrupoles (Q), and spaces of 50 cm or 1 m between magnetic elements as shown. Each cell would have $\beta_{\max} \approx 40$ m, $\beta_{\min} \approx 8$ m, and a phase advance of $\sim \pi/2$.

The experimental insertions would have a momentum matching part consisting of 5 bending magnets and some focusing elements. The purpose is to take the horizontal momentum dispersion function, $x_p^{\max} \approx 1.8$ m, to zero in the collision region. With a symmetric insertion, this requires about 25 m at each end. This leaves 110 m of length which will be used for making the beams collide (with bending magnets), for providing the proper beam characteristics necessary for experiments (quadrupoles), and for experimental apparatus. An experimental insertion is shown schematically in Fig. 3.

A more detailed description of the interaction region is shown in Fig. 4. The bunches collide head-on. The beam separation constraint is therefore that a given bunch after collision must be bent away from the collision line before it meets the next bunch of the other beam. A second constraint deals with the growth of the β -function which is given by

$$\beta(\ell_I) = \beta_0 + \frac{\ell_I^2}{\beta_0} ,$$

where β_0 is the value of β at the collision point and ℓ_I is the distance to the focusing elements. The actual β growth is a little bigger because of the non-zero length of the focusing magnets.

We suggest that the focusing action on the beam be applied before the bending to separate the beams. The problem with this idea is that the quadrupoles act on both beams which are moving in opposite directions.

In other words, the two beams see opposite quadrupole polarity. However, by using a symmetric triplet, we can minimize the difference, which can be corrected for independently at the ends of the insertions, where the beams are separated and independent.

The main lattice consists of two rings separated vertically by 50 cm (beam center to beam center). Thus, the bending action must move each beam from the collision line to parallel lines 25 cm above and 25 cm below for the two beams. A common dipole separates the beams and independent dipoles bend the two beams onto their main orbits. If we assume about 5 m length for the triplet and 5 m of bend required to insure that the beams are separated, then the fact that the bunches are about 60 m apart means that we have a maximum of 40 m free straight around the collision point. Leaving 20 m for vertical bending and 10 m for β -function matching, as shown in Fig. 4, we arrive at an insertion length of 160 m (including the 50 m for matching of the horizontal dispersion function). A small vertical dispersion results in the collision region, but this has a negligible effect on performance (i.e. luminosity). To maintain matching of the vertical dispersion function, a quadrupole is inserted in the vertical bend region. An example of the type of configuration that may be required is shown in Fig. 4. The vertical bending field required is about 35 kG.

The multipurpose matched insertion will each provide 50 m of "straight" with about 35 m "free". Momentum dispersion matching sections for this symmetric insertion are used and greatly simplify the design. The insertion is shown schematically in Fig. 5.

The total number of bending magnets is $64 \times 4 + 8 \times 10 = 336$ magnets giving a total bending length of $336 \times 3.5 = 1176.0$ m. For 200 GeV protons, $B\rho = 6666.7$ kG-m. Therefore, the bending field required in the superconducting dipoles is

$$B = \frac{2\pi \times (B\rho)}{\text{length of } B} = \frac{2\pi (6666.7)}{1176.0} = 35.6 \text{ kG}.$$

The gradient required in the normal cell quadrupoles to achieve the above quoted characteristics is about 6 kG/cm and would also be superconducting.

The normal cells (N) have a phase advance of about $\pi/2$, and with 64 of them, they contribute 16 units to the tune. Assuming the insertions each

have a phase advance of roughly π , the total tune will be about 20. Since the injection energy is about 30 GeV, the particles are well above transition. That is,

$$\nu \approx 20,$$

$$\nu_{\text{tr}} \leq 20,$$

and

$$\nu_{\text{INJ}} \approx 30.$$

Fig. 1: Schematic of lattice. Ring 1 is above Ring 2.

Fig. 2: Normal Cell (FODO): Total length = 21.6 m.

Fig. 3: Schematic of Experimental Insertion

Fig. 4: Experimental Insertion

B - vertical bending magnets.

T - symmetric triplet to focus both beams at the collision point.

C - collision line.

Q - quadrupole for matching vertical dispersion function.

F - β -function matching quadrupoles.

The length units are meters. The beam separation units are cm. The horizontal dispersion matching sections are not shown. The insertion is symmetric about the collision point.

Fig. 5: Schematic of Multipurpose Insertion

4. Beam Transfer and Acceleration

For an ISA circumference three times the circumference of the AGS, three AGS pulses would be transferred consecutively. The timing requirements on the fast kickers, both in the ISA and in the AGS are that rise and fall be accomplished in the distance between bunches. Since in the AGS, we have 12 equally spaced bunches, the distance between bunches is

$$d = \frac{C_{AGS}}{12} = 6.73 \text{ m} ,$$

with the AGS circumference, $C_{AGS} = 807.4 \text{ m}$.

Thus, the kickers must be capable of rising and falling in

$$\tau_r = \frac{d}{c} = 0.22 \text{ } \mu\text{sec} ,$$

Once at full current, the kicker acts on 12 bunches or about 11 times $\tau_r = 2.4 \text{ } \mu\text{sec}$. Injection will take place in one of the multipurpose sections as previously indicated.

In a moving bucket, the 12 elliptical AGS bunches at $\sim 30 \text{ GeV}$ have a total momentum spread and bunch length given by¹²

$$\frac{\Delta p}{p} = \sqrt{\frac{4A \Omega_s}{\pi E \beta^2 |\eta|}} , \quad (4.1)$$

$$\Delta L = \frac{|\eta| c \beta}{\Omega_s} \frac{\Delta p}{p} , \quad (4.2)$$

where E is the energy (γ is the energy in proton mass units)

β is the velocity in units of c ,

$$\eta = 1/\gamma_{tr}^2 - 1/\gamma^2 , \quad (4.3)$$

γ_{tr} is the transition energy in mass units,

$$\Omega_s = 2\pi f_{AGS} \gamma_s , \quad (4.4)$$

the synchrotron frequency is given by

$$\nu_s = (eVh|\eta| \cos \varphi_s / 2\pi E)^{\frac{1}{2}} , \quad (4.5)$$

the synchronous phase is φ_s ,

V is the peak voltage per turn,

h is the harmonic number,
the AGS frequency is given by

$$f_{\text{AGS}} = \frac{c\beta}{2\pi R_{\text{AGS}}} \quad , \quad (4.6)$$

R_{AGS} is the radius of the AGS,

and
$$A = \frac{\pi}{c} \Delta E \Delta \mathcal{L} \quad , \quad (4.7)$$

is the invariant area in units of eV-sec.

Using, $\beta = 1$, $\gamma = 30$, $E = 28.14$ GeV, $eV = 384$ keV/turn, $h = 12$, $\varphi_s = 150^\circ$,
 $\gamma_{\text{tr}} = 8.21$, $R_{\text{AGS}} = 128.5$ m, $c = 3 \times 10^8$ m/sec, we find

$$|\eta| = 0.0137,$$

$$f_{\text{AGS}} = 371.57 \text{ kHz},$$

$$\nu_s = 5.56 \times 10^{-4},$$

and
$$\Omega_s = 1298.2 \text{ rad/sec}.$$

If we further assume an invariant area of 0.35 eV-sec, then we have for
a bunch at 28 GeV ($\gamma = 30$),

$$\frac{\Delta p}{p} = 1.2 \times 10^{-3} \quad , \quad (4.8)$$

$$\Delta \mathcal{L} = 3.88 \text{ m} \quad .$$

The AGS bunches can be matched into identical ISA bunches (in an equivalent
stationary bucket) if

$$\frac{\Omega_{\text{AGS}}}{|\eta|_{\text{AGS}}} = \frac{\Omega_{\text{ISA}}}{|\eta|_{\text{ISA}}} \quad , \quad (4.9)$$

as follows from (4.1) and (4.2). This leads to the constraint,

$$\frac{Vh \cos \varphi_s}{\eta R^2} \sim \text{constant} \quad . \quad (4.10)$$

If we assume

$$R \propto h \quad (4.11)$$

then (4.10) is just the ISA voltage requirement,

$$V_{\text{ISA}} = V_{\text{AGS}} \left(\frac{h_{\text{ISA}}}{h_{\text{AGS}}} \right) \left(\frac{\eta_{\text{ISA}}}{\eta_{\text{AGS}}} \right) \left[\frac{\cos(\varphi_{s,\text{AGS}})}{\cos(\varphi_{s,\text{ISA}})} \right] \quad . \quad (4.12)$$

48.9 times 145.6 kV = 7.1 MV peak per turn, with $\Delta p/p$ becoming 6.6×10^{-4} . However, to obtain 2 m bunches

$$V = 3.04 \times 145.6 = 442.0 \text{ kV per turn.}$$

Thus, with a voltage $V = 442.0$ kV at 200 GeV, we have stationary buckets with bunches having the characteristics

$$\frac{\Delta p}{p} = 3.3 \times 10^{-4} , \quad (4.16)$$

$$\Delta L = 2.0 \text{ m} .$$

These stored bunches can be used for collisions.

We have assumed an invariant area of $A = 0.35$ eV-sec per bunch. If this is increased to $A = 1.0$ eV-sec per bunch, say, because of blowup in crossing transition in the AGS, what are the implications for stored characteristics in the ISA? Both bunch length, ΔL , and momentum spread, $\Delta p/p$, go like $A^{1/2}$. Therefore, for $A = 1.0$ eV-sec per bunch and a voltage $V = 145.6$ kV/turn,

$$\Delta L = 4.46 \text{ m} , \quad (4.17)$$

$$\frac{\Delta p}{p} = 4.2 \times 10^{-4} .$$

We have already seen that a luminosity of $\sim 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ can be obtained with a β -value of 5-6 m at the collision point. However, with this value of β_0 , the luminosity is insensitive to total bunch length up to $\sim \Delta L = 10$ m. Thus, the bunch characteristics in (4.17) give the same luminosity as 2 m bunches would give, namely $L = 10^{32} \text{ cm}^{-2} \text{ sec}^{-2}$ per collision region.

Another possibility, which would mediate the beam-cavity interaction as well as lower power consumption, is to increase the harmonic number of the rf system from 36 to $3 \times 36 = 108$. This increases the rf frequency from 4.46 MHz to 13.38 MHz. The matching voltage is then 48.53 kV per turn. For storage at this voltage, the bunched beam characteristics are unchanged from (4.17) and can be used in collisions, giving a luminosity of $L = 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ per collision region. The acceleration time can be kept below 1 min by either temporarily increasing the voltage and/or by increasing the stable phase angle, φ_s .

Assume a transition energy in the ISA, $\gamma_{tr}^{ISA} = 18$; then at 30 GeV $\eta_{ISA} = -0.002$. Also, if $h_{ISA} = 3h_{AGS} = 36$, and $(\varphi_{s,ISA}) = 0^\circ$, then the matching voltage is

$$V_{ISA} = 145.6 \text{ kV peak per turn.}$$

After matching, the 36 bunches in the ISA [the bunches have the characteristics given by (4.8)] can be directly accelerated. Acceleration is governed by the equation

$$\dot{p} = eV \sin \varphi_s f_{ISA} . \quad (4.13)$$

Thus, the time to accelerate an amount δp is

$$\delta t = \frac{1}{f_{ISA} eV \sin \varphi_s} (\delta p) . \quad (4.14)$$

With $f_{ISA} = 123.9 \text{ kHz}$, $eV = 145.6 \text{ keV/turn (peak)}$, $\delta p = 172 \text{ GeV/c}$, and $\varphi_s = 10^\circ$, the acceleration time would be

$$\delta t = 55.0 \text{ sec.}$$

This could be increased by reducing the voltage or the stable phase angle should this be required by limitations on the rise rate for superconducting magnets or because of a too high rf power consumption.

With this low value of φ_s , the bunches in the moving bucket will change only insignificantly from (4.8). At high energy, since

$$\frac{\Delta p}{p} \propto \frac{E^{-3/4}}{\eta^{1/2}} ,$$

and

$$\Delta L \propto E^{-1/2} \eta^{1/2} ,$$

and $E_{\text{final}}/E_{\text{initial}} = 200/28.14 = 7.1$, while $\eta_{\text{final}}/\eta_{\text{initial}} = 1.55$ then it follows that at 200 GeV in a stationary bucket, the bunches have the characteristics

$$\begin{aligned} \frac{\Delta p}{p} &= 2.5 \times 10^{-4} \\ \Delta L &= 2.64 \text{ m} . \end{aligned} \quad (4.15)$$

The bunch length goes like $V^{-1/2}$ while the momentum spread increases like $V^{1/2}$. So, to reduce the bunch length to 1 m requires a voltage $(2.64)^4$ or

5. Aperture

The betatron aperture required by the beam is

$$a_B = 2 \sqrt{\epsilon \beta'} = 2 \sqrt{2.5 \times 40} \text{ mm at 30 GeV,}$$

or

$$a_B = 2.0 \text{ cm .}$$

Horizontally, we must add synchrotron aperture,

$$a_s = \gamma_{\max} \left(\frac{\Delta p}{p} \right) = 1.8 \times 1.2 \text{ mm at 30 GeV ,}$$

or

$$a_s = 0.2 \text{ cm .}$$

This is for $A = 0.35 \text{ eV-sec/bunch}$. If A is increased to 1.0 eV-sec/bunch , then $a_s = 0.34 \text{ cm}$. Thus, taking into account sagitta (0.6 cm horizontally), closed orbit errors (1.5 cm) and leaving 0.7 cm for "reserve", we arrive at a total aperture, when superconducting magnets are used,

$$a_{\text{TOTAL}} = 5 \text{ cm .}$$

For normal magnets, only the vertical dimension is relevant. Using a beam requirement of 2 cm , 1.5 cm for closed orbit errors, and 0.5 cm for reserve, we get

$$a_{\text{TOTAL}}(\text{vertical}) = 4 \text{ cm .}$$

6. Vacuum Requirements: Beam Lifetime and Background

It is assumed that the AGS can provide bunches of 10^{12} protons with the characteristics we have previously designated. This means 1.2×10^{13} protons per AGS pulse. [Such an intensity seems entirely probable, with an intensity close to 10^{13} already achieved. In order to achieve the luminosity $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, we require emittances of about $2.5 \times 10^{-6} \text{ rad-m}$ ($\epsilon = \text{Area}/\pi$) at 30 GeV in both horizontal and vertical dimensions. This seems reasonable. However, in order to obtain bunch lengths of 2 m in the ISA at 200 GeV with reasonable voltages, it is important to maintain the longitudinal phase area of 0.35 eV-sec per bunch. For a luminosity $L \approx 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, we can choose $\beta_0 \approx 5 \text{ m}$. But with this β -value, the luminosity is insensitive to bunch length up to about 10 m. It is thus perfectly acceptable to have a longitudinal phase space area of $A = 1.0 \text{ eV-sec/bunch}$ as is presently obtained, with a factor of 3 blow up in crossing transition.]

In the ISA there will be 3 AGS pulses or 3.6×10^{13} protons. This corresponds to an average current of 0.72 A, and, for 2 m bunches, a peak current of 24 A, or, for 5 m bunches, $I_{\text{peak}} \approx 10 \text{ A}$.

With these currents, we can assume that pressure bump phenomena observed at the CERN ISR are negligible.⁹ The primary high energy effect is due to nuclear scattering of protons off residual gas molecules. Beam-beam interactions also contribute to the loss rate,¹⁰ and by comparing these, we can estimate the background compared to the desired interactions. The beam-gas lifetime $\tau_{\text{b-g}}$ is given by

$$\tau_{\text{b-g}} = \frac{1.9 \times 10^{-28}}{\sigma_N p} \quad , \quad (6.1)$$

where $\sigma_N = 360 \times 10^{-27} \text{ cm}^2$ is the cross section for high energy protons against nitrogen, and

p is the average N_2 equivalent pressure (in torr).

$$\text{Thus,} \quad \tau_{\text{b-g}} = \frac{5.2 \times 10^{-4}}{p} \text{ sec} \quad . \quad (6.2)$$

For $p = 10^{-8}$ torr, we have

$$\tau_{\text{b-g}} = 14.4 \text{ hours} \quad .$$

The lifetime for beam-beam (that is, proton-proton) scattering is

$$\tau_{bb} = \frac{4.6 \times 10^{12} I}{\sigma_{tot} L}, \quad (6.3)$$

where $\sigma_{tot} = 40 \times 10^{-27} \text{ cm}^2$ is the total p-p cross section,

I = average beam current in A,

L = luminosity (in $\text{cm}^{-2} \text{ sec}^{-1}$) averaged over the four collision areas,

$$\text{or} \quad \tau_{bb} = 1.15 \times 10^{38} \frac{I}{L}. \quad (6.4)$$

For $I = 0.72 \text{ A}$, $L = 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$,

$$\tau_{bb} = 2305.5 \text{ hours.}$$

Thus, the beam-beam event rate is 160 times less than the beam-gas event rate. To make them comparable would require a pressure 100 times less. That is, with $p = 10^{-10} \text{ torr}$, $\tau_{b-g} = 1440 \text{ hours}$, which is to be compared with $\tau_{bb} = 2305.5 \text{ hours}$, the lifetime for desired events. Remember, however, that beam-gas events take place over the whole circumference, while beam-beam events occur only in the collision regions of which there are 4, each 2 m long, or along 1/300 of the circumference. This means that the background, that is, the ratio of beam-gas events and desired beam-beam events, is

$$B = \frac{\text{beam-gas rate}}{\text{beam-beam rate}} (\text{in collision area}) = \frac{\tau_{bb}}{\tau_{b-g}} \times \frac{n_c \ell_c}{C}, \quad (6.5)$$

where n_c is the number of collision areas,

ℓ_c is the length of each collision region, and

C is the ISA circumference; or

with a pressure of 10^{-8} torr ,

$$B = 2305.5/14.4 \times 1/300 = 0.53.$$

Thus, at $p = 10^{-8} \text{ torr}$, the beam-gas background is 53%. At 10^{-9} torr , this is reduced to 5.3%, and at 10^{-10} torr , we get 0.53%.

7. Intensity Dependent Effects: Bunched Beam Instabilities

Our point of view here is to take the parameters we have developed (see Table I), and determine whether unstable conditions exist and, if so, how to avoid them. We find that, for the most part, unstable conditions are absent and in the cases where they represent a possible hazard, they can be avoided, within the bounds set by our performance criteria.

Incoherent Space Charge Tune Shifts

From Laslett,⁶ we write for the vertical incoherent space charge tune shift,

$$\Delta v = - \frac{r_p R N_T}{\pi v \gamma} \left\{ \frac{1}{b (a + b) B \beta^2 \gamma^2} + \frac{\epsilon_1}{h^2} \left[1 + \frac{1}{B \beta^2 \gamma^2} \right] + \frac{\epsilon_2}{g} \left(\frac{\rho}{R} \right) \right\}, \quad (7.1)$$

where R is average radius,

ρ is the bending radius,

N_T is the total number of protons [$I = N_T e f_{ISA}$],

v is the vertical tune,

γ is the energy in mass units,

β is the velocity in units of c,

B is the bunching factor (bunch length/separation),

a is the horizontal $\frac{1}{2}$ size of the beam,

b is the vertical $\frac{1}{2}$ size of the beam,

h is the half size of the vacuum chamber,

g is the $\frac{1}{2}$ gap,

ϵ_1 is the electric image coefficient,

ϵ_2 is the magnetic image coefficient, and

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

For a circular geometry, as is suitable for superconducting magnets,

$\epsilon_1 = \epsilon_2 = 0$. Then, with $R = 385.5$ m, $N_T = 3.6 \times 10^{13}$ (corresponding to $I = 0.72$ A), $v = 20.25$, $\gamma = 30$, $B^{-1} = 15.09$, $a = b = 1$ cm,

$$\Delta v = 9.4 \times 10^{-4}.$$

Using a geometry where the chamber width is much greater than its height, we can use $\epsilon_1 = \pi^2/48$, $\epsilon_2 = \pi^2/24$, and with $h = 2$ cm, $g = 2.25$ cm,

$$\Delta v = 0.01.$$

Thus, the current is well below the normal space charge limit⁶ of 0.25 in both cases.

Bunched Beam Transverse Resistive Wall Instability

Multibunch beams are unstable in the presence of resistive walls. Landau damping, induced by a spread in the betatron tunes, can prevent the formation of unstable collective modes, which can be found by solving the dispersion relation,⁴

$$Z_m^* \int \frac{f(v)}{v - v_m} dv = 1, \quad (7.2)$$

where $f(v)$ is the particle distribution in tune, normalized to unity, v_m is the complex collective betatron tune, and Z_m^* is a complex constant dependent on the physical conditions of the beam and its surroundings. The point is that a solution v_m means that the dipole moment of the beam will behave like

$$P(t) \rightarrow e^{-i v_m \Omega t}, \quad (7.3)$$

with Ω the angular frequency of the protons. Thus, we look for a solution with a positive value for $\text{Im}(v_m)$, as implied by (7.2).

It can be shown that for the worst mode, m , Z can be expressed by

$$Z = \alpha \left\{ \bar{U} + \left[\frac{8\sqrt{2\pi}}{3\sqrt{N_B}} - 4 \right] \bar{W} + (1 + i) \bar{V} \right\}, \quad (7.4)$$

where for a circular geometry,

$$\begin{aligned} \bar{U} &= -\frac{1}{B} \left(\frac{1}{b^2} - \frac{1}{h^2} \right), \\ \bar{V} &= \frac{c\beta^2 \gamma^2}{h^3} \sqrt{\frac{2\epsilon_0 \rho_e}{\Omega |k - v|}}, \\ \bar{W} &= |k - v|^{\frac{1}{2}} \bar{V}, \\ \alpha &= \left(\frac{1}{\delta v} \right) \frac{2r_p R}{e v \Omega \beta^2 \gamma^3}, \end{aligned}$$

ρ_e is the chamber resistivity (in ohm-m),

δv is the full width in the betatron tune distribution,

k is an azimuthal mode number ($k > v$), and

ϵ_0 is the free space dielectric constant ($10^{-9}/36\pi$ sec/ohm-m).

While, strictly speaking, these expressions hold only for a circular geometry, we will use them also in the case of a wide, elliptical chamber, interpreting b and h as vertical dimensions. (This will give an overestimate of the tune spread required for stability.)

With stainless steel for the vacuum chamber, $\rho_e = 0.7 \times 10^{-6}$ ohm-m. We also use the lowest azimuthal mode, $k = 21$. Then by methods given in Ref. (13), [see especially Fig. (1)], where a narrow distribution in v with $\sin^2$ flanks is used, we can solve the dispersion relation and arrive at a stability criterion, which is just a lower limit on the tune spread, δv . We find, with $h = 2.5$ cm, $b = 1$ cm (appropriate for the superconducting magnet case),

$$\delta v > 2.8 \times 10^{-3} \text{ (superconducting magnets);}$$

while, with $h = 2.0$, $b = 0.8$ cm (appropriate for the normal magnet case),

$$\delta v > 5.4 \times 10^{-3} \text{ (normal magnets).}$$

(Although this latter figure is probably an overestimate.) The computations have been done for $\gamma = 30$, where we get the most stringent criterion. In either case, superconducting or normal magnets, the criterion can be met by having a sufficient chromaticity — that is, obtaining tune spread from momentum spread. That this is a proper means of obtaining tune spread follows from the fact that the synchrotron period is very much larger than the betatron period. Thus, since $v_g \approx 5 \times 10^{-4}$ and $v \approx 20$, chromaticity provides an effective means of Landau damping the transverse collective instability. The amount of chromaticity needed for this purpose will be discussed below when we consider the head-tail effect.

The Head-Tail Effect Due to Resistive Walls

Zotter⁵ has calculated growth rates for the head-tail instability appropriate for our conditions. For the azimuthal mode, m , the growth rate β_m (that is, it is a growth rate and meaningful if $\beta_m > 0$) is given by

$$\beta_m = -0.46 \frac{r_p^2}{h^3} \sqrt{\frac{2\pi\epsilon_0\rho_e B}{M\omega}} \frac{N}{\eta\gamma} \xi C_m G_m(\chi) , \quad (7.5)$$

where M is the number of bunches,

N is the number of protons per bunch,

$\eta = 1/\gamma_{tr}^2 - 1/\gamma^2$ (γ_{tr} is the transition energy),

ξ is the chromaticity,

$$\xi = \frac{p dv}{v dp} , \quad (7.6)$$

$$\chi = \frac{4\pi v B \xi}{M \eta} , \quad (7.7)$$

and $C_m G_m(\chi)$ is a function computed by Zotter⁵ and is reproduced here in Fig. 6 for $m = 0, 1, 2$ and 3.

With the values for the parameters that we have previously used, we find that if $\xi = +0.12$, all modes are stable up to $m = 11$. However, to obtain this stability, it is important to recognize that ξ must be positive. The natural chromaticity of the lattice is, however, negative. Since the chromaticity must be used to produce tune spread for Landau damping of the transverse resistive wall instability, it turns out that we require a much larger chromaticity than given above. For $\xi = +1$, the tune spread is¹⁴

$$\delta v = \xi v \frac{\Delta p}{p} = 8.4 \times 10^{-3} ,$$

which appears sufficient when compared to the required spreads for Landau damping given in the section on the transverse resistive wall effect. As far as concerns the head-tail effect, the number of stable modes becomes much higher and when we add the tune spread due to the natural nonlinearities in the lattice, the beam should be stable against the head-tail effect for all modes.

Longitudinal Stability of a Bunched Beam Interacting with an RF Cavity

The theory has been developed by F. Sacherer.¹⁵ We apply it in the case of short bunch lengths ($B < 0.1$), high Q cavities, and for the rigid bunch mode. Under such conditions, we can write the constraint on the cavity shunt impedance, R_s , for stability as

$$R_s < 0.39 \left(\frac{V \cos \varphi_s}{I} \right) \left(\frac{h^3 B^2}{r M^2} \right) , \quad (7.8)$$

where I is the average current,

V is the peak voltage per turn,

r is the harmonic number of the cavity resonance driving the instability, and

φ_s , h , B , and M have been previously defined.

The damping of the instability, which, of course, is represented by the above stability criterion, comes from Landau damping due to a spread in synchrotron frequencies in the beam as a result of the nonlinearity of the synchrotron force. We have taken the "octupole" contribution to this spread, S , which is given by

$$\frac{S}{\Omega} = \frac{\pi^2 h^2 B^2}{16M^2} . \quad (7.9)$$

This expression is valid provided B is sufficiently small and the bucket is sufficiently removed from the bunch. Both these conditions are satisfied for the parameters we are considering here.

With $I = 0.72$ A, $B^{-1} = 15.09$, $r = h$, $\varphi_s \approx 0$, $M = 36$, then (7.8) becomes

$$R_s < 1.8 \times 10^{-6} Vh^2 . \quad (7.10)$$

If $V = 48.5$ kV and $h = 108$ (corresponding to a frequency, $f_{RF} = 13.4$ MHz), then we have for the stability criterion,

$$R_s < 1.04 \text{ k}\Omega .$$

Notice that by increasing the rf frequency by three times the natural frequency (i.e., where the harmonic number, h , and the number of bunches, M , are equal), we can keep the bunch characteristics unchanged by reducing the voltage by 3. That is, the product

$$Vh = \text{constant},$$

to keep identical bunches.

Therefore, not only does the required shunt impedance increase linearly with h under these circumstances, but the power consumption,

$$P = \frac{V^2}{2R_s} , \quad (7.11)$$

decreases with h^3 because,

$$R_s \sim h \quad (7.12)$$

and

$$V \sim h^{-1} . \quad (7.13)$$

For V and R_g given above, we have

$$P \geq 1.1 \text{ MW} .$$

However, with electronic feedback, which will presumably be necessary, in any case, to damp noise induced effects, we could perhaps raise the cavity shunt impedance to, say, 5 k Ω , giving a power consumption, $P \geq 500 \text{ kW}$.

Electron-Proton Instability

In continuous (unbunched) beams, electrons, produced through ionization of the rest gas by the proton beam, can be trapped in the potential well of the beam and give rise to unstable betatron oscillations of the proton beam.⁸ Because of betatron tune spreads in both proton beam and trapped electrons, the instability can be avoided. The Landau damping is expressed as an upper limit on the degree of neutralization of the proton beam. An expression for the critical neutralization can be found in Zotter and Keil.⁸ With the ring and beam parameters that we have used, and taking the average current, $I = 0.72 \text{ A}$, we find

$$\eta_{\text{critical}} = 0.3\% ,$$

which is three times the critical neutralization in the ISR.¹⁶

However, we might expect that by having a bunched beam, all instabilities of this sort could be avoided.¹⁷ To see how this might occur, consider an electron produced with a typical kinetic energy,¹⁷ $T = 1 \text{ eV}$. Neglecting image forces, the electron has 200 nsec (bunch separation) to escape the proton trap. Since the electron is nonrelativistic, its velocity is

$$v = c \sqrt{\frac{2T}{E_0}} = 6 \times 10^5 \text{ m/sec} . \quad (7.14)$$

where $E_0 = 0.5 \text{ MeV}$ is the electron mass. Thus, in 200 nsec, an electron can travel 12 cm, which means that electrons will be able to reach the walls (vertically, since the magnetic field for bending protons will trap the electrons in tiny orbits horizontally) in the time between bunches. It would thus appear that the need for clearing electrodes, so severe in the continuous beam design, is far less in the bunched beam case.

Intrabeam Scattering

The scattering of protons in the same beam on each other, i.e. intra-beam scattering,¹⁶ can lead to the diffusion of protons. We, as in Ref. (16), consider two types of diffusion processes:

(a) Increase of betatron amplitude via dipole kicks from intrabeam scattering which results in an rms change in betatron angle. The effect is an increase in betatron size of the beam. To obtain a rough estimate for the diffusion constant, D , for the beam height, b , we use Keil's expression derived for the ISR in Ref. (16),

$$D = 2 \times 10^4 \frac{I}{p^5 b^2 \epsilon} , \quad (7.15)$$

where I is the average beam current, in A,

p is the momentum, in GeV/c,

b is the full beam height (beam is assumed circular), in mm,

ϵ is the transverse emittance of the beam at momentum p , in $\mu\text{rad-m}$, and

D is the diffusion constant, in $\text{mm}^2 \text{sec}^{-1}$.

Using $p = 200 \text{ GeV/c}$, $b = 20 \text{ mm}$, $I = 0.72 \text{ A}$, $\epsilon = 0.4 \mu\text{rad-m}$ (at $p = 200 \text{ GeV/c}$), we obtain

$$D = 1.8 \times 10^{-10} \text{ mm}^2 \text{sec}^{-1} ,$$

which roughly means that in 1 second, the rms betatron beam size increases by $\sqrt{2D} = 1.9 \times 10^{-5} \text{ mm}$. The time for the betatron beam size to double is roughly given by

$$t_{\text{double}} = \frac{b^2}{8D} = 4 \times 10^{17} \text{ hours} . \quad (7.16)$$

This effect is thus insignificant; this is primarily a result of the high energy, since $D \propto 1/p^5$.

(b) Momentum diffusion can act as a feeding mechanism for nonlinear resonances when the chromaticity is non-zero. This reduces the effective aperture available to particles, since resonances can exist well within the physical aperture of the rings. Again, to obtain a crude estimate of the rate of loss of beam current, we use Keil's expression in Ref. (16),

derived for the ISR,

$$\frac{\dot{I}}{I} = - 1.4 \times 10^{-6} \left(\frac{I}{I_{ISR}} \right) \left(\frac{\gamma_{ISR}}{\gamma} \right)^3 / w^2 \text{ (hour}^{-1}\text{)} , \quad (7.17)$$

where $\dot{I}$ is the rate of change of current with time,

w is the distance between two resonances, capable of producing beam loss, around which the working line of the beam is enclosed.

If δ is the distance in betatron tune, ν , corresponding to w in momentum spread

$$w = \frac{\delta}{\xi \nu} , \quad (7.18)$$

where ξ is the chromaticity.

Using $\xi = 1$, $\nu = 20$, and taking $\gamma_{ISR} = 0.14 \gamma_{ISA}$, $I_{ISA} = 0.06 I_{ISR}$,

$$\frac{\dot{I}}{I} = - 9.6 \times 10^{-8} / \delta^2 \text{ (hour}^{-1}\text{)} . \quad (7.19)$$

Thus, by choosing a working "line" (note that the tune spread is $\delta \nu \approx 0.01$) around 20.17, the loss rate for third order resonances ($\delta \approx 1/3$) is

$$\frac{\dot{I}}{I} = - 8.6 \times 10^{-7} \text{ per hour;}$$

while for 4th order resonances ($\delta \approx \frac{1}{4}$), the loss rate is

$$\frac{\dot{I}}{I} = - 1.5 \times 10^{-6} \text{ per hour.}$$

Suppose, for example, that (7.19) is applied to higher order resonances, such as 6th and 7th order. Suppose further we tried to stay away from low order resonances, up to and including 5. Since our beam has a tune spread of about 0.01, we can place the working line between the 6th order resonance at 20.167 and the 7th order resonance at 20.143. Thus, with $\delta = 0.024$, we have a loss rate for a working line between resonances of 6th and 7th order of

$$\frac{\dot{I}}{I} = - 1.7 \times 10^{-4} \text{ per hour,}$$

or, in other words, 1% of the beam is lost in 59 hours. This means that even if these high order resonances are 100% efficient in transporting particles to the physical aperture, which is questionable, the resulting beam decay rate is acceptably low.

Fig. 6: Function for computing growth rates due to head-tail effect.

This figure is reproduced from B. Zotter, Ref. (5).

8. Conclusions

(a) With head-on collisions, a bunched beam ISA can provide a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ for p-p collisions at an energy of 200 GeV. With a β_0 of 5 m, the luminosity is not sensitive to bunch lengths up to about 10 m. Dilutions in longitudinal phase space area of the order of 2 are easily tolerable. The performance is beam-beam limited, with an assumed maximum allowable linear tune shift of 0.005.

(b) With an average radius of 385.5 m ($R_{\text{ISA}} = 3 R_{\text{AGS}}$), 200 GeV protons can be stored with a magnetic field of 35 kG, i.e. using superconducting magnets. With the same radius, 100 GeV protons can be collided, using normal magnets operating at 17.5 kG.

(c) The rf system proposed would operate at 48.5 kV peak per turn at a frequency of 13.4 MHz. The rf power consumption would be less than 1 MW, perhaps as low as 200 kW. Acceleration could be accomplished in less than 1 minute.

(d) A gas pressure in the vacuum chamber of 10^{-9} torr seems adequate from the point of view of (i) radiation effects arising from beam loss to magnets and equipment, (ii) background to experiments, and (iii) beam lifetime as it relates to performance.

(e) The short time required for dumping and refilling means that the operation of this device could function far more like a conventional accelerator than could a high current, stacked storage ring. For example, it is conceivable that it could be operated in 1 hour cycles. In fact, consider the following operating procedure; Monitor luminosity. As longitudinal phase space dilutes, say due to rf noise, the luminosity would ultimately begin to decrease. At a predetermined lower bound, the beam could be dumped. Refilling could possibly be accomplished within a minute or so of dumping. Of course, monitoring current and so beam loss would proceed simultaneously with luminosity monitoring, and the beam would, of course, be dumped when the loss rate is at the limit of acceptability.

(f) The required AGS parameters for operating the ISA at the design luminosity appear to be readily achievable: an intensity of 1.2×10^{13} ppp, with conservative emittances: $\epsilon_{\text{transverse}} = 2.5 \times 10^{-6}$ rad-m; and $A_{\text{longitudinal}} = 1.0 \text{ eV-sec/bunch}$ (at 30 GeV).

(g) Since the bunched beam ISA could be operated in cycles of short duration (say, 1 hour), it is conceivable that the beam-beam limit assumed is conservative. In this event, luminosity could be improved by improving brightness (i.e., decreasing ϵ , and not decreasing N). With our conservative requirement on ϵ from the AGS, it is also quite possible that injection stacking in the AGS could be shaped to give an increased brightness without sacrificing intensity. The result would be a higher luminosity proportional to the allowable increase in the beam-beam limit.

(h) Potential Beam Instabilities. The incoherent space charge tune shift is negligibly small. The bunched beam transverse resistive wall instability can be damped with a ν -spread of about 0.01. This can be achieved with a chromaticity of +1, which seems sufficient to avoid all head-tail modes. The cavity-bunched beam interaction can be Landau damped if the shunt impedance $R_s \sim 1 \text{ k}\Omega$. With electronic feedback, this could perhaps be increased to $5 \text{ k}\Omega$, resulting in a decrease in power consumption from 1 MW to 200 kW. Electrons produced from the ionization of the residual gas appear to create no difficulties in the bunched beam case, reducing considerably the need for clearing electrodes. And finally diffusion phenomena arising from intrabeam scattering seem to be within acceptable limits. Direct increase of betatron amplitude is insignificant, while the combination of narrow working line, low current, and high energy gives low beam loss rates from resonance feeding, even for 6th and 7th order resonances.

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