PERFORMANCES OF BNL HIGH-INTENSITY SYNCHROTRONS*

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Abstract

The AGS proton synchrotron was completed in 1960 with initial intensity in the 10^{10} proton per pulse (ppp) range. Over the years, through many upgrades and improvements, the AGS now reached an intensity record of 6.3×10^{13} ppp, the highest world intensity record for a proton synchrotron on a single pulse basis. At the same time, the Booster reached 2.2×10^{13} ppp surpassing the design goal of 1.5×10^{13} ppp due to the introduction of second harmonic cavity during injection. The intensity limitation caused by space charge tune spread and its relationship to injection energy at 50 MeV, 200 MeV, and 1500 MeV will be presented as well as many critical accelerator manipulations. BNL currently participates in the design of an accumulator ring for the SNS project at Oak Ridge. The status on the issues of halo formation, beam losses and collimation are also presented.

1. INTRODUCTION

The AGS (Alternating Gradient Synchrotron) was the first high-energy proton synchrotron to incorporate the strong focusing principle in its lattice structure (1, 2). This revolutionary discovery allowed the field gradient index n, limited to less than 1 for a weak focusing synchrotron, to be as high as 300 to 1000 to drastically reduce betatron function and make smaller aperture possible. The AGS was originally designed with intensity in the order of a few 10^{10} ppp in mind. However, even at such modest intensity, by today's standard, epoch discoveries, such as: two neutrinos, CP-violation, Ω^- and J/ψ were made at the AGS. Over the years, through many upgrades and accelerator improvements, the AGS reached 6.3×10^{13} ppp in the spring of 1995, a world intensity record.

The parameters, upgrades and over-all performance of the AGS complex will be reviewed in this introductory section. Several important accelerator improvements will be presented in Section 2. The demanding design considerations for 1MW SNS accumulator ring will be presented in Section 3.

The schematic layout of the existing AGS complex is shown in Fig. 1. To assist the readers and facilitate the discussion, some of the relevant accelerator parameters of the Booster and AGS are summarized in Table 1.

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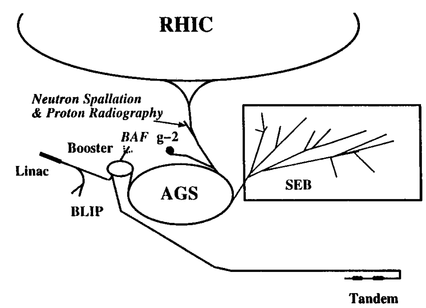

Figure 1. Layout of the AGS complex.

Shown in Figure 2 is the intensity evolution of the AGS since its completion in 1961. Two major upgrades to the AGS complex were carried out since its operation for physics research in 1961. The first one was the "Conversion Project" from 1967 to 1972 to replace a 50 MeV linac by a 200 MeV linac and to raise the AGS rep-rate from 0.15 Hz to 0.5 Hz (3). The second one was the "Booster Project" from 1987 to 1991 to build a Booster to raise the injection energy from 200 MeV to 1.5 GeV and to provide high intensity high mass heavy ions for RHIC (4). Major improvements in the intensity record are summarized briefly in the following chronology of Table 2.

It is clear that raising the injection energy is the most effective way to increase the achievable intensity for a space charge limited low energy proton synchrotron. It is also clear that many accelerator physics manipulations have to come into play to keep all those particles inside the synchrotron. The reason that raising injection energy

Table 1. Accelerator parameters of the Booster and AGS.

	Booster	AGS
Circumference (m)	201.78	807.12
Injection energy (GeV)	0.2	1.5
Extraction energy (GeV)	1.5	28.0
ν_x / ν_y	4.82 / 4.83	8.7 / 8.8
x_p (m)	2.9	2.2
γ_{tr}	4.5	8.5
Harmonic number (h)	3 (2)	12 (8)
RF voltage (kV)	90	400
Intensity (10^{13} ppp)	2.2	6.3
Estimated tune shift $\Delta\nu_y$	0.35	0.35

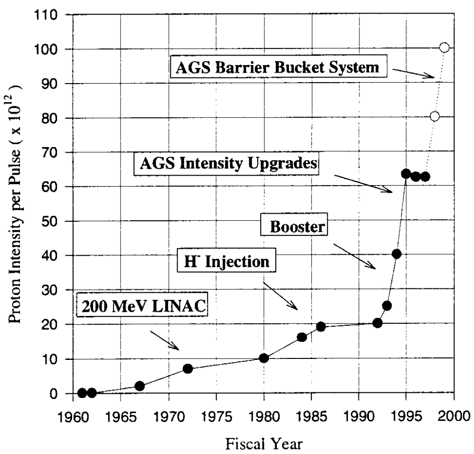

Figure 2. The evolution of the AGS proton intensity.

helps to store more particles is due to the reduction of the incoherent space charge tune shift during injection.

A good indication of the space charge effect at injection is given by the expression of incoherent space charge tune shift (5):

$$\Delta\nu = \frac{N r_p}{2\beta\gamma^2 \varepsilon_N B_f} \quad (1.1)$$

where r_p=1.54×10^{-18} m is the classical proton radius, N is the total number of protons, ε_N is the normalized beam emittance, B_f is the bunching factor, and β and γ are the beam velocity and energy. At the tune shift level about 0.35 unit, the acceptable proton intensity changed from 3×10^{12}, to 10^{13} and to 6×10^{13} ppp at three different injection energies respectively.

Table 2. Major improvements in the intensity record.

Year	Parameters or Improvements	AGS Intensity
1970	50 MeV linac injector Space charge limited at injection $\Delta\nu_y \approx 0.3$	3×10^{12}
1976	200 MeV linac H^+ injector Resonance stopband correctors Transverse damper	10^{13}
1990	200 MeV linac H^- injection RF feedforward compensation $\Delta\nu_y \approx 0.55$	1.6×10^{13}
1995	1.5 GeV Booster injection Resonance stopband correctors Direct RF feedback γ-transition jump $\Delta\nu_y \approx 0.35$	6.3×10^{13}

2. IMPORTANT ACCELERATOR IMPROVEMENTS

Among accelerator improvements implemented at the AGS over the past 30 years, the following are the most essential in raising the AGS intensity.

2.1 Resonance Stopband Corrections

As shown in Table 2, the incoherent space charge tune shift at injection can reach as high as 0.55 unit. That means many particles in the beam can move cross half integer and third integer resonance lines. Properly placed quadrupoles and sextupoles are used to correct the stopband width of those resonances to minimize the amplitude growth (6). Experiences showed that each correction could account for from few percent to tens of percent of reduction of particle losses.

Due to the strong energy dependence of the amount of tune shift caused by the space charge force, raising injection energy can alleviate this limiting effect. This is also the reason that the US Spallation Neutron Source design chooses to have full energy injection at 1GeV.

2.2 Second Harmonic Cavity

If the accelerating RF system has only one and the same frequency, the resultant RF bucket usually assumes a parabolic shape with the maximum around the synchronous phase angle. The final charge distribution tends to have a sharp maximum in the middle and hence a larger space charge force according to Eq. (1.1).

Along with the main RF system an additional second harmonic cavity can also be added, so that the voltage can be descried as

$$V = \frac{e}{2\pi h} V_0 \{\sin\phi + r\sin[2(\phi - \delta)]\}, \quad (2.1)$$

where V_0 is the first amplitude, r=r(t) is the second amplitude (as a fraction of V_0), δ=δ(t) is the phase shift of the second harmonic with respect to the first harmonic.

The reason for the large space charge tune shift at capture is due to the charge inhomogeneity resulting from the single RF system. By judiciously choosing ϕ_s, r and δ the charge distribution in the vicinity of ϕ_s can be made to be uniform, hence, reducing the bunching factor and space charge force. In other words, the capture efficiency of the double RF system should be better than that of the single RF system by about 20-30% (6). This is the reason why the AGS Booster can accelerate 2.2×10^{13} ppp higher than the design of 1.5×10^{13}.

2.3 Direct RF Feedback

At injection into the AGS, the cavities are operated at 1.5 kV/gap, which requires 0.5 A of current from the power amplifier, (I_0). At 6×10^{13} ppp the RF beam current, (I_B), is 6.0 A, implying a beam loading parameter, I_B/I_0, of 12. It has been shown that when the beam loading parameter becomes greater than 2, the beam control loops, tuning, AVC, and phase, are cross-coupled and become unstable. RF feedback is needed to reduce the effective beam loading parameter. Feedback reduces the perturbations of the cap voltage by the value of the loop gain, and the beam current, seen from the control loops, is effectively reduced. Loop gains of 17 dB and greater (depending on the operating point of the tetrode) are used to reduce the beam loading parameter to less than 1.7.

Without such a direct feedback system, the beam loading effect will limit the achievable AGS intensity to about 2.0×10^{13} ppp. The RF feedback is also essential for keeping the proton within the RF bucket provided to have a clean gap region that is crucial for avoiding e-p instability in the SNS (7).

2.4 γ-Transition Jump

At an intensity of approximately 1.5×10^{13} ppp, AGS beam losses at transition are less than 5%. However, as improvement plans are implemented and the intensity is increased to 6×10^{13} ppp, when new mechanisms will become important and the losses will increase. A γ-transition jump system has been built to reduce these losses by speeding up passage through transition, which was first suggested by Werner Hardt (8) at CERN.

Hardt's idea, which has been implemented at the CERN PS, was based on the observation that quadrupole pairs separated by ½-betatron wavelength and configured as doublets can alter γ_t, of a synchrotron without affecting, its tune. By arranging to cross transition while γ_t is rapidly decreasing, the bunch area blowup caused by

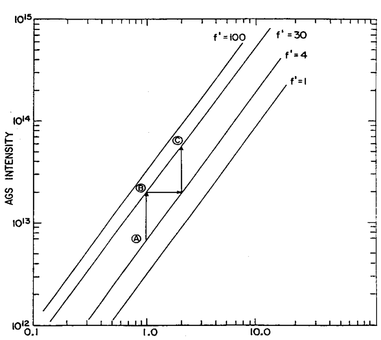

Figure 3. AGS intensity for lossless transition as a function of bunch area and crossing speed enhancement factor, f'

negative mass instability can be substantially reduced. The criterion for no blowup due to negative mass rapidly decreasing, the bunch area blowup caused by the instability is shown in Figure 3 (9). Here the attainable AGS intensity is plotted as a function of bunch area for several crossing speed enhancement factor, f'.

As can be seen from Fig. 3, to pass through transition at 6×10^{13} ppp without appreciable loss requires $f' \approx 30$ with bunch area about 2.0 eV-sec, which is conveniently satisfied by the VHF cavity in the AGS after injection (6).

2.5 Transverse Coupled-Bunch Instability and Its Damping

It has been estimated that the threshold for transverse coupled bunch instability excited by the resistive wall is at about $4\text{-}5\times10^{12}$ ppp. A damper system has been constructed to damp such instability when it occurs. When the instability occurs, about 60% of the beam are lost. The suppression of coherent motion had been tried successfully by the transverse damper system. The actual threshold vertical instability has been found to be about 7×10^{12} ppp, when ν_x=4.94 and ξ_x=-0.25, which can be avoided by adjusting the tune and chromaticity of the machine. Active damping is necessary when the beam intensity is larger than 10^{13} ppp. Shown in Figure 4 is the FFT output of the orbit signal, indicating the growth over time and the dominant mode of n=7.

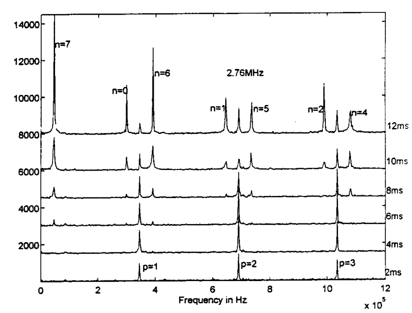

Figure 4. Spectral signal of coherent transverse oscillation.

2.6 H^- Charge Exchange Injection

In 1982, the AGS injection was changed from H^+ beam to the H^- charge exchange process. Due to the constraint of Liouville's theorem, only 15 to 20 turns were allowed by H^+ beam. However, the foil-stripping process allows the repetitive stacking of incoming beam into the same phase space area that is impossible with a H^+ beam. Typical foil used is carbon or graphite foil of about 200 to 400 µg/cm^2. The stripping efficiency ranges from 98% to 99.5%. The critical issues faced in this process are the foil temperature, the collection of H^-, H^0 and electrons. In the event that beam losses in the order of a few 10^{-4} have to be realized, careful identification of H^0 population in various excited states is necessary (10). Other important design concerns are the emittance blow up due to multiple traverse of foil, which has to be minimized, maximum foil temperature, and collection of stripping electrons.

Another advantage of the H^- injection process is the reduction of beam losses at injection time. Shown in Fig.5 is the historical performance record of the AGS annual collective dose from 1973 to 1997 (11). The first drastic reduction in 1978 was due to the new switchyard design and the subsequent drop in 1982 was the H^- injection.

This discussion on the history of particle losses in the AGS leads naturally to the most important issue in the design of next generation spallation neutron source.

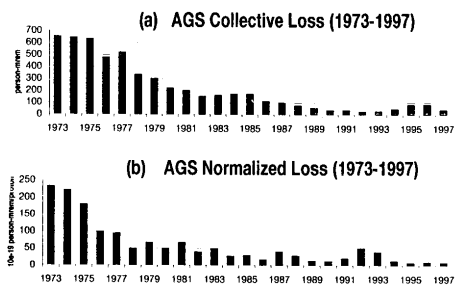

Figure 5. Particle losses at AGS.

3 LOW LOSS DESIGN OF THE SNS RING

The Oak Ridge National Laboratory is leading a conceptual design for a next generation pulsed spallation neutron source, the Spallation Neutron Source (SNS) (12).

The proton Accumulator Ring is one of the major systems in the design of the SNS (13). The primary function of the AR is to take the 1 GeV H^- beam of about 1msec length from the linac and convert it into a 0.5 μs beam through a stripping foil in about one thousand turns. The final beam should have 1.0×10^{14} ppp, resulting in 1MW design average beam power at 60Hz repetition rate. Provisions have been reserved for a future upgrade to 2MW beam power by doubling the stored current to 2.0×10^{14} ppp without changes in both the magnet and vacuum system.

One of the major performance requirements is to keep the average uncontrolled particle loss during the accumulation time to less than 2.0×10^{-4} per pulse. The reason of this stringent requirement is to keep the residual radiation to such a level that the hands-on maintenance is possible except for a few localized areas, such as: injection, extraction and collimation.

Typical beam losses of existing low power proton synchrotron are in the order of a few percent. Let us use the AGS and the proposed SNS ring as example. The relevant beam parameters are summarized in Table 3. It can be clearly seen that 1% loss of the SNS ring is equivalent to the entire flux of the AGS beam. Such a situation is totally unacceptable.

Table 3. AGS and SNS parameters.

	AGS	SNS
Proton Intensity	6×10^{13} ppp	10^{14} ppp
Rep-Rate	0.5	60
Flux	3×10^{13} pps	6×10^{15} pps
Loss of 1%	3×10^{11} pps	6×10^{13} pps

In addition to those good accelerator practices learned over the past 30 years, the following design features have been implemented for the SNS accumulator ring to minimize particle losses.

3.1 Large Aperture

All existing low energy high intensity proton synchrotrons have operated at a condition that the available physical apertures are fully occupied. Quantitatively, it can be characterized as

$$\varepsilon_A / \varepsilon_B \approx 1.0 \quad (3.1)$$

where ε_A signifies the equivalent emittance of the aperture and ε_B is the beam emittance. For the SNS accumulator ring design,

$$(\varepsilon_A / \varepsilon_B)_{SNS} \geq 3.6 \quad (3.2)$$

In other words, there is almost factor of two of space allowed in both vertical and horizontal dimension.

3.2 Full Energy Injection

As has been discussed in Section 1, the incoherent space charge tune shift is inversely proportional to the injection energy. Chosen to inject at 1.0 GeV, the tune shift for the SNS ring is estimated to be

$$(\Delta \nu_{S.C.})_{SNS} \leq 0.1 \quad (3.3)$$

which allows optimum selection of working point with minimum possibility of resonance crossing.

3.3 Dual Harmonic RF System

As shown in Section 2, the employment of dual harmonic RF system can reduce the incoherent space charge tune shift by about 25%. Effectively raising the acceptable particle intensity accordingly. In the SNS ring design, the first harmonic RF system provide 40 kV and the second harmonic RF system provide 20 kV for designed beam longitudinal emittance of 10 keV-sec.

3.4 Halo Formation

It has been found that the large amplitude particle can interact with the core particles to move either closer to the center or away from the center. This process can be understood by an envelope oscillation created by the mismatch between the beam shape and the lattice of the focusing channels. A particle in the halo region tends to be driven away in such a mismatched focusing channel. Although the smaller amplitude particles stay close to the stable fixed point in the center, the larger amplitude particles can drift away following the multiple islands. The crucial questions now, are first how far the islands can extend away from the center, what is the dynamical nature of the islands, and when the chaotic motion will set in. Those are all-important questions to be answered by any new high power accelerators. It can happen both in the linac and in the circular rings.

A thorough understanding of the halo dynamics as function of mismatch, power supply ripple, space charge tune shift, and the lattice structure, etc., is necessary to be able to estimate the degree of beam losses and placement of collimators with confidence. An effort to create a particle-in cell tracking code based on ACCSIM for particle-core model calculation is underway by the SNS collaboration (14).

3.5 Collimation of Lost Particle

To contain those particles inadvertently migrating toward the wall, after all careful considerations and provisions, a collimator system has to be designed to catch the bulk of them before hitting the wall. For example, for the SNS four collimators, 3.2m each, enclosing a 4π solid angle around the source point and stuffed with segmented material to capture all secondary particles generated by the incident protons will be provided to reduce the radiation effects by a factor of 100. This way, most of uncontrolled losses will occur at the collimator, leaving ring components relatively intact for reliable operation (15).

3.6 Control of Electron Population

Excessive electron population in a proton synchrotron can result in e-p instability. Such phenomena have been observed both in the ISR and PSR (16). Experiences showed that if the population of electrons reaches certain level, characterized by the neutralization coefficient, η_e defined to be the ratio of electron to proton, the proton beam can become unstable due to coherent motion excited by the presence of electrons. This threshold is lower for a continuous distribution of proton beam in the ring and is higher for beam with a clean gap. The reason is the gap serves as a clearing mechanism of the electrons.

There are many ways electrons can be generated in a synchrotron. For example, they can be generated at stripping foil, by residual gas ionization, or by secondary electron emission from the wall.

Ways to eliminate e-p instability include better vacuum, collect electrons at stripping foil location, TiN coating of vacuum chamber, and clearing electrodes. In the event that the instability does occur, an active damping system can be provided to suppress the instability.

For the SNS design, electron collector is provided at the downstream of stripping foil and electron clearing is provided along the collimator to minimize the population of electrons.

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