HEAVY ION ACCELERATION STRATEGIES IN THE AGS ACCELERATOR COMPLEX -- 1994 STATUS REPORT*

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Abstract

The strategies invoked to satisfy the injected beam specifications for the Brookhaven Relativistic Heavy Ion Collider (RHIC) continue to evolve, in the context of the yearly AGS fixed target heavy ion physics runs. The primary challenge is simply producing the required intensity. The acceleration flexibility available particularly in the Booster main magnet power supply and rf accelerating systems, together with variations in the charge state delivered from the Tandem van de Graaff, and accommodation by the AGS main magnet and rf systems allow the possibility for a wide range of options. The yearly physics run provides the opportunity for exploration of these options with the resulting significant evolution in the acceleration plan. This was particularly true in 1994 with strategies involving three different charge states and low and high acceleration rates employed in the Booster. The present status of this work will be presented.

I. INTRODUCTION

The AGS accelerator complex has supplied Gold ions at a kinetic energy of about 10.5 GeV/nucleon for the annual AGS Heavy Ion Physics run during each of the past three years[1,2]. The present beam is adequate both in intensity and emittance to satisfy the slowly extracted beam (SEB) Physics Users who allow the primary ion beam to interact in their detectors - unlike the High Energy Physics proton users who bring secondary beams (e.g. kaons) into their detectors. However, the beam produced thus far does not meet the intensity goals for injection into the Relativistic Heavy Ion Collider (RHIC)[3]. This situation has both motivated and permitted the exploration of a variety of strategies in the configuration of the accelerator chain, with the setup each year evolving significantly from the previous year. Last year (1994) several modifications occurred during the course of the run. A summary of this evolution will follow a brief description of the major relevant acceleration components and the resulting beam.

II. GOLD ACCELERATION

Gold ion acceleration at Brookhaven begins with the 15 MV Tandem Van de Graaff and then continues through the Booster and AGS synchrotron. Au^{1-} ions produced by a pulsed source are accelerated to the center terminal of the Tandem where they pass through a foil which strips away electrons to produce ions with charge states ranging from +10 to +15. The ions emerge from the Tandem with about 1 MeV/nucleon kinetic energy, and beam currents of a few particle uAmps are possible during the .5-1 msec beam pulse. (The maximum charge output per pulse is roughly constant.) A second foil just downstream of the Tandem may be inserted to allow additional stripping of the ions, thereby increasing the charge state options available for injection into the Booster. Transport, injection, and acceleration of charge states 14,15, and 33 have been explored. For the case of Au^{33+} (which requires the additional stripping after the Tandem) the rigidity is about a factor of two lower than for Au^{14+}, reducing the requirements on the Tandem to Booster transfer line. In addition the final momentum to which the ion can be accelerated in the Booster (for the maximum Booster magnetic field) is increased by the same factor of two. Since the ions must be further stripped to at least Au^{77+} before transfer to AGS a higher momentum at BTA (Booster to AGS) transfer is desirable. For the first gold run, in 1992, the planned charge state in AGS was Au^{79+} - fully stripped - and the higher momentum at Booster extraction was considered necessary. The Au^{33+} beam is also more resistant during acceleration to losing electrons due to interactions with the Booster residual gas (typical pressure 2×10^{-11} Torr). Requiring a stripping foil after Tandem does have a cost. It results in the loss of about 80% of the ions accelerated in Tandem since that fraction strip to charge states other than 33+ and are not transported to the Booster. In addition the beam transverse emittances grow slightly due to the additional foil passage. Stripping after the Tandem to Au^{33+} was the plan followed for the ’92 and ’93 runs. This choice allowed AGS physics program intensity requirements to be satisfied while providing the opportunity for studies of the implications of removing this stripping foil.

The beam produced by the Tandem has excellent emittance properties. Both transverse emittances at Booster injection even with the additional stripping are small (about 1% horizontal and 1.7% vertical) compared to the Booster acceptance, making stacking in transverse phase space effective. The possible number of turns efficiently stacked has been extended further by introducing coupling between the horizontal and vertical betatron oscillations during injection[2]. Typically more than forty turns can be injected with efficiencies

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above 70%. The longitudinal emittance of the Tandem beam is negligible relative to the smallest practical emittance associated with capturing the beam in the Booster. The resulting longitudinal emittance is sufficiently small relative to RHIC (or AGS) requirements and relative to the capabilities of the Booster and AGS accelerating systems to allow adiabatic merging of adjacent bunches during the acceleration cycle. Each such merging drops the required accelerating frequency for that momentum as well as the number of bunches in the ring by a factor of two.

The power supply for the Booster main magnets was designed with two operating modes. The "proton" mode allows rapid ramping (up to 9 Tesla/sec) but cannot exceed a magnetic field of about .6 Tesla. The "heavy ion" mode can ramp to more than twice this field but at less than one third the ramp rate. The cycle for high intensity proton operation typically involves four Booster accelerations at a 7.5 Hz rate for each AGS acceleration cycle, with two bunches transferred to AGS each Booster cycle until the AGS ring is filled. (The AGS circumference is four times the Booster circumference.) For heavy ions the original plan was to accelerate the same three bunches first in Booster and then on to extraction in AGS, so the Booster cycle rate was required only to be equal to that of the AGS. The power supply modes described above satisfy this situation. This plan called for three sets of acceleration cavities (with frequency "Bands" I, II, and III) in the Booster to cover the large frequency range required. There were no bunch merges in the plan.

For the first Gold run (1992) only the proton "Band III" acceleration system was available. This system comprises two independent low and high level rf drives and cavities. At this time each system had the capability for little more than a factor of two frequency sweep. From Booster injection to extraction the revolution frequency of the accelerating Au^{33+} would have to increase more than a factor of twelve. Nevertheless Au^{33+} was successfully accelerated with acceleration responsibility handed back and forth between the two cavities; one accelerating and sweeping up through its frequency range while the other reset to the low starting frequency. Longitudinal dilution (beyond the factor of four from the four mergings) was small. This acceleration approach was verified. A second set of rf cavities and drive systems, referred to as "Band II" was in place for the 1993 run. This allowed the rf gymnastics for that run to be simplified to a single merge, from 12 bunches to 6, which were then transferred to AGS. That 6 rather than 3 bunches were transferred to AGS represented another modification to the original acceleration plan.

The capabilities required of the AGS rf have evolved from the original idea of catching and accelerating the three booster bunches in three of the twelve buckets and carrying them to extraction to the present operational mode of debunching the injected Booster beam and then rebunching it as desired. This change has been motivated in part by the present slow extraction work. Spreading the beam around the AGS circumference at injection and capturing equally in twelve buckets yields a smoother spill at extraction than carrying the beam up in only three buckets. The post-Booster evolution of the AGS rf system has also given that system most of the capabilities necessary for bunch merging with the rest to come next year. This will open the option of AGS bunch coalescing for RHIC injection optimization.

III. THE 1994 RUN

By the end of the ’93 Gold run, most of the open questions concerning the switch to Au^{14+} at Booster injection had been answered. First, it was still relevant. The efficiencies at each step in the accelerator process were reasonably high and yet the AGS output was only about 3×10^8 ions per cycle. RHIC requires 1×10^9 ions per bunch. The factor of six intensity increase possible by removing the post-Tandem stripping foil was very attractive. Second, it had been shown experimentally, using Au^{33+} extracted at the velocity to which Au^{14+} could be accelerated, that stripping at Booster extraction to Au^{77+} had an acceptable efficiency, provided an optimized stripping foil was used. (In this case a carbon foil of thickness 29 mg/cm^2 or 5 mils gives nearly 60% efficiency at 380 MeV/c/nucleon)[4]. Third, vacuum studies in Booster predicted that increased beam loss due to electron stripping during acceleration would be at an acceptable (20%-30%) level. Fourth, the survival of the lower velocity Au^{77+} in the AGS was predicted to be adequate based on beam survival measurements on the AGS injection porch with higher velocity Au^{77+} and Au^{78+}. The transfer line between Tandem and Booster had been upgraded to allow transporting the higher rigidity Au^{14+} beam. Transferring all of the ions accelerated in Booster to AGS would not be possible in 1994, the revolution period of the Au^{14+} ions at the maximum Booster field being longer than the kicker pulses; but the predicted intensity would be adequate for the physics program.

In fact the ’94 run began using Au^{15+} rather than the more intense Au^{14+} from Tandem. This slight rigidity reduction allowed a high enough extraction momentum to be achieved (for BTA stripping and for the AGS rf capture at h=12) while significantly reducing the requirements for the maximum Booster magnetic field and for the fields in several other extraction systems. The test of accelerating without a post-Tandem foil was made no less rigorous by this choice. The Booster main magnet power supply was configured in the usual "heavy ion" mode, with a slow dB/dt and a high final field relative to the "proton" mode. The frequency range of the Booster Band II cavities had been extended so that the ninth harmonic of the revolution frequency could cover the entire acceleration range with no merges required. Five of the nine bunches fit within the pulses of the extraction kickers and were transferred to AGS.

Neither the momentum shift nor the momentum spread introduced by the BTA stripping foil for this low momentum beam had been anticipated. The first moved the ratio for the revolution frequencies in the AGS and Booster below the one quarter predicted by the ratio of machine radii, which was a surprise but not a problem for a single transfer. The deterioration in longitudinal emittance from the foil was reduced by another set of rf gymnastics. Using the second Band III cavity in Booster the nine bunches were held in h=3 buckets for one quarter of a synchrotron oscillation just before extraction and then the two of the resulting three "pseudo-bunches" which fit within the kicker widths were sent into the BTA line. In the AGS they were caught in two of the twelve buckets and allowed to roll another quarter oscillation. At this point the AGS rf was turned off and the beam was allowed to debunch, with a smaller energy spread as a result. Finally the beam was adiabatically rebunched at h=12 filling the twelve buckets equally.

The predictions for survival in Booster and stripping efficiency at Booster extraction were all verified for low ($5x10^8$ ions/cycle) intensities. Slow losses during acceleration with a time dependence consistent with electron stripping were seen at the predicted levels. Additional foil choices available for this run in BTA allowed a slight improvement over the previous stripping efficiency to Au^{77+} using a 4 mil thick carbon foil rather than the 5 mil optimum of the preliminary study. Nevertheless, as the intensity of the beam from Tandem increased the Booster acceleration efficiency decreased with the maximum accelerated beam in Booster less than $1x10^9$ ions. This loss behavior was fascinating but is neither understood nor corrected[5].

IV. THE MULTIPLE CYCLE OPTION

At this point another way to configure the accelerator components offering increased intensity was proposed. The possibility of bunch merging in AGS allows ions accelerated on multiple Booster cycles to contribute to one bunch later in the AGS cycle. To make this useful both from the point of view of survival of the accumulating beam in AGS and of delivering beam either to the SEB program or to RHIC, a fast Booster cycle short compared to the AGS cycle is required. The momentum at Booster extraction obtained using Au^{15+} and the slow "heavy ion" magnet mode could also be obtained using Au^{33+} and the fast "proton" magnet mode. The quite acceptable stripping efficiency to Au^{77+} in BTA for ions with this momentum whether Au^{15+} or Au^{33+} would remain. A "proton mode" magnet cycle was built which maintained unchanged the low field ramping during the multiturn Booster injection and allowed acceleration to a field high enough to produce the same rigidity ion after stripping in BTA with Au^{33+} as was produced with the former magnet cycle and Au^{15+}. The length of the resulting Booster cycle was 200 ms. The idea then is to accelerate and transfer four Booster batches into the AGS and then accelerate and merge them into a few RHIC bunches. The first transfer of Au^{77+} to AGS must wait 600 ms while the other three Booster loads are accelerated and transferred. Survival in AGS was tested while still in the Au^{15+} mode - same momentum in AGS - and found to be satisfactory, though significant losses were observed. This approach gives up the potential intensity gains from eliminating the stripping foil just after Tandem, but at this point the higher current can not be efficiently accelerated in Booster.

The switch to Au^{33+} was successfully accomplished along with the reconfiguration of the Booster power supply and the associated machine functions. The intensity available to the Physics program, with one Au^{33+} Booster cycle feeding the AGS was still adequate and in fact was not much different from the Au^{15+} situation. Of course nearly half the beam was still lost at BTA transfer due to the present kicker lengths. The complex ran in this mode for the second month (the second half) of the Heavy Ion run.

The next step in this approach, and the last change attempted in ’94 was to multiple pulse the Tandem and Booster at the 5 Hz rate. This was a new request, well beyond the scope of the instrumentation and controls defined for the Tandem, but nevertheless was accomplished. Four Tandem bursts, coming at 200 msec spacings, were successfully accelerated in the Booster. The reorganizations required to further transfer these cycles into the AGS proved too hard given the short time available, but do not involve exploring new territory since this part of the setup closely resembles normal high intensity proton operation.

V. FUTURE PLANS

The final step of actually transferring four Booster batches of Au to AGS remains for the 1995 run. A further optimization of BTA foils to reduce energy spread is possible. The slow losses observed in AGS still require understanding. Perhaps some of what has been learned about AGS stopbands in accelerating high intensity protons will contribute to this effort. Synchronizing the four transfers of Booster bunches, with their slightly "wrong" frequencies into AGS buckets, and bunch merging in AGS to achieve RHIC bunch intensities still lie ahead.

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