BNL-101834-2014-TECH
AD/RHIC/RD/52;BNL-101834-2013-IR

Beam Loss Scenario in RHIC

M. Harrison

January 1993

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC/RD-52

RHIC PROJECT

Brookhaven National Laboratory

Beam Loss Scenario in RHIC

M. Harrison and A. J. Stevens

January 1993

Beam Loss Scenario in RHIC

M. Harrison and A.J. Stevens

I. Introduction

The purpose of this note is to document an estimate of beam loss in the RHIC facility which is required for analysis of a variety of issues related to radiation safety. The spirit here is that such an estimate should be both realistic and conservative. What is meant by "realistic" is that the scenario should model the intended operation of the facility as a heavy ion collider for physics research. Although the accelerating systems in principle allow the acceleration and disposal of full energy heavy ion beams every 4 minutes, such operation is certainly **not** realistic. What is meant by "conservative" is that this scenario should both (a) allow for an expansion of the currently envisaged operation of RHIC, and (b) define a conservative "Safety Envelope" for the foreseeable future. This note supercedes an earlier estimate of beam loss in RHIC made for the same purpose.[1]

II. Collider Operating Scenario

A. Beam Intensity and Cycle Frequency

For safety purposes an "upgraded" RHIC will be assumed which stores 4 times the beam intensities (twice the intensity per bunch and twice the number of bunches) listed in the Conceptual Design Report (CDR)[2].

Although RHIC is designed to accelerate and collide a variety of ion species only Au and protons at full design energy will be considered here. The Au beams have the shortest lifetimes among the heavy ion species and thus permit the highest fill rates. Protons, at 250 GeV, dominate muon radiation[3] and lead to slightly higher radiation levels under fault conditions (see section III below).

Reference 1 assumed 10 hour physics runs for Au on Au. This assumption was predicated on the mode of operation described in the CDR wherein the initial Au transverse emittance is deliberately blown up from 10π mm•mrad to 60π mm•mrad. This results in a slow and uniform loss of luminosity during a physics run which has been considered desirable for experiments. However, operation at the smaller initial emittance value[4] maximizes the time-integrated luminosity and, in order to allow this possibility within the "safety envelope" of operation, we will here assume 6 hour physics running periods. In 6 hours, the beam loss due to intrabeam scattering is 35%[5] in this mode.

For p,Au running, we assume a 4 hour physics running period. This interval is chosen to match the Au beam loss in Au,Au running as discussed in section II.C.3 below.

The operating year is assumed to consist of 34 weeks of physics operations and 4 weeks of studies. The 34 weeks of physics operations are here assumed to be divided into

26 weeks with Au,Au running and 8 weeks with p,Au running, but the sensitivity to the exact division as regards safety considerations is very slight, and a wide range of program options can be covered under the safety envelope developed here. For example, no explicit consideration of p,p running is made because such running has a very long beam lifetime which will subtract from the annual radiation burden.

Each run for physics operations will consist of a "set-up" procedure followed by the physics run proper. The set-up procedure will be conservatively assumed to be accomplished in 1 hour and to be equivalent to accelerating to full energy and disposing of 1.25 times the full beam intensity in each ring[6]. Thus, each physics operation run will consist of cycles composed of 1.25 fills of 1 hour duration followed by a physics run of either 6 hours (Au,Au) or 4 hours (p,Au). The studies, also conservatively taken at full energy and intensity, will be assumed to be with Au in both rings and to have a minimum duration of 1 hour and an average duration of 2 hours[7].

In summary, the total annual fills per ring are bounded by:

Au + Au: 1404 fills for physics + 336 fills for studies
p + Au: 605 fills for physics

Combining these bounds with the upgraded beam intensities defines the upper limit for the "source term" for annual radiation burden in the collider:

Au:
2×10^{9} ions/bunch X 114 bunches X 1740 fills X 2 rings
\+ " " X 605 fills X 1 ring
= 9.314×10^{14} ions/year at 100 GeV/u

protons:
2×10^{11}protons/bunch X 114 bunches X 605 fills X 1 ring
= 1.379×10^{16} protons/year at 250 GeV

For most purposes, disposal of the total kinetic energy determines the radiation burden. A proton at 250 GeV is therefore equivalent to (250/100)X(1/197)=0.0127 Au ions at 100 GeV/u. Expressed in Au ion equivalents, the annual source of radiation is 11.06×10^{14} ions at 100 GeV/u. This compares to the annual source term of 8.577×10^{14} Au ions per year of Reference 1.

The source for maximum hourly burden is the required disposal of 1.25 times the full (upgraded) beam intensity in 1 hour, which is the assumed duration of a set-up fill:

5.70×10^{11} Au ions in both rings at 100 GeV/u equivalent
or
2.85×10^{11} Au ions at 100 GeV/u equivalent
\+
2.85×10^{13} protons at 250 GeV/c equivalent

B. Loss Locations

It is a fact that superconducting accelerators are most unforgiving of sloppy beam handling. FNAL has established a fast-loss quench threshold of 1-2 mJ/g at 80% of quench current[8]. If the vast majority of beam energy does not end up on the (well shielded) internal dump or a Limiting Aperture Collimator (LAC), unintentional beam loss will limit the stored beam energy to values much lower than have been assumed here.

Given this requirement - that the vast majority of beam **must** be "lost" at a well-shielded location, and excepting fault conditions which are discussed in section IV below, most radiation hazards are relatively insensitive to the exact location of unintentional beam loss. For the sake of completeness, we elaborate here locations where beam loss is likely to occur: (1) the internal dump, (2) one of several LAC's[9], (3) the injection septum, (4) beam crossing points, (5) the warm sections of the intersection regions where beam-gas interactions occur, and (6) "other points". The catch-all "other points" incorporates losses corresponding to (a) particles which intercept an LAC but which out-scatter (LAC inefficiency) and interact "elsewhere", and (b) particles which directly encounter an aperture other than the internal dump or an LAC. In practice, the most likely location for non-intentional beam loss are maximum beta locations (Q2,Q3).

C. Loss Assumptions

The assumptions here are based on the calculated loss rates in the CDR and recent calculations of loss due to intrabeam scattering[5] mentioned in section II(A) above.

1. Injection Septum

Although 1/2% loss is assumed here, the consequences of such a loss - at injection energy - present a small and well-defined radiation hazard and will be ignored in the remainder of this note.

2. Loss on Apertures

Aperture losses arise from a variety of causes including loss from rf buckets during acceleration, intrabeam scattering, and beam-beam Coulomb dissociation and Bremsstrahlung interactions. The latter two sources cause approximately 15% loss in 6 hours for Au, Au running in the 10π initial emittance mode[10]. Adding this to the 35% intrabeam scattering loss gives a total aperture loss of 50%, all of which should ideally take place on either the internal dump or on one of the LAC's. We will assume that these apertures are 90% efficient, so that 45% of the loss occurs on an LAC and 5% at other locations.

For the studies and set-up fills, all the aforementioned losses should be small, including the intrabeam scattering loss which is small during the first hour. We will conservatively scale the 6 hour loss rates linearly and take 8.3% loss for a 1 hour set-up fill and 16.6% loss for a 2 hour studies fill.

For p,Au running, the proton beam loss is extremely small and will likely be dominated by nuclear beam-beam and beam-gas interactions. We will, nevertheless, conservatively assume a 5% aperture loss. For the Au beam, the Coulomb beam-beam losses do not exist in this mode and the intrabeam loss (again assuming an initial 10π initial emittance) is ~ 23%.

3. Beam-Beam, Beam Gas Effects

The beam-beam nuclear interaction is, of course, the raison d'etre for the RHIC facility. Calculation of this "loss", as well as losses for beam-gas interactions which occur in the warm sections of the intersection regions, are given in Table IV.3-10 of the CDR.

For the 6 hour Au,Au physics runs, the ratio of aperture losses discussed above to beam-beam nuclear interactions to beam-gas interactions, expressed in percent, is 97.2/1.6/1.2.

For p,Au running, the high luminosity causes a high beam-beam nuclear interaction rate. In 4 hours, the "signal" reaction has caused a 27% loss in the Au beam[10]. As mentioned above, the 4 hour running period was chosen to match the total Au beam loss (27% + 23% from intrabeam scattering) to the 50% loss rate in 6 hours in Au,Au running. The ratio of aperture to crossing point to beam-gas loss, again expressed in percentage, is 46.0/52.9/1.1 for the Au beam in this mode, and 83.1/15.9/1.0 for the proton beam. The latter ratios are dominated by the artificial 5% aperture loss assumed above for protons.

D. Annual Loss Summary

The assumptions given above can be combined to estimate an annual loss distribution. In the table below, the internal dump has been assumed to "catch" 1/3 of the aperture losses with the remaining 2/3 impinging on the LAC's.

Location	Annual Loss Au ($X10^{14}$)	Annual Loss protons ($X10^{16}$)
Dump	7.616	1.343
LAC	1.270	0.024
Crossing Point	0.185	0.006
Other Points	0.212	0.004
Beam-Gas	0.031	0.002
	-----------	------------
Total	9.314	1.379

III. Transfer Line Operating Scenario

A. Operation for Collider Running

The AGS cycle structure for filling RHIC for physics runs is shown schematically in Fig. 1. For Au ions at 10.4 GeV/u, 3 bunches are injected every 1.5 seconds. With the (upgraded) intensity assumptions made herein, filling both rings is accomplished at a rate of 4 X 10^9 ions/sec for 114 seconds. For protons at 28 GeV, the (single ring) fill scenario is at a rate of 1.2 X 10^{12} protons/sec for 19 seconds. It should be noted that the AGS will be capable of storing 6 X 10^{13} protons in the 2 second cycle period which is a factor of 25 more than required by the collider.

Experience with AGS Fast Extracted Beam operation has shown that transport line loss is extremely small; nominally 0.1% over the entire line.[11] For beam injected into the collider, therefore, radiation hazards associated with Transfer Line operation are small: crudely, the "lost" energy in the Transfer Line relative to the collider is in the ratio (0.1X28)/(100X250) ~ 10^{-4}. The "normal running" loss assumed here is that 0.1% of all injected beam will be lost over the entire length of the transfer line and that half of this, 0.05%, will be lost at an arbitrary point (on any magnet).

The maximum local loss rate in an hour is determined by the fill rate during set-up[6] and the 0.05% loss assumption which yields:

8.28 X 10^8 Au ions per hr at 10.4 GeV/u (Au,Au)
or
3.39 X 10^{10} protons per hr at 28 GeV (p,Au)
\+ 4.14 X 10^8 Au ions per hr at 10.4 GeV/u

The maximum hourly loss rate over tens of seconds at a point, which is of interest for radiation monitors, is set by the normal filling process to be:

7.20 X 10^9 Au ions per hr for 114 seconds
or
2.16 X 10^{12} protons per hr for 19 seconds

The arithmetic for annual losses not presented here in detail. For the total distributed losses (0.1% loss assumption), the result is:

Au:	13.18 X 10^{11} ions (Au,Au set-up+running)
	2.84 X 10^{11} ions (p,Au set-up+running)
	1.53 X 10^{11} ions (Au studies)

Total:	17.55 X 10^{11} ions at 10.4 GeV/u
Protons:	24.37 X 10^{12} protons at 28 GeV

Again, one-half this annual loss is assumed to occur at a single point.

It may be desirable to employ emittance-shaving collimators at some point either in the Transfer Line itself or at some appropriate position upstream of the Transfer Line. In order not to preclude this possibility, allowance should be made for shaving up to 5% of the total injected beam, or 100 times the beam loss at an arbitrary point.

B. Operation for Set-up and Studies

As was done for the collider, allowance must be made for Transfer Line set-up and studies. For these modes of operation the beam is disposed of at a dump within the Transfer Line itself. The Transfer Line dump is planned to be located immediately downstream of the splitting magnet which is not powered in this mode of operation. Set-up can in principle be accomplished when the collider is nearing the end of a physics run so that they overlap in time. It is believed that Transfer Line set-up can be done using low beam intensities, but we will allow for 50 bunches (1 bunch every 4 AGS cycles as in collider set-up) at full intensity per collider physics run or collider study. Automatic beam-tuning algorithms should, in fact, enable the Transfer Line to be tuned with a single bunch which emphasizes the conservative nature of the allowance made here. From the scenario developed in Section II above, a year is comprised of (or bounded by) 624 Au,Au physics runs, 269 p,Au physics runs, and 336 collider studies. The total yearly beam on the Transfer Line dump for the purpose of set-up is therefore:

$$50 \text{ X } 2 \text{ X } 10^9 \text{ X } 1229 = 1.229 \text{ X } 10^{14} \text{ Au ions @ } 10.4 \text{ GeV/u}$$
$$+$$
$$50 \text{ X } 2 \text{ X } 10^{11} \text{ X } 269 = 2.690 \text{ X } 10^{15} \text{ protons @ } 28 \text{ GeV/c}$$

It is anticipated that most, but not all, Transfer Line studies can likewise be accomplished at low beam intensity. We will allow the equivalent of 1 full intensity Au bunch per AGS cycle (1.5 sec.) for up to 1 hour per study and 10 hours per year. The beam on the dump for studies is therefore bounded by the equivalent of:

$$2 \text{ X } 10^9/1.5 \text{ sec. X } 3600 \text{ sec.} = 4.8 \text{ X } 10^{12} \text{ Au ions @ } 10.4 \text{ GeV/u per hour}$$
or
$$4.8 \text{ X } 10^{13} \text{ Au ions @ } 10.4 \text{ GeV/u per year}$$

C. Summary of Annual Losses

The table below summarizes annual beam loss in the Transfer Line.

Location	Annual Loss Au @ 10.4 GeV/u	Annual Loss protons @ 28 GeV/c	Comment
Beam Dump	1.71×10^{14}	2.69×10^{15}	Set-up/Studies
Unintended Loss Entire Transfer Line	1.75×10^{12}	2.44×10^{13}	0.1% based on msmt.
Unintended Local loss	8.78×10^{11}	1.22×10^{13}	.05% based on msmt.
Allowance for Emittance Shaving[12]	9.64×10^{13}	1.35×10^{15}	5% upper limit

IV. Fault Assumptions

A. Collider

1. "Normal" Faults

Both quench detection circuitry and beam loss monitors will exist to trigger the abort system in the event of rapid accidental beam loss. A recent simulation[13] indicates that ~ 10^9 250 GeV protons, or about 5×10^{-4} of the beam intensity assumed here, impinging on a magnet will result in a quench. It is reasonable to assume that on the order of 10-20 such "normal faults" will occur per year, and that a higher frequency of such incidents will result in corrective action on the accelerator systems.

2. Maximum Credible Fault

A worst-case fault would be the uncontrolled loss of the 2.28×10^{13} 250 GeV proton beam on a single location where "location" denotes a magnet or other object (e.g., an LAC) which intrudes into the vacuum chamber aperture. It is not possible to envisage such an occurance **on any magnet** because failures of the beam loss monitors or (fail-safe designed) abort kicker would still result in the internal dump and LAC's - which define the collider aperture - "catching" most of the loss. As an example, a shorted magnet coil would result in the magnetic field in the magnet in question decreasing with a time constant of a few seconds. This very slow failure, relative to the 12.6 microsecond revolution period causes a slow beam growth which first intercepts the aperture limiting objects. However, for grazing incidence on an aperture-limiting object, ~50% of the protons will out-scatter and interact elsewhere. We therefore consider the **maximum credible fault** to be loss of the entire beam at any aperture-defining location, which includes high β quadrupoles, and loss of one half of the entire beam at other locations. Shielding and access restrictions should allow for this possibility at a rate of once in several years. At FNAL, the entire full energy beam has been lost twice in ~ 10 years of running, but in both instances the loss was spread over many locations as would be expected. The maximum credible loss defined here is therefore conservative.

B. Transfer Line

1. "Normal Faults"

Beam mis-steering in the Transfer line will no doubt occur at some frequency and will cause loss at levels greater than the 0.1% level. We again stress that loss monitoring and the generation of alarms and interlocks which inhibit injection to the Transfer Line will be an important aspect of Transfer Line operation but are beyond the scope of this note. Here we suggest that a reasonable "allowance" for the frequency of such faults at this time might be that 5% of the total fills have an order of magnitude higher loss than "normal", i.e., 1% of the injected beam overall and 0.5% at a single point. Should this later prove overly restrictive, appropriate modifications to shielding and/or changes in access restrictions can be adopted.

2. Maximum Credible Fault

In the case of component failure (e.g. - a shorted coil) or a drastically mis-steered beam, the full injected intensity - 1.2×10^{12} protons/sec or 4×10^{9} Au ions/sec - can fault on any magnet. We assume here that this level would exceed a radiation monitor interlock threshold by a large factor which will terminate injection within 2 AGS pulses . Since it is planned that inappropriate states which indicate either a power supply fault or closed vacuum valves will not permit injection, the frequency of such faults should be small. We suggest that five such faults per year should be considered credible.

Clearly redundant fail-safe hardware should exist in the AGS to prevent the possibility of injecting the 3×10^{13} protons/sec which the AGS will be capable of accelerating into the Transfer Line. It is assumed here that such a fault is not credible, but this assumption must be critically evaluated when control procedures and hardware are fully specified.

V. Commissioning

The scenario described in this note is for a "mature" machine. Proper control of beams in the collider will, of course, involve a "learning curve;" beam intensity will grow to the design value (and perhaps beyond as has been assumed here) only as progress is made on the ability to handle beams cleanly. Although "faults" will no doubt occur with greater frequency than assumed above during commissioning, the beam intensities will be very low. For this reason, the commissioning process should be well within the safety envelope developed here. In any event, prior to the initiation of operations with beam for commissioning, a formal plan and a commissioning safety envelope will be developed, reviewed by the Radiation Safety Committee and approved by BHO.

References/Footnotes

1. A.J. Stevens, "Radioisotope Production in Air and Soil in RHIC," AD/RHIC-29, 1987. Appendix A)

2. Conceptual Design of the Relativistic Heavy Ion Collider, BNL 52195, 1989.

3. A.J. Stevens, "Radiation from Muons at RHIC," AD/RHIC-46, 1989.

4. Doubling the bunch intensity and retaining an initial emittance of 10π are not compatible because of tune shift and space charge limitations. If the bunch intensity were in fact doubled, the initial emittance would be perturbed to 20π mm•mrad. Intrabeam scattering losses and reaction rates given in Table IV.3-10 of the CDR are invariant under this change. For simplicity, we retain the expression "10π" in this note.

5. J. Wei, private communication. This large loss is from the longitudinal phase space. This loss may be translated by non-first order effects to a transverse growth which can be passively collimated. If such growth does not occur, the "loss" becomes a DC beam which is unlikely to bother experiments and is simply aborted on the dump at the end of each run.

6. The initial phase of set-up will utilize 1 bunch every 4 AGS cycles (see section III) which is ejected on the internal dump without acceleration. In one hour the beam energy aborted in this phase is equivalent to $\sim 1/4$ the full beam intensity at full energy. Additionally allowing for acceleration and disposal of the full beam intensity during set-up is an extremely conservative assumption.

7. Many studies will be performed with 1 or at most a few bunches in each ring. For this reason the assumption that the full beam is accelerated to full energy is believed to be so conservative that no explicit "set-up" procedure is added to the studies runs.

8. R. Dixon, N.V. Mokhov, and A. VanGinneken, "Beam Induced Quench Study of Tevatron Dipoles," FN-327, 1980.

9. At least one LAC in each ring will exist for the purpose of intercepting off-charge ions which result from electron pick-up (beam-beam Bremstrahllung). An additional LAC in each ring, which nominally matches the internal dump aperture but which can provide more flexible mechanical alignment, will likely be present.

10. CDR, Table IV.3-10 and formula on page 121.

11. W. Glenn, memorandum to A.J. Stevens, dated 02/27/92. This memorandum describes the analysis of FEB loss for 14 randomly selected runs during the FY85 & FY86 running periods. The average loss for the entire U line was 0.076% and the highest local loss (30 ft. section) was 0.03%.

12. The numerical values for the emittance shaving allowance are 100 times the 0.05% local loss plus 5% of the beam dumped.

13. A.J. Stevens, "Radiation Levels at Floor Level from Local Beam Loss in RHIC," AD/RHIC/RD-27, 1991.

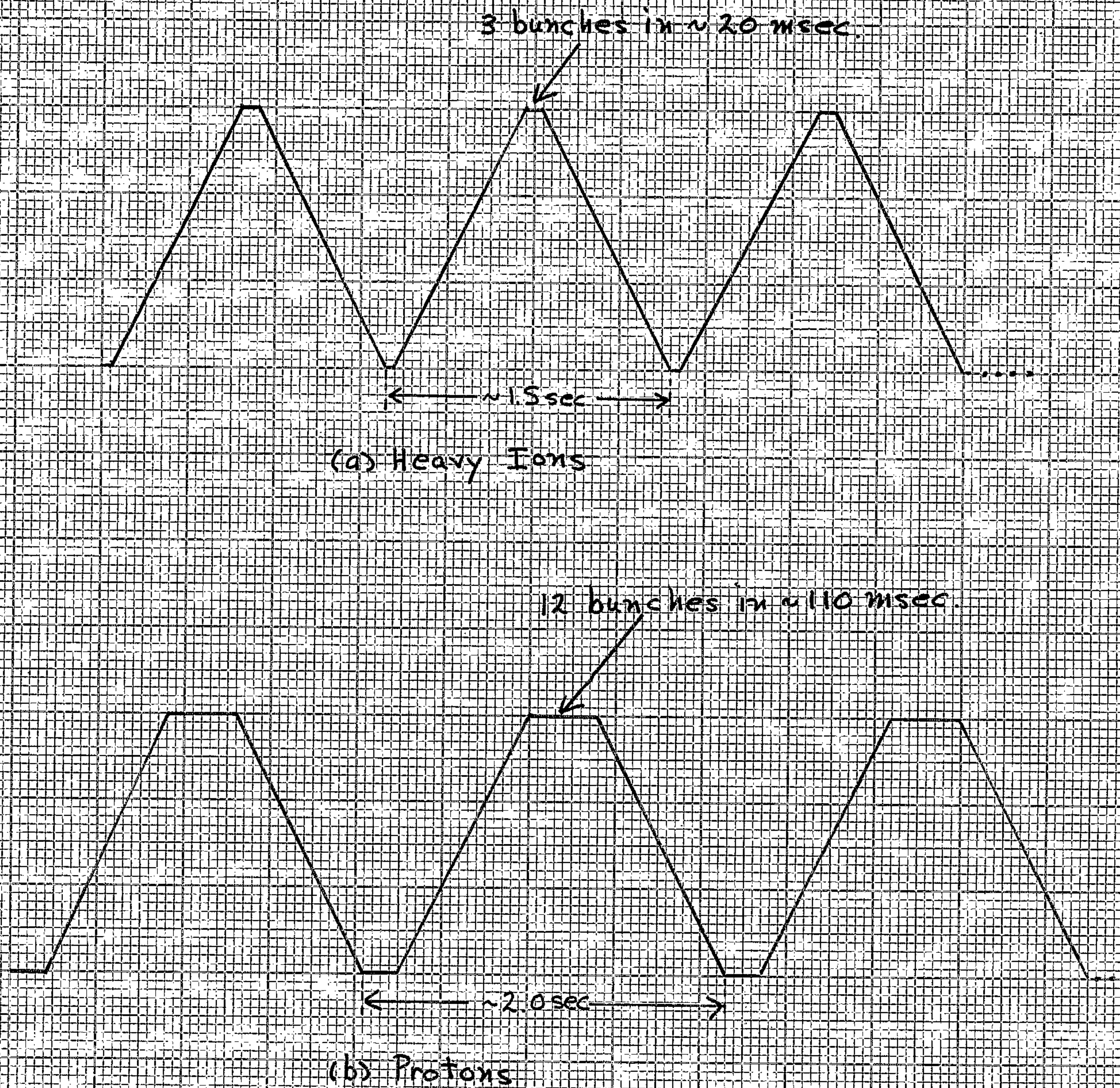

Fig 1. Schematic Representation of the AGS cycle for filling RHIC