The Recycler Commissioning Plan

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1. Introduction

The Run II Luminosity Upgrade Plan requires the Recycler to play a key role, starting mid-2005, as the repository of large stacks of antiprotons (600E10) to be used in the collider stores. In order to maximize the stacking efficiency of the antiproton accumulator, small stacks of antiprotons will be transferred to the Recycler, frequently. In the Recycler, the stacks are initially cooled by stochastic cooling and then stored and cooled by electron cooling until the antiprotons are ready to be used in Tevatron shots.

The upgrade plan foresees the Recycler fully integrated into collider operations in two major steps. First, the Recycler is commissioned to bring its performance to the level that it is ready to begin the implementation of electron cooling. This milestone is to be achieved by June 1, 2004. In the second phase, the installation of electron cooling and its commissioning takes place. The electron cooling is expected to be operational by June 1, 2005. This document primarily outlines the Recycler commissioning plan for the first phase which is to prepare the Recycler for start of the electron cooling implementation.

An R&D effort to facilitate the electron cooling project is underway at the Wide-band Lab at Fermilab. The facility with a 5 MV Van de Graaff accelerator (Pelletron) and proto-type electron beamlines is being used to develop and demonstrate the required system parameters for the electron beam that would be used in the cooling of antiprotons in the Recycler. The project has made significant progress in the past few months. Once the Recycler is ready to start the implementation, the equipment will be moved to the MI/RR premises.

2. Performance Goals and Readiness for Electron Cooling

To facilitate planning of the Recycler commissioning, a set of performance criteria for FY 2004 and beyond were developed in October 2003, reviewed and approved (http://www-bd.fnal.gov/run2upgrade/reviews/Recycler_perf.html; Appendix A). The measurement techniques to be used to demonstrate these criteria were also described. Achieving those performance goals would (a) allow the Recycler ring to be an operational machine, (b) make the Recycler ready for the installation of electron cooling, and, most importantly, (c) help commission the electron cooling.

To get the Recycler ready for electron cooling, the following tasks need to be successfully performed, routinely:

(1) inject a stack into the Recycler with high efficiency and perform necessary phase-space manipulations in the Recycler with minimal emittance dilution,

(2) cool the injected stack (using gated stochastic cooling) to achieve emittance within the range for on-set of electron cooling,

(3) merge the new stack (after it has been cooled transversely) with the main stack with minimal emittance growth,
(4) maintain the main stack with long lifetime and with small emittance growth rates and
(5) maintain stable orbit parameters for optimal electron cooling
Also, in order to integrate the Recycler into collider operations, the stored antiprotons need to be extracted into the Main Injector with high efficiency and minimal emittance dilution. The set of tasks comprising (1)-(3) above is referred to as "Recycler Transfers".

Recycler Performance Criteria (and status as of Feb 1, 2004) for antiprotons

	Lifetime	**Longitudinal properties**	$E_{\perp}\{\Delta\varepsilon_{\perp}\}$	**Comments**
MACHINE READINESS STATUS (ACHIEVED)	$\geq$ 150 hr OK	Δp_{rms}< 2 MeV/c OK	{$\leq 6\pi$ mm-mrad/hr} growth rate OK	Zero-current, pencil beam OK
PERFORMANCE @ $\geq 100\times10^{10}$ STATUS (WORK IN PROGRESS)	$\geq$ 100 hr OK	$\varepsilon_L \leq$ 100 eV-s OK	$\leq 10\ \pi$ mm-mrad {$\leq 3\ \pi$ mm-mrad /transfer from MI} OK	Injection efficiency from MI $\geq$ 85% Achieved once
GATED TRANSVERSE STOCHASTIC COOLING @ 20×10^{10} IN INJECTION BUCKET STATUS (WORK IN PROGRESS, SEE TEXT FOR DETAILS.)		Initial injected $\varepsilon_L \leq$ 15 eV-s Debunched < 50 eV-s Minimum value unknown	From 15 π mm-mrad to $\leq 10\ \pi$ mm-mrad in 20 minutes Tested once, successfully	Injection efficiency from MI $\geq$ 85% for a 20×10^{10} batch Tested once, successfully
EXTRACTION PERFORMANCE STATUS (WORK IN PROGRESS, SEE TEXT FOR DETAILS.)		36 bunches @ 1.5 eV-s in 30 min. unknown	$\leq 10\ \pi$ mm-mrad {$\leq 3\ \pi$ mm-mrad /transfer} unknown	Extraction efficiency to MI $\geq$ 90% unknown

Table1. The performance criteria to be met by June 1, 2004, to start implementation of electron cooling. Present status is also indicated. ε_L and $\varepsilon_{\perp}$ are 95% normalized longitudinal and transverse emittances, respectively. $\Delta\varepsilon_{\perp}$ is the $\varepsilon_{\perp}$ growth rate.

A sub-set of the FY04 performance criteria has been recently identified as performance goals for readiness of the Recycler for electron cooling. These criteria are shown in

Table 1. The present status for meeting each criterion is also indicated in the table. The ones that are yet to be met are discussed below.

4. Present status

At present, the basic "**Machine Readiness**" goals for Recycler Commissioning have been fully and reproducibly achieved. The measured zero-beam current, pencil-beam emittance growth rate is < 6 π mm-mrad and the beam lifetime is > 150 hours. Other parameters require further studies and development time. The mechanics of stacking and storing operations and parameter measurement techniques are outlined in the Appendix.

Since both the gated stochastic cooling and the efficient extraction are required for the Recycler transfers scenario, we will summarize the present status for these tasks in detail.

1. **Required:** The transfer efficiency between the MI and the Recycler for a single 20E10, 10 eV-s, 10-π mm-mrad antiproton batch should be >85%;
   Present status: On one occasion (Jan 13, 2004), a batch of 20E10, 10 eV-s, 10-π mm-mrad antiprotons was transferred to the Recycler with 85% efficiency. All antiproton injections into the Recycler to date have been made in 5-transfer batches. On Jan. 13, 2004, four out of five batches were intentionally made small (3E10) to use them as pilot batches. The last (fifth) batch was made to simulate the future Recycler transfer. The time that these 5 transfers currently take varies from 1 to 3 hours. All of these transfers are done on a timeline event; however they require a significant amount of human intervention mostly for beamline tuning between the Accumulator and the Main Injector. The MI to Recycler portion presently requires some human intervention with injection orbit closure, the rf phase and the kicker timing adjustment. The Recycler adjustments are usually minor and can be implemented as feed-forward corrections when the shots to the Recycler are done on regular 30-minute intervals.
2. **Required:** Longitudinal phase-space manipulations should be accomplished in less than 5 minutes;
   Present status: An antiproton batch transfer into the Recycler consists of the following Recycler rf operations performed sequentially: (a) create an injection barrier bucket (1.6 μs between barriers); (b) on a transfer event, create four 2.5MHz buckets (3.44 eV-s each) within the injection bucket and accept the newly injected batch of antiprotons, and (c) adiabatically decrease 2.5MHz waveform voltage to zero. All of these operations can be and have been done within 5 minutes without increasing the longitudinal bunch emittance. However, the transverse stochastic cooling rate (for an ideal system with zero thermal noise) increases with the longitudinal emittance. We have not yet studied experimentally the dependence of the transverse rate on the longitudinal emittance of an injected bunch, confined in a 1.6-μs barrier bucket. If the longitudinal emittance needs to be increased, we have demonstrated that one of the efficient ways to do it quickly and in a controlled manner is by opening up the notch filter of the gated longitudinal stochastic cooling system while keeping the cold stack intact.

3. **Required:** Gated transverse stochastic cooling should bring the initial emittance of 15 π to below 10-π mm-mrad in 20 minutes or less;
   Present status: On one occasion (Jan 21, 2004), 20E10 antiprotons, confined within a 1.6-μs injection barrier bucket, were cooled transversely from about 19 π mm-mrad to about 9 π mm-mrad in 25 minutes by a gated cooling system. The longitudinal emittance was 19 eV-s. This was a very encouraging result. We are planning to study in detail the dependence of the cooling rate on the longitudinal emittance. The preferred outcome would be to cool the batch transversely while keeping its longitudinal emittance at about 15 eV-s. This will greatly reduce demands on the future electron cooling system.
4. **Required:** Merging the new batch with the stack and getting ready for the next injection should take less than 5 minutes.
   Present status: This has been attained.
5. **Required:** Create 36 equally populated bunches for the extraction; the bunches are formed by a 2.5-MHz rf voltage, each with ≤ 1.5 eV-s longitudinal and ≤ 10-π mm-mrad transverse emittances.
   Present status: This work is in progress. The method of creating 36 equally populated bunches has been successfully tested with protons on February 5, 2004. The transverse emittances were not measured during this process. A comprehensive description of this process can be found at http://beamdocs.fnal.gov/DocDB/0009/000933/002/rr-mmmining-v2.pdf

In summary, none of the requirements seem particularly difficult to achieve and some have been already met. However, much work remains in the areas of gated stochastic cooling optimization and rf manipulations.

5. Milestones

The following is a summary of all commissioning milestones:

	Milestone	Plan	Actual
1.	Vacuum performance	01/19/04	01/09/04
2.	Vacuum and machine admittance	01/27/04	01/12/04
3.	MI to RR Trans. eff. >85%, round trip <3π growth	02/27/04	-
4.	Performance with 100E10 antiprotons	03/15/04	-
5.	Recycler transfers commissioned	04/20/04	-
6.	Extraction commissioned	05/03/04	-
7.	Recycler commissioned for electron cooling	06/01/04	-

Milestones 1-6 are related to specific performance criteria (see Appendix A for definitions). Milestone 7 completes the overall evaluation of the Recycler readiness for the electron cooling installation. All of these milestones shall be demonstrated with antiprotons.

6. The Plan & the WBS

The Recycler commissioning project began on December 1, 2003. This was approximately one month after the end of the shutdown, when it was unambiguously determined that the Recycler vacuum work during the shutdown was successful.

The project scope for FY2004 has two major tasks: (1) Recycler commissioning and (2) Recycler upgrades. The "Recycler commissioning" task includes all of the work *necessary* to make the Recycler completely operational and commission electron cooling. This task ends on Dec. 31, 2004. A portion of this task, pertaining to the Recycler readiness for the electron cooling, ends on June 1, 2004. The "Recycler upgrades" task includes sub-projects that are highly desirable for future Recycler operations. This task ends at the end of the 2004 shutdown (Jan. 2005).

The list of tasks in the work breakdown structure (WBS) in the Recycler Commissioning and Recycler Upgrades projects at the top two levels is shown in Table 2. A resource-loaded WBS to level 7 and a schedule has been created in Microsoft Project. Detailed plan documents for accomplishing the top level tasks are being written. Presently, all planning is done at a weekly department meeting and through a "Recycler study plan" document, which is usually developed for each Level 3-4 task.

The plan is being executed in the following manner. Approximately every two weeks the Recycler mode of operations is changed from protons to antiprotons and back. While the "Proton beam commissioning" task has been fully complete, the proton mode is now being used strictly to develop and test procedures, operations and diagnostics tools for the antiproton mode commissioning. In the antiproton mode the study time is carefully planed at weekly meetings and study plans are submitted for approval to the run coordinator. The injected antiprotons are used for commissioning and testing of various cooling scenarios, beam manipulations and instruments. Eventually, we plan to take about 30E10 antiprotons after each Tevatron store. This is sufficient for two pilot shots plus a large 20E10 Recycler transfer. Every time the Recycler stack reaches >100E10 antiprotons, we plan to extract the beam into the Main Injector and, possibly, send it to the Tevatron for a collider store. Beam studies are organized in two 6-hour shifts, Monday through Friday. Presently, the antiproton injections are performed by Recycler group experts. Once the commissioning is complete (i.e., by June 1, 2004), this will be handled by an MCR operator on shift. The remaining commissioning tasks are ongoing; some constitute theoretical studies, modeling, off-line development, evaluation etc.

7. The deliverables

By June 1, 2004 we plan to document and save a set of machine files, sequences and procedures that would allow an MCR operator (a) to inject the antiproton beam efficiently, (b) to manipulate the beam longitudinally, (c) to cool the beam transversely, (d) to merge the beam with the cold stack and (d) to extract the beam to the Main Injector.

Table 2. The WBS structure for the Recycler commissioning and upgrades. Further breakdown and details are available in the Run II upgrade Resource-loaded schedule.

Task WBS		Start Date	End Date
	Sub-tasks		
26.3.4.7	**Recycler commissioning**	**11/17/2003**	**– 1/24/2005**
26.3.4.7.1	**Proton beam commissioning**	**12/1/2003**	**– 4/26/2004**
	Injection commissioning		
	Circulating beam commissioning		
	Extraction commissioning		
26.3.4.7.2	**Antiproton beam commissioning**	**12/1/2003**	**– 4/26/2004**
	Injection commissioning		
	Circulating beam commissioning		
	Extraction commissioning		
	Recycler transfer commissioning		
26.3.4.7.3	**RF systems**	**11/21/2003**	**– 5/3/2004**
	RF front end modifications		
	Baseline correction		
	Beam loading compensation		
	Auxiliary ion-clearing bucket generator		
	Beam phase/frequency feedback loop		
	Longitudinal time-domain emittance monitor		
	Extraction upgrades		
26.3.4.7.4	**Beam physics and modeling**	**12/1/2003**	**– 7/6/2004**
	Update collider scenarios with Recycler		
	Energy matching for all machines (Recycler portion)		
	Injection upgrades (kicker placement, counter-wave optimization)		
	Removal of abort line		
	Linear coupling correction		
	Chromaticity (modeling, optimal choice)		
	Sextupole grouping (optimal choice)		
	Broad-band transverse damper (specification)		
	High-intensity operations (optimization)		
	Longitudinal emittance (modeling)		

26.3.4.7.5 Vacuum		**11/17/2003 – 1/24/2005**
	Electron cooling section installation (plan)	
	Flying Wire installation	
	Clearing current monitors commissioning	
	TSP upgrades (plan)	
	Vacuum monitoring and TSP firing	
26.3.4.9 Management, evaluation and planning		**12/1/2003 – 12/30/2004**
	Vacuum evaluation	
	Lifetime evaluation	
	Transfer performance evaluation	
	Stacking evaluation	
	Beam properties evaluation	
	Rapid transfer performance evaluation	
	Extraction evaluation	
	Overall evaluation	
	Studies planning and scheduling	
	Shut down planning and scheduling	
26.3.4.8 Recycler upgrades		**4/1/2004 – 11/12/2004**
26.3.4.8.1 Transfer line upgrades		**7/7/2004 – 11/10/2004**
	Lambertson removal	
	Procure new kicker	
	Reconfigure R22 and R32 lines	
26.3.4.8.2 Stochastic cooling upgrades		**4/1/2004 – 11/12/2004**
	Longitudinal cooling	
	Transverse cooling	
	Diagnostics	
26.3.4.8.3 Shutdown vacuum work		**8/23/2004 – 11/1/2004**
	TSP upgrades	
	Transfer lines rework	

APPENDIX A

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FY 2004: Recycler Operational Scenario, Responsibilities and Parameter Measurements

Recycler FY2004 Performance Criteria (for antiprotons)

	Lifetime	ε_L $\{\Delta\varepsilon_L\}$	$\varepsilon_\perp$ $\{\Delta\varepsilon_\perp\}$	**Transfer/Stacking Performance**
MACHINE READINESS	$\geq$ 150 hr		$\{\leq 6\pi$ mm-mrad/hr$\}$	
PERFORMANCE @ 100×10^{10}	$\geq$ 100 hr	$\{\leq$15 eV-s/batch$\}$	$\leq$ 10 π mm-mrad $\{\leq$ 3 π mm-mrad /transfer$\}$	$\geq$ 85%
EQUILIBRIUM PROPERTIES @ 200×10^{10} STOCHASTIC COOLING ONLY		100 eV-s	$\leq$ 10 π mm-mrad $\{\leq 6\pi$ mm-mrad/hr$\}$	$\geq$ 200×10^{10} in 10 hrs
EXTRACTION PERFORMANCE		36 bunches @ 1.5 eV-s in 30 min.	$\{\leq$ 3 π mm-mrad /transfer$\}$	$\geq$ 45%

Table 1: ε_L and $\varepsilon_\perp$ are the longitudinal and transverse 95%, normalized beam emittances (see text below for details).

Recycler Final Run II Goals (with electron cooling)

	Lifetime	ε_L $\{\Delta\varepsilon_L\}$	$\varepsilon_\perp$ $\{\Delta\varepsilon_\perp\}$	**Efficiency/Stacking Performance**
EQUILIBRIUM PROPERTIES @ 600×10^{10}	$\geq$ 150 hr	$\leq$ 50 eV-s	$\leq 10\pi$ mm-mrad $\{\leq 6\pi$ mm-mrad/hr$\}$	Rapid transfers every 30 minutes

Table 2: Run II performance goals (see Run II upgrade documentation for details)

Performance Criteria (for antiprotons) for Readiness for electron cooling

	Lifetime	Longitudinal properties	$\varepsilon_{\perp}\{\Delta\varepsilon_{\perp}\}$	Comments
MACHINE READINESS	$\geq$ 150 hr	$\Delta p_{rms} < 2$ MeV/c	{$\leq 6\pi$ mm-mrad/hr} growth rate	Zero-current, pencil beam
PERFORMANCE @ $\geq 100\times10^{10}$	$\geq$ 100 hr	$\varepsilon_L \leq 100$ eV-s	$\leq 10\ \pi$ mm-mrad {$\leq 3\ \pi$ mm-mrad /transfer from MI}	Injection efficiency from MI $\geq$ 85%
GATED TRANSVERSE STOCHASTIC COOLING @ 20×10^{10} IN INJECTION BUCKET		Initial injected $\varepsilon_L \leq 15$ eV-s Debunched < 50 eV-s	From 15 π mm-mrad to $\leq 10\ \pi$ mm-mrad in 25 minutes	Injection efficiency from MI $\geq$ 85% for a 20×10^{10} batch
EXTRACTION PERFORMANCE		36 bunches @ 1.5 eV-s in 30 min.	$\leq 10\ \pi$ mm-mrad {$\leq 3\ \pi$ mm-mrad /transfer}	Extraction efficiency to MI $\geq$ 90%

Table 3: A sub-set of FY2004 criteria identified as necessary for readiness of the Recycler for installation of electron cooling. ε_L and $\varepsilon_{\perp}$ are the longitudinal and transverse 95%, normalized beam emittances

Document Scope

Recycler operations in the context of the Run II Upgrade are outlined. The performance parameters given are general in scope and implicitly contain performance goals for the Recycler subsystems (e.g. cooling, vacuum, etc.) The measurement techniques used to determine performance parameters are outlined. Longitudinal and transverse emittances are given in eV-s and π mm-mrad respectively. Any given transverse emittance refers to both horizontal and vertical emittance.

Operational Scenario

In the general Run II Upgrade plan, the Recycler is to stack, store and extract antiprotons for use in collider operations. The mechanics of these operations are roughly outlined here. Implicit moderate assumptions regarding the Tevatron complex performance upstream of the Recycler are made.

Stack

Antiprotons are stacked longitudinally in the Recycler and beam sections are usually designated by the confining RF barrier bucket. To initiate an antiproton transfer into the Recycler, the Antiproton Source is requested to transfer a particular phase space volume (or number) of antiprotons as a single Recycler **batch** which is contained in four 2.5MHz buckets. At transfer from the MI into the Recycler, the antiprotons shall be within a 15 eV-s and 10 π mm-mrad phase space volume. An antiproton transfer into the Recycler consists of the following Recycler RF operations performed sequentially:

1. Create Injection barrier bucket.
2. On transfer event, create four 2.5MHz buckets within the Injection bucket and accept the newly injected batch of antiprotons.
3. Adiabatically decrease 2.5MHz waveform voltage to zero.
4. Merge the new batch into the Stack.

Store

Antiprotons are stored within a barrier bucket system. The stored antiproton phase space volume and intensity are maintained with Stochastic Cooling.

Extract

Antiprotons are unstacked longitudinally in the Recycler. For a detailed description of the unstacking and extraction process see http://beamdocs.fnal.gov/DocDB/0009/000933/002/rr-mmmining-v2.pdf

Operational Responsibilities

To perform the outlined scenario in the context of Run II operations, the Recycler department shall take the following responsibilities:

1. Determine and request from the MI the beam position, angle and energy at the exit face of the extraction Lambertson magnet of the MI.
2. Determine and maintain the optimal settings for the injection and extraction transfer line components between the MI and Recycler closed orbits.
3. Determine and maintain the optimal Recycler closed orbit, cooling and RF system settings for antiproton storage.
4. Set the beam position and angle at the injection in the MI based on the MI department request.
5. Work closely with the MI department to maintain longitudinal emittances by matching RF bucket areas and phasing.

Parameter Measurement

The Recycler performance parameters and measurement techniques are listed.

1. **Transverse emittance** is reported as the normalized transverse emittance containing 95% of the beam.
    a. This is monitored using the 1.75 GHz Schottky detectors.

   b. This is measured destructively with either a scraper or flying wire to unambiguously determine if a performance criterion has been met.
2. **Beam lifetime** is measured
   a. in the absence of cooling as **zero-zero beam** lifetime or the initial derivative of the beam current vs. time for a zero-current ($<0.5\times10^{10}$ particles), zero-emittance ($<4\ \pi$ mm-mrad) beam.
   b. with cooling as an exponential fit to the beam current as measured by a DCCT based on a sample time ≥ 1 hour.
3. **Longitudinal emittance** is measured as the product $\Delta E\cdot\Delta T$. ΔE is the beam energy spread containing 95% of the beam as measured by the 1.75 GHz Schottky detectors; ΔT is the bunch length.
4. **Longitudinal emittance dilution** for a Recycler RF manipulation is the difference between the longitudinal emittance before and after the manipulation is performed.
5. **MI ↔ Recycler transfer performance** will be measured for the round-trip transfer of a single batch $\geq 10\times10^{10}$ antiprotons from the Main Injector to the Recycler and back again within 1 minute. The beam emittance measured by the Main Injector flying wires before leaving the Main Injector shall be $\leq 10\ \pi$ mm-mrad ($\varepsilon_L \leq 10$ eV-s). The round-trip **transfer efficiency** MI-RR-MI is measured by the MI DCCT. The round-trip **transverse emittance increase** is measured by the MI flying wires. This performance parameter can be also demonstrated by having the round trip process RR ->MI ->RR. The method to measure the emittances would remain the same.
6. **Gated cooling performance** will be demonstrated in the following manner:
   a. The Accumulator holds about 30E10 antiprotons in a 10 eV-s, 10 π mm-mrad phase space volume.
   b. The Recycler has a cold stack of antiprotons (being cooled by a stochastic cooling system). The stack size should be reasonably high: 50-100E10.
   c. A small portion of antiprotons (about 5E10) is transferred to the Recycler to verify orbit closure and transfer sequences. This portion is added to the stack.
   d. The Accumulator returns to stacking.
   e. Thirty minutes later, 22E10 antiprotons with 10 eV-s, 10 π mm-mrad emittances are transferred to the Recycler in a single shot.
   f. This batch is then cooled and merged as described in Section 2.c below.

Performance Criteria

To make these criteria unambiguous, they shall be met with antiprotons while the MI is operating with only stacking cycles spaced by at least 1.6 seconds.

1. Machine Readiness

These are the basic requirements to be met to proceed with the commissioning of the machine.

a) Vacuum

Transverse emittance growth ≤ 6 π mm-mrad /hr measured destructively for zero-zero beam without cooling.

b) Vacuum and Machine Acceptance

Beam Lifetime ≥ 150 hr measured with zero-zero beam without cooling.

2. Performance @ 100×10^{10} with cooling and Batch Intensities ≥ 10×10^{10}

a) Cooling, Intensity Effects, Vacuum and Machine Admittance

Beam lifetime ≥ 100 hr and transverse emittance ≤ 10 π mm-mrad.

b) MI ↔ Recycler Transfer Performance

The round-trip transfer efficiency MI-RR-MI (or RR-MI-RR, if developed) shall be ≥ 85%. The round-trip transverse emittance increase of the beam shall be ≤ 3 π mm-mrad.

c) Recycler transfers with gated cooling

- The transfer efficiency between the MI and the Recycler for a single 22E10, 10 eV-s, 10-π mm-mrad antiproton batch should be >85%;
- Longitudinal phase-space manipulations should be accomplished in less than 5 minutes;
- Gated transverse stochastic cooling should bring the initial emittance to below 10-π mm-mrad in less than 20 minutes;
- Merging the new batch with the stack and getting ready for the next injection should take less than 5 minutes.

d) Extraction

9 batch extraction, a complete Tevatron fill, shall not exceed 30 minutes. Only particles within 54 eV-s (as measured in the MI at 8.9 GeV/c) phase space shall be extracted. For ≥ 100×10^{10} antiprotons in a 100 eV-s stack, not less than 45% shall be extracted. This criterion may change if the 2.5-MHz acceleration in the MI becomes efficient.

3. Equilibrium Beam Properties @ 200×10^{10}

The Recycler should be able to accumulate ≥ 200×10^{10} particles and maintain the stack within a 10 π mm-mrad ×100 eV-s phase space volume. This is not a requirement but rather a test of ultimate properties of the Recycler stochastic cooling system.

4. For comparison only: Final Run II Equilibrium Properties @ 600×10^{10}

Contingent upon the availability of 20×10^{10} antiprotons for transfer to the Recycler every 30 minutes within a 10 π mm-mrad ×10 eV-s phase space volume, the Recycler will accumulate ≥ 600×10^{10} particles and maintain the stack within a 10 π mm-mrad ×50 eV-s phase space volume.