Accelerator Division Impact Statement for the TAPAS Proposal

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Abstract

The various impacts on the Fermilab accelerator complex of the implementation of the TAPAS (The AntiProton Annihilation Spectrometer at Fermilab) proposal are enumerated and assessed. The impacts considered include: the required preparations and changes to the Fermilab Accelerator complex, the impact on NOνA, Mu2e, and Muon g-2 operations, and the resources required to support TAPAS preparation and operation.

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1 Introduction

The TAPAS collaboration proposes the use the Fermilab Antiproton Source Accumulator as the venue for a facility to study medium-energy antiproton physics at Fermilab [1]. The proposed experimental approach is very similar to that of previous high energy physics experiments that have been undertaken in the Accumulator [2], [3]. The TAPAS experiment will deploy several different targets – both hydrogen and nuclear – in the Accumulator vacuum chamber in the A50 straight section. The detector and associated apparatus will be located in the AP50 pit, which was formerly constructed for Fermilab experiment E760. The TAPAS detector consists primarily of the E835 lead-glass calorimeter, a 1 T solenoid, and several small inner detectors (Figure 1).

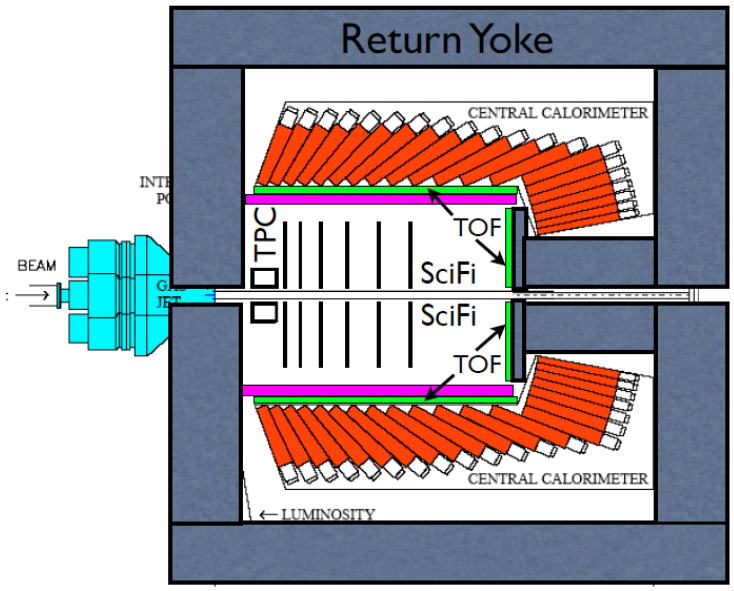

Figure 1: The TAPAS experimental apparatus is an upgraded version of the E835 detector consisting of: a 1T solenoid surrounding fine-pitch scintillating-fiber detectors, surrounded by precision TOF counters, all within the existing E760/835 Central Calorimeter. The current apparatus baseline also includes a small Time Projection Chamber and a return yoke.

A typical TAPAS operational cycle consists of 1) accumulating an antiproton stack of between 50 and 100 mA, 2) decelerating the accumulator beam to a central orbit momentum chosen by the experiment, 3) initiating $\bar{p}p$ or $\bar{p}N$ collisions by inserting (or turning on) the target, and 4) data taking until the beam intensity decreases to the minimum usable intensity.

Generally speaking, running TAPAS requires antiproton stacking and the ability to decelerate and operate the Accumulator at a large range of beam momenta below the nominal stacking momentum of 8.9 GeV/c. The Accumulator core stochastic cooling systems must also be operational at all accessible beam momenta.

The Antiproton Source is presently configured for antiproton stacking. Moreover, the required mode of operation has been successfully employed at Fermilab on several occasions in the past. Therefore, while the preparations are not trivial, the TAPAS proposal represents a relatively minor upgrade of the present facilities and capabilities[*].

2 Required Preparations for TAPAS

Since it is likely that a TAPAS run would take place after NOνA operations begin, some consideration must be given to the use of the Main Injector for antiproton stacking during NOνA operations. Also, for a variety of reasons, the Accumulator has not been able to decelerate and cool beam at lower energies since the end of the last E835 running period in 2000.

Thus, preparations for TAPAS consist primarily of 1) modifications to antiproton stacking to accommodate NOνA, and 2) recovering the ability to decelerate and cool the Accumulator antiproton beam. There are also various beam measurements and parameters that must be made accessible to the experiment's data acquisition system. These matters are discussed in this section.

1.1 Antiproton Stacking

The present average antiproton stacking rate of approximately 26 mA/hr is more than sufficient to meet the requirements of the TAPAS proposal. However, it is likely that modifications to the way the Main Injector is utilized for antiproton stacking will degrade the stacking rate by as much as 10-15%. Even with this reduction in stacking capability, antiproton stacking for the TAPAS experiment is eminently feasible. However, some accommodation must be made for the changes to the accelerator complex that are planned for the NOνA experiment.

1.1.1 Use of the Main Injector for Antiproton Stacking

During Collider Run 2 antiproton stacking was done in conjunction with the NuMI experiment. Proton batches from the Booster were slip-stacked in the Main Injector and accelerated to 120 GeV and extracted to the antiproton production target. For each pair of slip-stacked batches sent to the Antiproton Source, 9 additional batches were slip-stacked and extracted to the NuMI target[†].

During the NOνA era, slip-stacking will be accomplished in the Recycler Ring rather than in the Main Injector. In this case, 11 proton batches will be slip-stacked into five "double-batches" plus one additional single batch. .All of these proton batches are then extracted from the Recycler to the Main Injector for acceleration to 120 GeV. Four double batches plus the single batch would be extracted to NOνA and one double-batch would be extracted to the antiproton

[*] The required upgrade is minor in comparison to the proposed reconfiguration proposed by the Mu2e and Muon g-2 experiments.

[†] Of the 9 NuMI batches, 8 are slip-stacked in to 4 "double-batches" and the final 9th Booster batch is injected after slip-stacking of the first 8 is complete.

production target. Even though the Recycler Ring can accommodate seven proton batches around its circumference, only 5½ batches can be slip-stacked. The empty slot for the 7th batch provides a gap in the beam the Recycler extraction kicker to fire, as well as the longitudinal space required for slip stacking. Therefore, any "double-batch" sent to the antiproton target must be one of the six that would otherwise go to NuMI. *Stacking antiprotons for TAPAS will require protons that would otherwise be available to NOνA.*

1.1.2 Accelerator Timeline

During NOνA operations, the accelerator timeline will be a super-cycle of length 4/3 sec, consisting of twenty 1/15 Hz ticks, each of which may contain a Booster proton batch. Twelve of these batches are slip-stacked into six "double-batches". In principle, any number of these six double-batches could be extracted to the antiproton target. The optimal number is determined by the time required for the Antiproton Source stochastic cooling systems to act on the incoming antiprotons from the new batches.

During Collider Run 2, the optimal time interval between slip-stacked proton batches (for stack sizes less than ~80 mA) was 2.2 sec. The stacking rate rapidly degrades as the cycle time is reduced from 2.2 sec. Thus, it would appear that the optimum timing during NOνA operation would be an interval of two super-cycles (2.667 sec). This is a 20 % increase from the optimum determined from past performance. The degradation in the stacking rate will be significantly less than 20% since the stochastic cooling will perform much better with the longer cycle time, partially compensating for the loss of proton flux on target.

Accelerator timelines will have to be constructed of modules containing multiple 4/3 sec super-cycles. Every other module (or fewer) will send one of the six double batches to the antiproton target rather than the NOνA target. Such modules will be required for Switchyard beam as well.

1.1.3 Target Station Support

The continued use of the Antiproton Source target station will require the resumption of mechanical engineering support for target station components. While some spare components remain after the completion of Collider Run 2, the pbar target station group will need to resume production of spare targets, lithium lenses, and pulsed magnets. This requirement is not unique to TAPAS. The Antiproton Source target station will also be used (with some modifications) for the g-2 experiment.

Near the end of Collider Run 2, the antiproton target dump developed cooling water leaks in each of its two independent cooling coils. Any future use of the Antiproton Source target station will require the repair or replacement of this beam dump.

1.1.4 TAPAS DETECTOR PROTECTION

The TAPAS detector will be located in the Accumulator ring A50 straight section, across the aisle from the Debuncher injection straight section. It is at this location in the Debuncher that secondary particles from the AP2 beamline are injected into the Debuncher during antiproton stacking. While stacking, there is a considerable muon flux produced by the decay of pions produced from the antiproton target and transported down the AP2 line. This muon flux will be directed toward the vicinity of the TAPAS detector. The muon flux and radiation from Debuncher injection losses will cause the lead glass in the TAPAS central calorimeter to darken. Steps must be taken to minimize this radiation. In previous E835 runs the detector was shielded by a large number of concrete shielding blocks installed in the aisle adjacent to the detector. Since the proton flux on the antiproton target has increased by a factor of 2[‡] since the last E835 run, the issue of radiation damage to the calorimeter will be more urgent.

1.2 Deceleration

Perhaps the most time consuming element of preparation for TAPAS is the recovery of the ability to decelerate the beam in the Accumulator Ring. During the 1999-2000 E835 run, 141 Accumulator devices were controlled for each deceleration [4]. The ramp tables for each of these devices must be calculated [5], [6]. Previously developed ramp tables may be useful as a starting point. However, subsequent changes to the Accumulator lattice and associated equipment require much of this work to be redone.

The lowest beam momentum achieved for the E760 and E835 experiments was approximately 3.4 GeV/c (E760 η_c scan). The TAPAS proposal requests running at beam momenta as low as 1.6 GeV/c ($\Lambda\overline{\Lambda}$ running). It is very likely that beam momenta this low are unachievable in the Accumulator. There are multiple issues at low energies: power supply stability, beam lifetime with target on, stochastic cooling performance. A study will need to be undertaken to determine the lowest beam energy feasible in the Accumulator Ring.

1.2.1 DECELERATION RAMP DEVELOPMENT

Preparations for Fermilab experiments E760 and E835 have always required a lengthy period (several months) of beam studies to adapt the calculated ramps to actual beam conditions. Each row in the deceleration ramp tables requires something of a re-commissioning of the Accumulator at the beam energy associated with that row. This is a rather long and tedious process.

Additionally, a significant amount of software must be developed to facilitate beam decelerations and ramp development studies. Because many devices must be simultaneously set at each point the ramp, a dedicated front-end computer (previously called PAUX) has been used

[‡] The increase is primarily due to the implementation of slip-stacking during Collider Run 2.

to control decelerations[◊]. This computer no longer exists and therefore must be re-instated. The ACNET control system has evolved significantly since the most recent implementation of the PAUX front-end, thus much of the PAUX software must be rewritten.

Software tools would also need to be developed to facilitate parsing and correcting the deceleration ramp tables during deceleration beam studies. Sequencer compatible software must be written to automate the deceleration process for beam studies and for physics data taking.

1.2.2 Stochastic Cooling

The Accumulator core stochastic cooling systems will be required to operate at all beam energies of interest to overcome the large transverse and longitudinal emittance dilution caused by the TAPAS target. Two issues must be addressed to restore the Accumulator core cooling systems to the multi-energy capability required for TAPAS: 1) provision must be made for momentum cooling on the central orbit, and 2) provision must be made to increase the pickup to kicker time delays by tens of nanoseconds to accommodate the longer beam revolution periods as the beam is decelerated.

During antiproton stacking the Accumulator core cooling systems operate on the core orbit (low energy side of the Accumulator momentum aperture). During deceleration and TAPAS data taking, the antiproton beam will circulate on the central orbit and thus, the core cooling systems must be configurable to operate on the central orbit. In previous E760 and E835 runs, the beam was moved to the center of the momentum aperture after stacking was complete and then decelerated on the central orbit to the energy of interest. The decelerated beam was then cooled in all three dimensions on the Accumulator central orbit. Momentum cooling was accomplished with a core 2-4 GHz system that allowed cooling on the central orbit by means of a second set of pickups that were centered on the central orbit. There was also a 4-8 GHz momentum cooling system that utilized a pickup that could be moved from the core orbit to the central orbit.

After the 1999-2000 E835 run the central orbit pickup for the 2-4 GHz momentum cooling system was removed. Also, as a consequence of the Accumulator lattice upgrade prior to Collider Run 2, the 4-8 GHz moveable momentum pickup can no longer be moved all of the way to the central orbit. Both of these momentum cooling systems will be required for TAPAS. Therefore, the 2-4 GHz momentum cooling central orbit pickups must be reinstalled. The 4-8 GHz moveable momentum pickups will either have to be modified to increase their reach (difficult) or provision will have to be made to decelerate and run off of the central orbit (problematic, but probably doable).

The timing of the stochastic cooling systems must be adjustable to accommodate the longer revolution period as the beam energy is decreased. In the past this was accomplished by means of a system of switchable delays that allowed the insertion of as much as 64 nsec of delay in the

[◊] The use of ramp cards has been considered. Due to the number of ramp cards required, the cost would be large. Developing and managing the large number of ramps would be difficult.

electrical transit time from pickup to kicker. These switchable delays were removed after the 1999-2000 E835 run. These delays must be reinstalled and upgraded for TAPAS running. The TAPAS proposal requests running at beam momenta as low as 1.6 GeV/c. If running with such a low energy is possible, a total delay of ~115 nsec would be required. The longest delay of the previously used switchable delays was ~64 nsec.

The operation and maintenance of stochastic cooling systems depend on an expensive assortment of test equipment. The principle tool for setup and tuning stochastic cooling systems is the microwave network analyzer. The network analyzer presently in use by the Antiproton Source is very old (decades) and out of date. If TAPAS is approved, it is likely that this piece of equipment will need to be replaced.

1.2.3 TRANSITION CROSSING

The nominal transition energy of the Accumulator is approximately 5930 MeV. This corresponds to a fixed target center of mass energy of 3590 MeV. The energies of interest to TAPAS range from a beam energy of 4400 MeV to 8900 MeV. Therefore, the ability to decelerate the beam to energies below transition must be developed. There are two approaches that have been utilized in the past for E760 and E835: 1) Decelerate to an energy just above transition using ramps that preserve the stacking energy lattice down to the Accumulator transition energy; cross transition with a set of ramps that lower γ_t without changing anything else; continue deceleration below transition with ramps that preserve the lower γ_t lattice; or 2) Decelerate using ramps that lower the γ_t of the lattice as the beam energy decreases. These ramps keep the transition energy of the Accumulator always below the beam energy. It is likely that some combination of both of these approaches would be utilized for TAPAS decelerations.

1.2.3.1 Fixed γ_t deceleration

The procedure for deceleration with ramps that maintain a constant γ_t is the following:

1. Decelerate to an energy just above transition
2. Cool the beam above transition
3. Load and execute the ramps that lower γ_t
4. Cool the beam below transition
5. Load the below transition ramps and decelerate to the energy of interest

The procedure above can take a long time (hours) to complete since cooling near transition is very slow. More importantly, it has proven to be very difficult to cross transition with a large amount of beam. Previous attempts to cross transition in the Accumulator for experiments E760 and E835 have failed to transmit a beam intensity of more than 20 mA through transition. The extent to which this can be improved upon is not known.

1.2.3.2 Variable γ_t deceleration

The lowest beam energies required by the physics program of the last E835 run were only slightly below the nominal Accumulator transition energy. To simplify beam operations, the decision was made to lower the Accumulator γ_t as the beam was decelerated (see ref. [2]). The resulting γ_t and η ramps are shown in Figure 2. An attempt was made to keep the Accumulator lattice as constant as possible over the energy region of physics data-taking. Thus, the value of γ_t was ramped downward very early in the deceleration, and maintained constant thereafter. The execution of these ramps is very fast compared to the fixed γ_t ramps (minutes vs. hours).

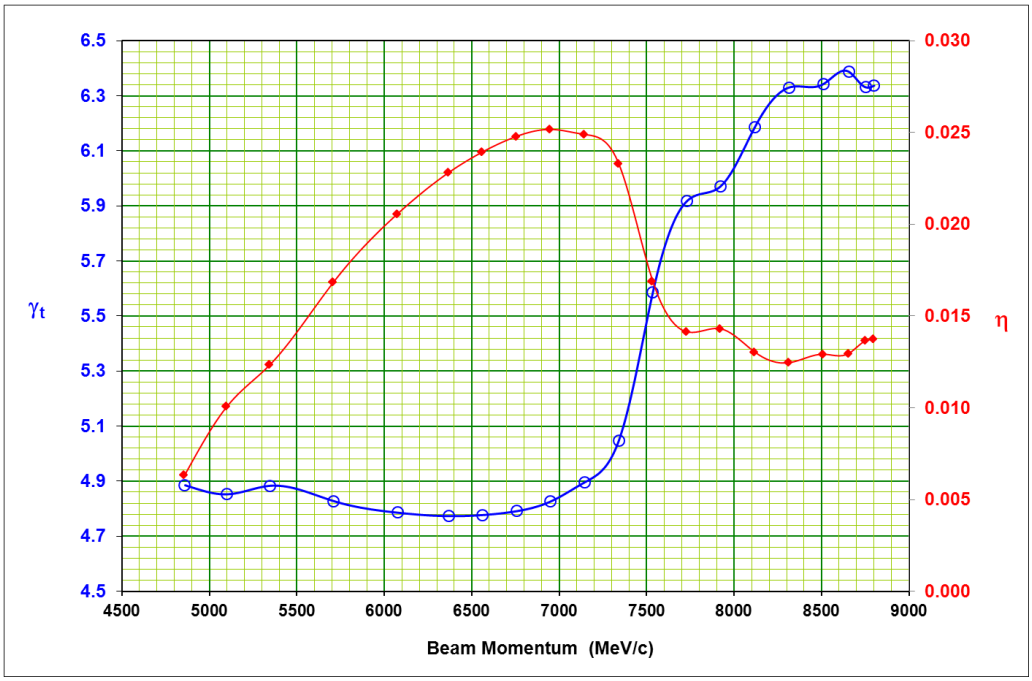

Figure 2: γ_t and η ramps for a variable γ_t deceleration

Since the energies of interest to TAPAS span a large range, it appears that transition crossings are inevitable. The likely strategy will be to develop variable γ_t ramps for above transition deceleration and fixed γ_t ramps for deceleration below transition. A set of transition crossing ramps will also need to be constructed. The development of these ramps will require a significant amount of beam study time.

1.3 Beam Energy measurement

Much of the TAPAS physics program requires a precision measurement of the beam energy and energy distribution. Software to measure the beam energy is required for the accelerator control system, for the TAPAS data acquisition system, and for the TAPAS offline analysis software. The code to calculate the beam energy is available for reuse from previous E760 and E835 runs [7]. However, the code to incorporate this calculation into the present accelerator control system and TAPAS software will need to be completely rewritten.

The beam energy measurement depends on the Accumulator Beam Position Monitor (BPM) system as well as the Accumulator longitudinal schottky detector and associated instrumentation. The Accumulator BPM system is ten years old and is uniquely different from other BPM systems at Fermilab. Some effort will be required to support this system for use by TAPAS.

1.4 TAPAS Operations

The preparations for TAPAS enumerated above will require a significant amount of effort from Physicists, Engineering Physicists, Engineers, and Software developers. The day-to-day beam operations for TAPAS will also require substantial effort. The operational cycle for TAPAS consists of stacking antiprotons, deceleration of the Accumulator beam, and physics data taking. Frequently a stack will require subsequent decelerations to alternative energies. During data-taking, intervention is often required to maintain constant beam energy.

The MCR operations crews are very familiar with stacking, so that part of the TAPAS cycle will be handled primarily by the MCR crews. Decelerations will require supervision by physicists and engineering physicists from the Muon Department. In the past, the deceleration software and procedures eventually became sufficiently well-developed that the operations crews could undertake above-transition decelerations and beam monitoring during data taking without supervision. Decelerations below transition, however, have always been problematic and will probably always require the supervision of a physicist or engineering physicist from the Muon department.

Operation of TAPAS will require support from the pbar target station group of the Accelerator Division Mechanical Support department. The target station group will be required to produce spare target station components and to replace components as they fail.

TAPAS will also require support from the Accelerator RF department for trouble-shooting and repairing RF and stochastic cooling equipment.

3 Impact on NOνA, Mu2e, and Muon g-2 activities

Beam operations for TAPAS preclude the running of the Mu2e and Muon g-2 experiments. These experiments must be run sequentially since the configuration of the Antiproton Source is significantly different for each experiment. If TAPAS is approved, it naturally precedes g-2 and Mu2e since the Antiproton Source is presently configured for antiproton stacking. Both Mu2e and g-2 require the removal of a large number of Accumulator quadrupole magnets. Mu2e and g-2 preparations also involve removing all of the stochastic cooling systems and much of the present RF infrastructure from the Accumulator and Debuncher. It would be extremely difficult and costly to reinstall and re-commission these systems if TAPAS were to run after Mu2e or g-2.

If TAPAS were to run first, and if the appropriate human resources are made available, preparations (deceleration ramp calculations) could begin immediately. The preparations not

requiring beam would very likely be complete by the end of the NOνA shutdown; at which point deceleration ramp development with beam could commence. Ramp development will likely require at least three months of beam studies (possibly longer depending on the availability of beam for deceleration studies). Thus, accelerator commissioning activities for TAPAS could be complete as early as late 2013. This is consistent with the schedule given in the TAPAS proposal.

If approval were granted, significant resources would have to be shifted from the Mu2e and g-2 projects to preparations for TAPAS. This would insert a delay into the schedules for Mu2e and g-2.

The present g-2 schedule plans for CD-2 in early 2014. Thus, a TAPAS run in 2014 would interfere with the implementation phase of the g-2 project. g-2 implementation would not be able to start until the completion of the TAPAS run. This delay would also propagate into the Mu2e project schedule.

It is clear that undertaking TAPAS will require a significant shift in Accelerator Division priorities and the insertion of significant delays into the Mu2e and g-2 project schedules.

4 Conclusions

If the TAPAS proposal were to be implemented, the impact to the Fermilab accelerator complex would be minor by comparison to the significant reconfigurations being planned for the Mu2e and Muon g-2 projects. However, the impact is still significant.

The preparations will require a substantial effort from Muon Department physicists and engineering physicists as well as engineering support from the Mechanical and RF departments in Accelerator division. The preparations include extensive software development, the calculation of deceleration ramps, target station preparation, and stochastic cooling system modifications. Also required is a substantial amount of beam study time for deceleration ramp development. The redirection of resources to accomplish these tasks would insert significant delays into the Mu2e and g-2 project schedules.

Operation of the TAPAS experiment will also require significant resources. All of the resources required to support antiproton stacking during collider running will be required to support TAPAS. Additionally, significant Muon Department physicist and engineering physicist effort will be required to support beam decelerations for TAPAS data taking.

5 Acknowledgements

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