FINAL REPORT
FOR CRADA NO. C-05-22
BETWEEN
BROOKHAVEN SCIENCE ASSOCIATES
AND
NANO-LIFE SCIENCES, INC.

Project Entitled: Conceptual Design of an Antiproton Generation and Storage Facility

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Memo

Date: December 21, 2009

To: M. J. Furey

From: S. Peggs

Subject: CRADA No. BNL-C-05-22 Between BNL and Nano-Life Sciences,
"Conceptual design of an Antiproton Generation and Storage Facility."

The term of the subject CRADA expired as of April, 2006. Nano-Life has since ceased operation, after the suicide of its CEO. This memo serves as the final abstract of the \$200k CRADA, while the document "*The Antiproton Generation & Storage Facility: A Study*" serves as its final report.

Significant accomplishments. BNL and AES worked with Nano-Life to prepare the aforementioned study.

Significant problems. This small CRADA was performed with relative ease and efficiency, notwithstanding the healthy skepticism that BNL and AES maintained as to the effectiveness and the ultimate business model of using anti-protons in hadron therapy for cancer.

Industry benefits. A first pass analysis of an AGSF has been performed, which could be built on and further pursued.

Laboratory benefits. A multi-disciplinary team was constructed and briefly activated, in the generation of the report. Lessons were learned from technical and sociological perspectives, even while it is unlikely that this work will be further pursued.

Recommended follow-on work. None.

Potential benefits from pursuing follow-on work. None.

The Antiproton Generation & Storage Facility: **A Study**

AES
BNL

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DRAFT date: October 19, 2005

Contents

1	Introduction	2
1.1	Baseline choices and options	2
1.2	Clinical Parameters and Performance	3
2	Trade Study Summary	7
3	Acceleration Linac	8
4	Main Ring	8
5	Proton Target and Antiproton Collector	12
6	Precooler	13
7	Accumulator	13
8	Deceleration Linac	14
9	Penning Trap	14
10	Transfer and Longitudinal Dynamics	14
10.1	Main Ring to Precooler	14
10.2	Precooler	14
10.3	Accumulator	14

1 Introduction

The Antiproton Generation and Storage Facility (AGSF) creates copious quantities of antiprotons, for “bottling” and transportation to remote cancer therapy centers. The schematic in Figure 1 shows the major components of the complex.

The first step in the generation and storage process is to accelerate an intense proton beam down the **Main Linac** for injection into the **Main Ring**, which is a Rapid Cycling Synchrotron that accelerates the protons to high energy. The beam is then extracted from the ring into a transfer line and into a **Proton Target**. Immediately downstream of the target is an **Antiproton Collector** that captures some of the antiprotons and focuses them into a beam that is transported sequentially into two antiproton rings.

The **Precooler** ring rapidly manipulates antiproton bunches from short and broad (in momentum) to long and thin. It then performs some preliminary beam cooling, in the fraction of a second before the next proton bunch is extracted from the Main Ring. Pre-cooled antiprotons are passed on to the **Accumulator** ring before the next antiprotons arrive from the target.

The **Accumulator** ring cools the antiprotons, compressing them into a dense state that is convenient for mass storage over many hours. Occasionally the Accumulator ring decelerates a large number of antiprotons, injecting them into a **Deceleration Linac** that passes them into a waiting **Penning trap**.

Figure 1: Schematic layout of the AGSF. The entire facility fits in a footprint of approximately ?? m by ?? m.

1.1 Baseline choices and options

Table 1 shows baseline values of the primary parameters of the AGSF, while Table 3 shows optional parameters. Here, in brief, are the advantages and disadvantages of the options.

Increasing the linac output energy from 800 MeV to 1200 MeV would increase the cost of the linac, but would decrease the cost of the main ring, and/or would enhance the ability of the main ring to deliver more protons on target. There is no significant technology risk.

The relative cost and performance advantages of superconducting versus room temperature RF in the linac have yet to be fully analyzed. It is worth noting that the 1 GeV proton linac at the Spallation Neutron Source used superconducting technology.

Increasing the pulse repetition rate of the main ring from 4 Hz to 5 Hz is mainly an issue of cost, through increased demands on the magnet power supply system and on the Radio Frequency (RF) acceleration system. There is also a technological risk with magnet and vacuum system performance. The number of antiprotons produced should increase proportionately, by 20%, except insofar as the performance of the debuncher ring might deteriorate slightly.

Increasing the number of protons per pulse from 2.5×10^{13} to 4.0×10^{13} is technologically aggressive, since there is a significantly increased heat load on the target, and beam dynamics in the main ring can suffer. A higher linac energy helps. The RF system is somewhat more expensive and the bore of many magnets may need to be larger.

The choice of copper for the critical proton target material is conventional, but brighter proton spots may be possible without thermal damage if other materials like iridium or inconel are used. Significant further study would be required if this issue were to need to be resolved in detail.

Preliminary indications are that a lithium lens is 20% to 30% more efficient at capturing antiprotons than a pulsed electromagnetic horn. Both technologies have proven sufficiently reliable in practice, although the lithium lens is more complicated and more user-unfriendly.

The so-called bottling efficiency – the probability of an antiproton making it from capture to Penning trap – is perhaps the least well known of all these parameters. The baseline value of 0.04 has been achieved, but it may be reasonable to achieve a value of 0.10 with a greend field design.

The bottling rate R – the number of antiprotons bottled per second – is given by

$$R = f N Y \eta \quad (1)$$

where f is the main ring pulse repetition rate, N is the number of protons per pulse, Y is the target yield and η is the bottling efficiency. The baseline parameters yield a rate of $R = 1.4 \times 10^7$ antiprotons per second. This rate which increases by a factor of five to become $R = 7 \times 10^7$ antiprotons per second if the most aggressive parameter set is assumed.

1.2 Clinical Parameters and Performance

Protons or other ions that enter a patient deposit much of their energy at the end of their range, in a sharp “Bragg peak”, as illustrated in Figure 2. This behavior gives protons a unique advantage over conventional radiation therapy with X-rays, electrons, or neutrons. The Bragg peak for neon (or Carbon) ions is sharper than for protons, enhancing their clinical desirability. However, ions other than protons deliver a significant dose beyond the sharp distal edge of the proton Bragg peak (beyond 16 cm in Figure 2), due to the creation of “knock-on” nuclear fragments. Protons also have the advantage of requiring far less bending magnetic field (measured in Tesla-meters) to achieve the same penetration.

Figure 3 summarizes our current understanding of antiproton dose distributions. The figure on the left shows data from an experiment at CERN, indicating a sharp cell-killing peak that is analogous to a Bragg peak, but which also contains relatively complex nuclear physics interaction. This holds the promise of an even sharper equivalent dose distribution curve, as sketched at the right.

The maximum number of treatment rooms M that can be operated in parallel at multiple therapy centers depends on the antiproton bottling rate R , the average tumor volume V , the average time per treatment T and the number antiprotons required per treatment D according to

$$M = \frac{RT}{DV} \quad (2)$$

This is a modest underestimate, since the uptime of the AGSF can be expected to be rather better than the uptime of a therapy center operating 16 hours per day.

Using the baseline numbers from Table 1, this yields only 2.8 rooms operating in parallel. In other words, the baseline performance is barely sufficient to generate enough antiprotons for a single therapy center. The most aggressive bottling rate of $R = 7 \times 10^7$ antiprotons per second is enough to supply 14 rooms in parallel.

Main ring circumference	[m]	1200
Main linac length	[m]	~ 300
Pre-cooler circumference	[m]	~ 240
Accumulator circumference	[m]	~ 240
Deceleration linac length	[m]	~ 30
Main linac output kinetic energy	[MeV]	800
Main ring pulse repetition rate, f	[Hz]	4
Main ring output kinetic energy	[GeV]	25
Pre-cooler momentum	[GeV/c]	3.5
Deceleration linac injection kinetic energy	[MeV]	~ 50
Target yield: antiprotons per proton, Y		3.5×10^{-6}
Protons per pulse on target, N		2.5×10^{13}
Bottling efficiency, η		0.04
Antiproton bottling rate, R	[Hz]	1.4×10^7

Table 1: Baseline primary parameters of the Antiproton Generation and Storage Facility.

Linac RF technology	Superconducting
Proton target material	Copper
Antiproton collector technology	Lithium lens

Table 2: Baseline technology choices.

Main linac output energy: option	[MeV]	1200
Main ring pulse repetition rate: aggressive	[Hz]	5
Protons per pulse on target: aggressive		4.0×10^{13}
Bottling efficiency: aggressive		0.10
Antiproton bottling rate: aggressive	[Hz]	7.0×10^7
Linac RF technology		Room temperature
Proton target material: option		Iridium, Inconel
Antiproton collector technology		Horn

Table 3: Optional primary parameters.

Figure 2: Dose distributions in conventional radiation therapy. LEFT: Protons and neon ions show sharp Bragg peaks, while X-rays and neutrons show poor surface penetration. RIGHT: A spread out Bragg peak accumulated by scanning the energy of a proton beam in 2 MeV steps.

Figure 3: LEFT: Survival and equivalent dose with antiprotons. LEFT: Survival data taken at CERN, showing a sharp cell-killing peak. RIGHT: Artists concept of equivalent dose versus depth for X-rays, protons and antiprotons.

Average tumor volume, V	[cc]	10
Antiprotons per cc per treatment, D		5×10^8
Average treatment time, T	[s]	1,000
Number of treatment rooms in parallel, M		2.8
Number of treatment rooms in parallel: aggressive		14

Table 4: Clinical parameters.

2 Trade Study Summary

A fundamental understanding of the layout of the AGSF is needed in order to properly reflect the inter-relation between system performance and cost. To support this, a modular EXCEL based system model was constructed that is capable of accepting upgrades (more detailed algorithms) for any of its major components. The baseline parameters shown in Table 5 are used throughout.

Antiprotons per treatment		8.4×10^8
Number of treatment per year		125,000
Antiproton yield per proton		3.5^{-6}
Main ring repetition rate	[Hz]	5
AGSF operation year (75% uptime)	[hrs]	6,575
Number of treatment centers		6

Table 5: Basic assumptions in all scenarios.

The first step is to calculate the antiprotons needed for each ATC. Using the assumptions above we arrive at 1.05×10^{14} antiprotons per ATC. Knowing we are targeting support of six ATC's yields a net demand for 6.3×10^{14} antiprotons from the AGSF.

To calculate the production required at varying stages of the AGSF we need to work backwards from the demand and make some assumptions concerning the efficiency of antiproton capture, deceleration, trapping, and storage. We expressed this as a total efficiency ratio (antiproton at the target per antiproton delivered to ATC) and assumed that this ranges from 1- to 25. For our scenario we have selected the efficiency rate from Taussig of approximately 2. In our current case that means we need 1.26×10^{15} antiprotons.

Now that the number of antiprotons produced from the target can be determined (based on the efficiency ratio selected) we can calculate the number of protons incident at the target (based on the target performance proton in to antiproton out). Currently we are using a generation rate (fixed) of 3.5×10^{-6} antiprotons per proton. For the case under examination this relates to a total of 3.6×10^{20} protons required.

In order to determine protons per pulse we first need total protons per second. We have taken the total number of seconds in a year and multiplied it by the percent of time the AGSF is operating and determined that at 75% uptime there are 2.36×10^8 seconds per year. This means 3.05×10^{11} protons per second are needed.

Knowing this incident flux on the target allows us to calculate the protons per pulse in the ring (for a particular repetition rate in the ring). Assuming a 5 Hz repetition rate, 6.1×10^{10} protons per pulse are needed to produce enough antiprotons to support six ATCs. This represents the number of protons per pulse needed from the ring, however there will be some loss of protons in the transfer from the Linac source to the ring, and ring to target. To determine the protons per pulse needed from the Linac the number from the ring is divided by 1 minus the loss factor. In our scenario assuming 80% of the protons produced in the Linac are transferred to the ring, then 7.63×10^{10} protons per pulse are needed. The power required to achieve this is dependent on the energies involved, and as such, is dependent on a specific configuration.

3 Acceleration Linac

4 Main Ring

The goal of the Main Ring is to accelerate protons to 25 GeV kinetic energy for efficient production of antiprotons upon hitting the target. The H^- ions accelerated by the linac are injected into the Main Ring at 800 MeV kinetic energy through charge-exchange injection, reaching intensity of 4×10^{13} per pulse. Longitudinally, these stripped ions (protons) are captured in 12 radio-frequency buckets. Upon the completion of injection, the magnetic fields of the Main Ring dipoles are ramped from 0.074 to 1.31 T. At the top energy, these 12 bunches are first debunched into a coasting beam and then rebunched and shortened through RF manipulations. The shortened proton beam is then extracted within one turn and transported to the target. This cycle repeats at a repetition rate of 5 Hz.

The average beam power in the Main Ring is 0.8 MW. At such beam power, beam loss induced radioactivation is a major concern. The tolerable uncontrolled beam loss is about 0.2% at extraction, and 5% at injection. Transition crossing must be avoided.

Proton beam power on target	[MW]	0.5
Main ring output kinetic energy	[GeV]	26
Pulse repetition rate	[Hz]	4
Average beam current on target	[μ A]	20
Protons per pulse on target		2.5×10^{13}
Radio Frequency gradient, V_{RF}	[kV/m]	13
Charge per pulse on target	[μ C]	4
Energy per pulse on target	[kJ]	100
Proton pulse length on target	[μ s]	4.12
Main ring circumference	[m]	1200
High energy beam transport length	[m]	~ 100
Filling time	[ms]	
Number of injected turns		
RF harmonic number, h		12
Number of bunches		12
Revolution frequency	[kHz]	210 - 250
RF frequency	[MHz]	2.52 - 3.00
Bucket filling fraction	[%]	67
Extraction beam gap	[ns]	> 200
Maximum uncontrolled beam loss rate	[W/m]	1

Table 6: Nominal parameters of the AGSF Main Ring

Proton magnetic rigidity (injection)	[Tm]	4.88
Injection β		0.8418
Injection γ		1.85
Proton magnetic rigidity (extraction)	[Tm]	86.46
Extraction β		0.9993
Extraction γ		27.65
Unnormalized 99% total emittance $\epsilon_H + \epsilon_V$	$[\pi\mu\text{m}]$	40+40
Ring betatron acceptance	$[\pi\mu\text{m}]$	100
Collimator acceptance	$[\pi\mu\text{m}]$	64
Peak RF voltage	[MV]	2
Vacuum chamber full-beam momentum acceptance	[%]	± 1
Bunching factor		0.23
Expected space charge tune shift		0.15
Maximum dipole field		1.305
Average bending radius	[m]	66.5
Arc module length	[m]	57
Arc module horizontal phase advance	[deg]	270
Straight section length	[m]	82
Transition gamma		31

Table 7: Optical and dynamical parameters of the AGSF Main Ring

Number of H frame sector dipoles		64
Dipole magnetic field	[T]	0.074 - 1.31
Dipole bend angle	[deg]	5.625
Dipole gap	[mm]	140
Dipole pole width	[mm]	
Dipole magnetic path length	[m]	6.5
Dipole radius of curvature	[m]	66.21
Dipole sagitta	[mm]	
Number of quadrupoles		144

Table 8: Parameters of the Main Ring magnets

Figure 4: Main ring layout. LEFT: schematic. RIGHT: geometric.

Figure 5: Optical functions through one arc and one straight (TOP) and entering one straight alone (BOTTOM).

5 Proton Target and Antiproton Collector

The target ...

Antiproton beam central momentum	[GeV/c]	3.5
Full captured momentum spread $\Delta p/p$	[%]	6.0
Target yield: antiprotons per proton		3.5×10^{-6}
Target material: nominal		Copper
Target material: option		Iridium, Inconel
Target length, L_T	[m]	0.07
Drift length (target to lens) L_D	[m]	
Lithium lens magnetic strength	[T/m]	700
Lithium lens length L_L	[m]	
Lithium lens active diameter	[mm]	
Debuncher ring acceptance	$[\pi\mu\text{m}]$	

Table 9: Nominal antiproton target and lithium lens parameters.

Figure 6: Geometry of the target and lens system.

6 Precooler

7 Accumulator

Figure 7: Schematic layout of the Accumulator.

8 Deceleration Linac

9 Penning Trap

10 Transfer and Longitudinal Dynamics

10.1 Main Ring to Precooler

10.2 Precooler

10.3 Accumulator

References

- [1] *Conceptual Design of the RCMS*, C. Gardner, S. Peggs (editors), internal document, March, 2003.