A MAGNETIC DEGRADING SPECTROMETER FOR TRAPPING OF LOW ENERGY ANTIPROTONS AT FERMILAB

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I. INTRODUCTION

On Aug. 19, 1998 G.A. Smith and S.D. Howe visited Fermilab for the purpose of briefing members of the Beams Division concerning scientific opportunities for low energy antiprotons confined in Penning traps. The meeting was hosted by Dr. Robert Noble, who has provided a Summary of the discussions and tours of facilities that followed the meetings. The Summary also references a significant repository of materials on low energy antiproton physics and applications, presented at the meeting and elsewhere. In the interest of keeping this proposal brief, the reader is asked to access these materials at Fermilab by first reading Appendix I. It is sufficient to say that the authors of this proposal feel that there are many exciting opportunities in the areas of antihydrogen and antimatter gravity physics, as well as in the areas of medical, plasma and space applications, to warrant building the beamline proposed herein.

II. ACCESSING ANTIPROTONS FROM THE MAIN INJECTOR

In our view, the most compelling option discussed on Aug. 19 (suggested by G. Jackson) was in the MI-8 Line (see Figure 1). Roughly 1 GeV/c (433 MeV) antiprotons decelerated in the Main Injector are extracted at MI-10 and transported in a relatively inexpensive beamline (perhaps permanent magnets) for 250 m back to the MI-8 service building. There they can be tansported up to ground level through the equipment hatch into a shielded area for final decleration in the magnetic degrading spectrometer and injection into a Penning trap. We have therefore considered a small emittance beam of 433 MeV antiprotons as a source for the magnetic degrading spectrometer, discussed in the next section of this proposal.

III. MAGNETIC DEGRADING SPECTROMETER

Figure 2 shows the proposed 433 MeV antiproton magnetic degrading beamline. The purpose of the spectrometer is to enrich the beam in low energy antiprotons over what would be realized with a single degrader. This is done by compression of longitudional (energy) phase space, as the expense of transverse emittance.

The beam passes through a 8.7 cm thick tungsten degrader, makes a - 45 degree bend in dipole magnet D1, passes through a second thin tungsten wedge degrader, makes a + 90 degree bend in dipole magnet D2, and a passes through a final ultra-thin degrader (an iris, which also serves as a radiation shield when antiprotons are not being loaded or unloaded) within the trap. For the purposes of this discussion, we assume the trap is HiPAT (High Performance Antimatter Trap), currently under development at the Propulsion Research and Technology Division, NASA Marshall Space Flight Center, Huntsville, AL (see Appendix II). The injection region of this trap is shown in Figure 3.

Antiprotons are swum through the degraders using the code TRIM to evaluate energy losses and scattering. Emerging antiprotons are swum through the magnetic spectrometer using the code TRANSPORT. The transport momenta in the two legs of the spectrometer are 300 and 200 MeV/c. Figure 4 shows ray traces from the simulation. The focus near z = 310 cm corresponds to the wedge degrader. The waist near z=450 cm corresponds to the final iris degrader located just outside the electrode structure of HiPAT, which produces 0-20 keV antiprotons which can be captured in the trap. The radius of curvature (60 cm) of D2 was chosen to reproduce the desired beam shape entering HiPAT.

Antiprotons which hit the iris degrader have momenta of 200 +- 9 MeV/c. Its thickness of 1 mm of stainless steel corresponds to the mean range of a 200 MeV/c antiproton. The probability for an antiproton which hits the foil to be degraded below 20 keV is 1.6 x 10^{-4}. Roughly half of the antiprotons stop in the iris degrader, while 99.97% of the antiprotons which emerge have energies above 20 keV and are not captured.

Trap electrode potentials are set to turn around antiprotons with less than 20 keV energy of axial energy at the far end of the trap. The down-and-back transit time for 20 keV antiprotons is about 400 ns, at which time the upstream electrodes are energized to complete the axial trapping. Radial confinement is provided by the 4 T axial magnetic field. Therefore, it is desireable that the incident antiproton beam have a pulse width of 100-200 ns. The behavior of individual antiprotons depends on where they originate within the fringe field of the 4 T solenoid and their energy. The efficiency for capture of 0-20 keV antiprotons has been simulated as a function of the distance of the iris degrader from the trap center. With the iris degrader positioned at 30 and 20 cm from the trap center, the capture efficiencies are 40 and 86 % respectively.

IV. YIELDS OF TRAPPED ANTIPROTONS

Table I shows calculated yields of trapped antiprotons per 2 x 10^{11} antiprotons incident on the first degrader.

Table I-Yields of Trapped Antiprotons

Incident no. of antiprotons	2 x 10^{11}
Fraction which survive annihilation in degraders	0.33
Geometrical acceptance of iris degrader	0.23
Fraction of antiprotons which degrades to < 20 keV	1.6 x 10^{-4}
Capture efficiency with iris degrader 30 (20) cm from trap center	0.40 (0.86)
No. antiprotons captured	1.0 (2.0) x 10^{6}

By comparison with calculations done with a single degrader placed in the throat of the trap, the spectrometer compresses the beam in energy by a factor of 16, but is accompanied by a factor of 4 increase in transverse emittance growth. Hence, the net gain in yield is about a factor of 4 over that of a single degrader.

V. OTHER CONSIDERATIONS

We are actively seeking funding for the magnetic degrading spectrometer. We are prepared to provide manpower for the installation of the spectrometer. On the other hand, we hope that it may be possible for Fermilab to be able to provide without significant expenditure the transfer line from the MI-10 extraction area to the MI-08 service building, using existing magnets and power supplies.

MI-8 Line

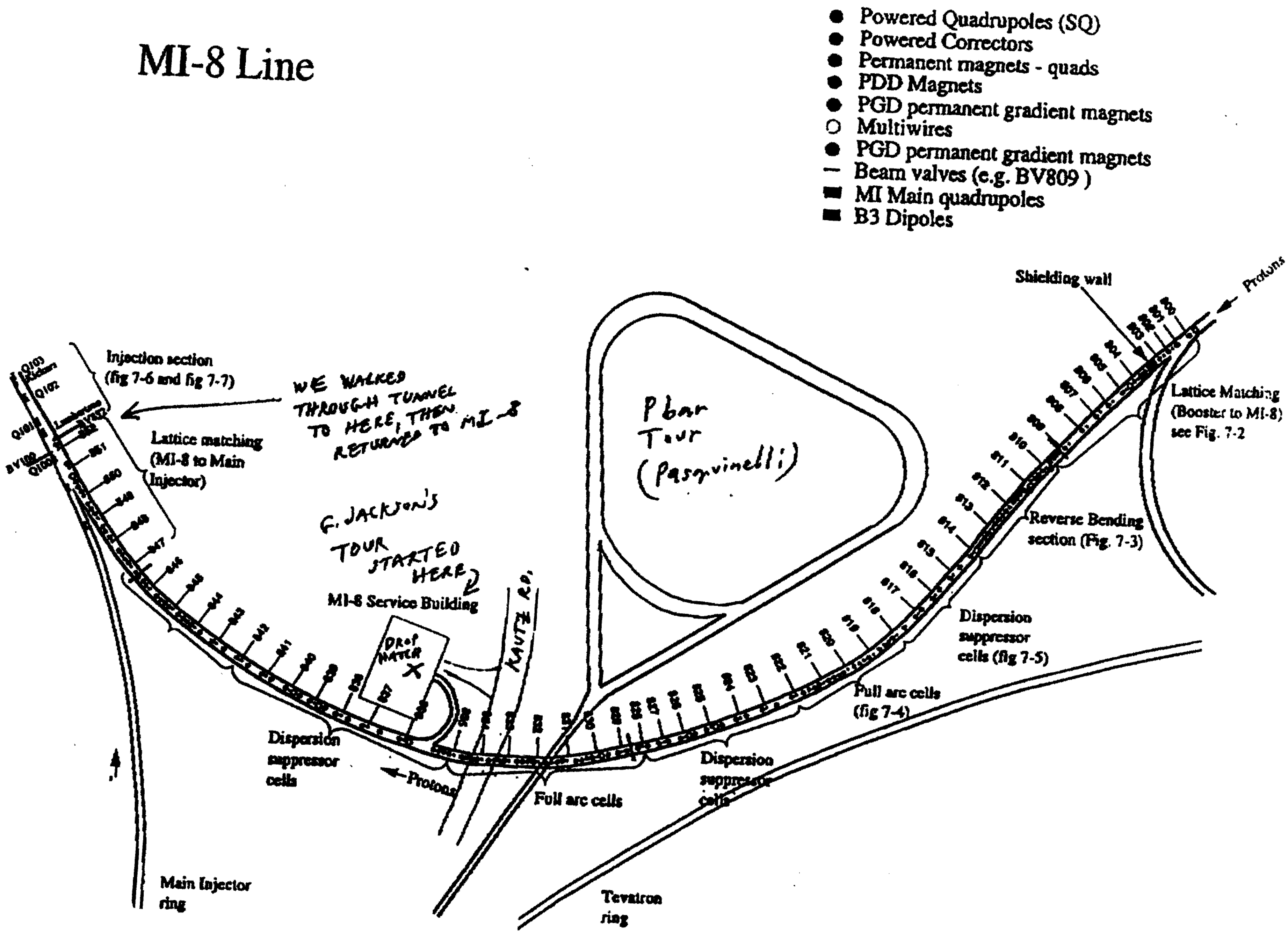


FIGURE 1

FIGURE 2

Antiproton Degrader/Accumulator Magnetic Spectrometer

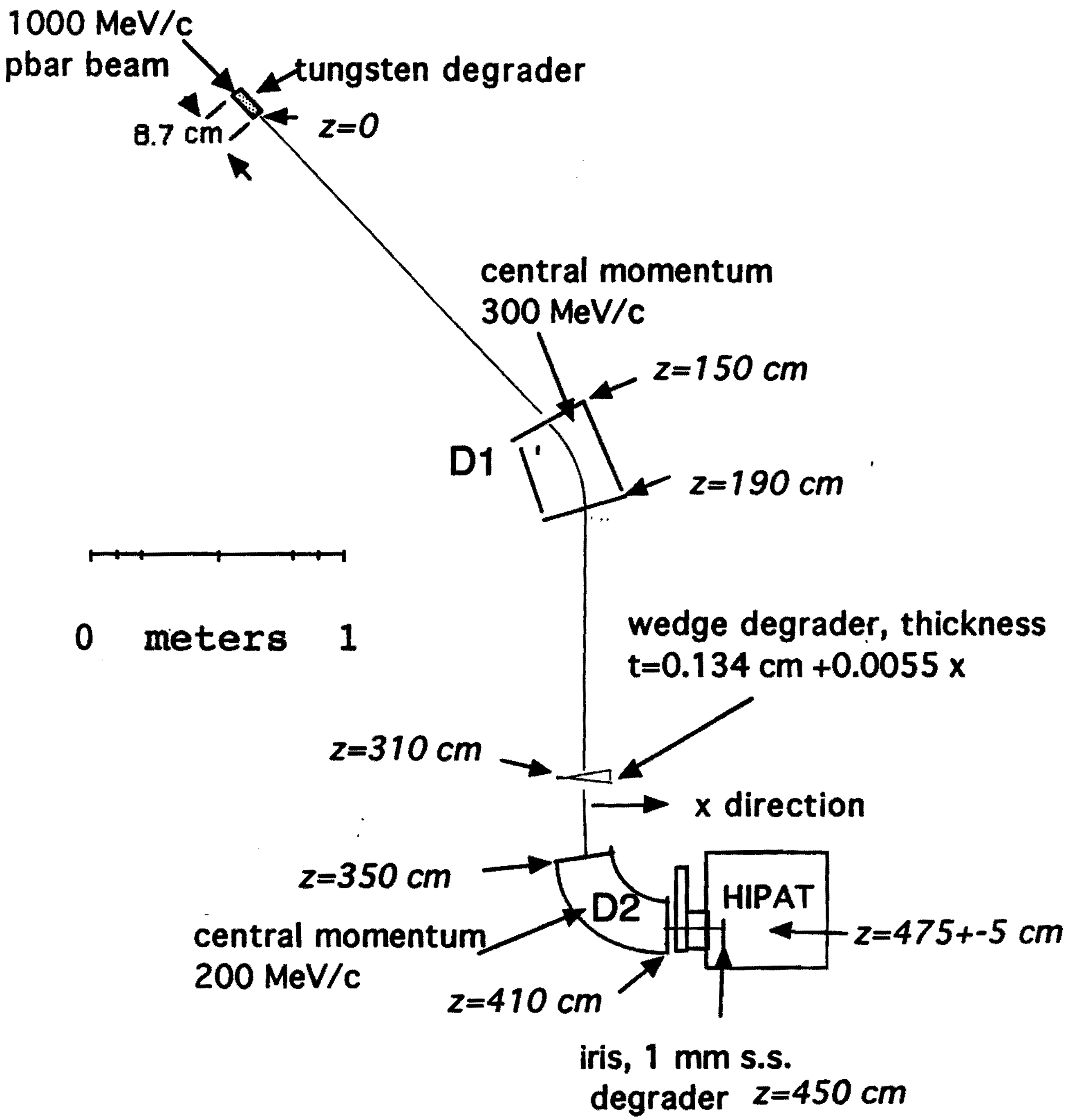
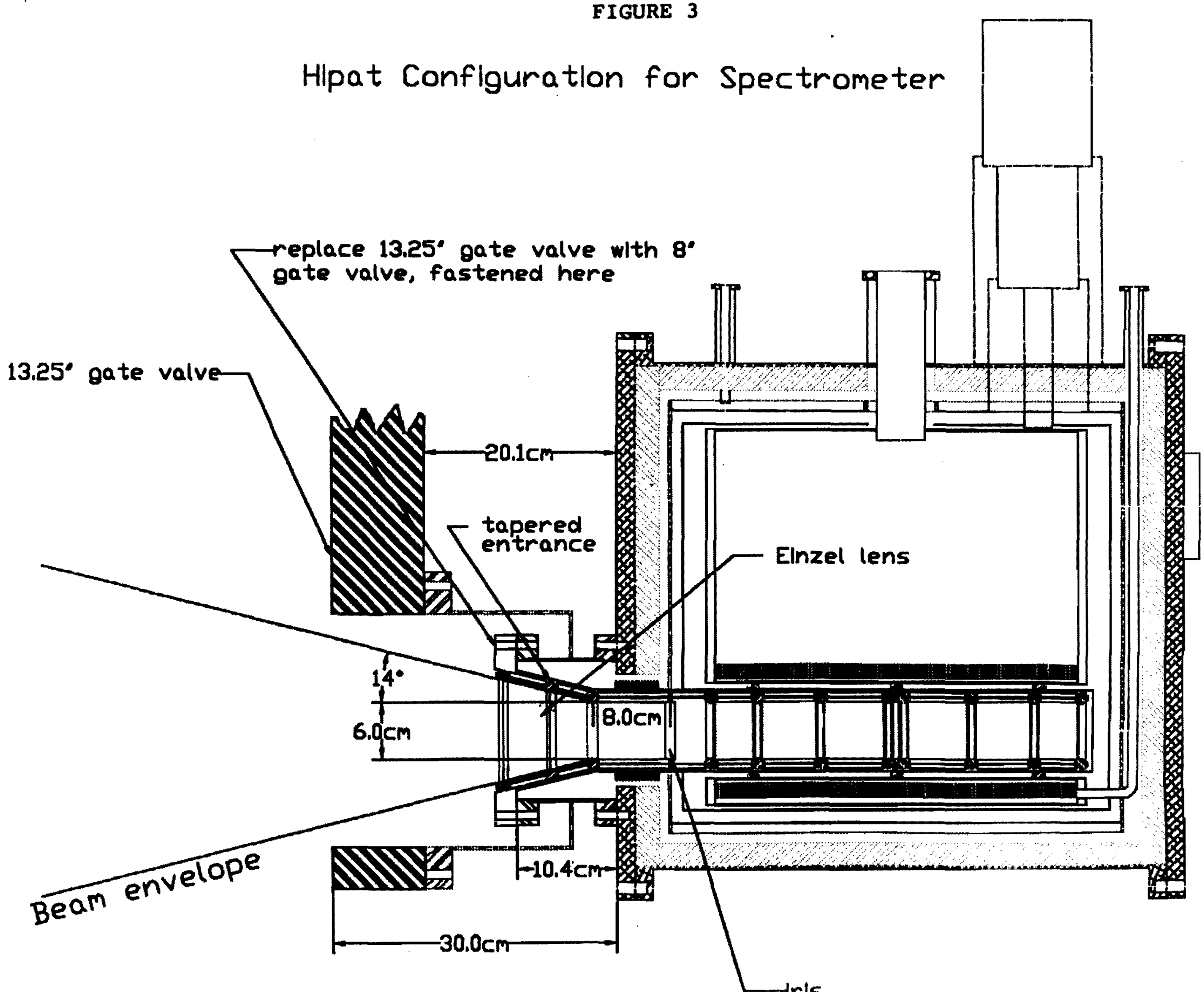


FIGURE 3

Hipat Configuration for Spectrometer



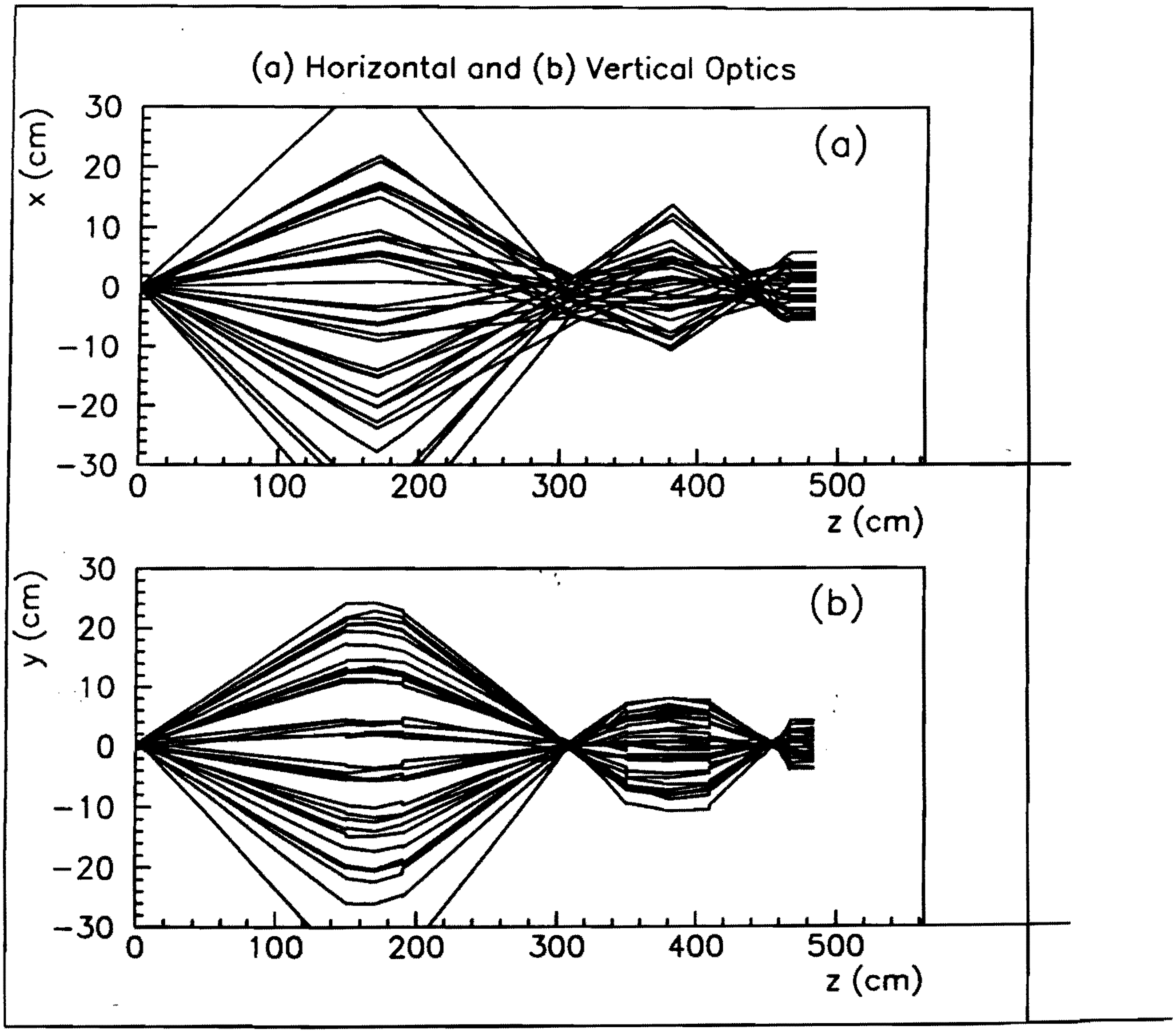

(a) Horizontal and (b) Vertical Optics
x (cm)
30
20
10
0
−10
−20
−30
(a)
0
100
200
300
400
500
z (cm)
y (cm)
30
20
10
0
−10
−20
−30
(b)
0
100
200
300
400
500
z (cm)

FIGURE 4

APPENDIX I

From: LEPS5::"noble@waldo.fnal.gov" 26-OCT-1998 11:17:50.37
To: lepsa::smith
CC:
Subj: LATEX file of Pbar Summary

```
% Pbar Meeting Summary (10/26/98 Version) - R. Noble, FNAL
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\textwidth 6.0in
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%\newcommand{\pgph}{\makebox[\parindent][c]{}}
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\begin{center}
\large{Summary of Discussions (R. Noble)}
\end{center}

 The purpose of this meeting was to receive a briefing from Prof. G.A. Smith
 and Dr. S.D. Howe on the need for low-energy antiprotons and antihydrogen
 in fundamental physics experiments and various applications including
 cancer/tumor treatment, customized short-life isotope production and
 high energy-density sources for space propulsion research, and to discuss
 the capability of the Fermilab complex to supply antiprotons for a staged
 Low-Energy Antiproton Facility serving users and customers from academia,
 government and industry. The meeting was attended by twelve Fermilab
 personnel. The agenda included in this transparency book was followed with
 the exception that
 tours occurred immediately after the meeting, and the Antiproton Ring tour
 led by R. Pasquinelli was followed by a tour of the Main Injector MI-8
 building and tunnel enclosure by G. Jackson. Copies of all transparencies
 presented by G. Smith and S. Howe are contained here, as well as some
 information on the CERN Antiproton Decelerator Project for reference. A
 companion set of papers on antiproton deceleration and applications was
 circulated before the meeting for the benefit of participants (ref.
 ``Selected Papers on Low-Energy Antiprotons and Possible Applications'',
 compiled by R. Noble, FNAL, 19 August 1998).

 Charged anti-particle production today is geared toward providing
 high-energy beams for exploring fundamental particle interactions.
 Only the CERN
 laboratory in Europe and Fermilab in the United States produce antiprotons
 (or ``pbars''). Motivated by the need to produce ever higher numbers of
 antiprotons for the high-energy physics program,
 Fermilab leads collection at $5\times10^{10}$ pbars per hour or 2 picograms
 of pbars
 per day. This will be increased by a factor of four by the year 2000.
 Antiproton collection efficiency is about $10^{-5}$ antiproton per proton on
 target due to both the kinematic difficulty in producing a heavy
 proton-antiproton pair and capturing the
 diverging pbar beam. Fermilab in fact produces several times
 more anti-particles than actually accumulated since many particles are
 lost transversely or have too large a momentum deviation to remain in the
 downstream transport and acceleration systems.
 Although charged anti-particles are routinely produced, only recently has
 antihydrogen been experimentally formed and observed in flight. The CERN
 experiment PS-210 reported observing 11 antihydrogen candidates in 1996,
 and the Fermilab experiment E862 reported 57 antihydrogen events in 1997.

 G. Smith presented plans for the Antiproton Decelerator (AD) project at
 CERN and the physics experiments to be done with antimatter. With the
 LEAR (Low-Energy Antiproton Ring) closed at CERN, the new AD project,
 funded by groups in the EU and Japan, is underway to fill the continuing
 needs of experimentalists. The AD will produce $10^{7}$ low-energy
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antiprotons
per one-minute cycle. Antiprotons will be decelerated from 3.5 GeV/c momentum at injection down to 100 MeV/c (5.3 MeV kinetic energy) in the AD by radio-frequency deceleration with an efficiency of 25 percent. (Note 1 GeV = 10^{9} electron volts, and 1 MeV = 10^{6} electron volts). Antiproton emittances in the AD will be reduced by both stochastic cooling and electron cooling which are essential to keep the beams small enough to avoid excessive beam loss during deceleration. Deceleration to keV energies is not supplied directly by the AD but is the responsibility of the experimentalists. This deceleration can be done with foils and/or gas cells at about 10^{-4} to 10^{-3} efficiency or with a radio-frequency
quadrupole (RFQ) accelerator at about 50 percent efficiency, though the latter is a costly device. AD physics start-up is scheduled for mid-1999. There are three approved experiments for the initial program, two involving antihydrogen and one that will form antiprotonic helium. The latter experiment will use an RFQ decelerator to slow pbars with high efficiency. Antihydrogen physics was recently featured in Physics Reports, Vol. 241 (1994), pp. 65-117. CPT violation via the comparison of antihydrogen versus hydrogen spectroscopy and the difference in the gravitational force between matter and antimatter are two fundamental topics.

For future precision physics experiments, medical applications and engineering applications, 10^{6} to 10^{12} antiprotons or antihydrogen atoms will be needed. These can be stored in magnetic traps for transport to other locations and use over extended periods. For antiproton collection, a so-called Penning trap is adopted by G. Smith and coworkers for the ATHENA experiment at the CERN AD. This is an electrostatic analog of a cylindrical magnetic bottle with annular electrodes
providing a potential barrier to prevent longitudinal escape and a solenoidal magnetic field to provide transverse containment. About 10^{6} to 10^{7} antiprotons will be collected over one or more hours and cooled with
an electron cloud to 10 to 100 milli-eV energies. The antiproton cloud and a cold
positron cloud (10^{10} positrons collected from a Na-22 source) will be injected
into a separate multi-ring trap where recombination occurs at a rate of 10^{4} antihydrogen atoms per second. Antihydrogen can be stored in a magnetic
bottle consisting of strong quadrupoles whose magnetic field gradients interacting with the positron magnetic moment result in restoring forces (as in a Stern-Gerlach experiment). Extended storage of antiprotons in traps is limited by annihilation with residual gas and radial diffusion via scattering. The planned HiPAT (''High Performance Antimatter Trap'') storage device is intended
to hold up to 10^{12} antiprotons (Brillouin space-charge limit for the device) in a 10^{-12} Torr vacuum with a storage time of about 18 days.

S. Howe presented various applications of antiprotons which are of interest once storage of 10^{6} to 10^{12} pbars becomes feasible from a facility like
Fermilab. Antiproton storage could enable a portable source for very short-lived, positron-emitting radioisotopes used in Positron Emission Tomography (or PET). Pbar annihilation in natural O-16 and F-19 systems would produce
the positron emitters O-15 (2 min. life) and F-18 (110 min.) at any diagnostic
location on demand. The O-15 diagnostic is particularly useful for brain blood-flow studies. A single diagnostic application requires about an 8 milli-Curie dose. With an expected conversion efficiency of 0.7 to 0.9 O-15 per pbar, about 5×10^{10} pbars are needed per application, or 10^{12} pbars for 20 applications.
It should be noted that at the Fermilab complex, the cost of producing each antiproton is roughly 10^{-7} dollar, so 5×10^{10} pbars would

cost about \$5000. For initial research into this diagnostic use, only 10^{6} to 10^{8} antiprotons would be needed. G. Jackson expressed the opinion that once antiproton accumulation gets to 2×10^{11} pbars per hour at Fermilab, taking 10^{10} pbars out to decelerate for low-energy research would not significantly impact the high-energy collider program. With a deceleration efficiency down to keV energies of 10^{-4} to 10^{-3}, roughly 10^{6} to 10^{7} pbars could be captured in a Penning trap from 10^{10} initial high-energy pbars.

In principle antiprotons can also be used for direct tumor treatment. Stopped pbars annihilate in the atomic nuclei of high-Z elements in the tumor region. An annihilation event knocks out many low-energy neutrons and fissions the resulting neutron-poor nucleus. The high-energy fragments that destroy the tumor are then much less radio-active and do less harm to surrounding tissue. For this application 10^{8} to 10^{9} pbars are needed per treatment. To get the pbars into the body, the kinetic energy must be 50 to 80 MeV for occular tumors and 200 MeV for brain tumors.

Experiments on a plasma thruster powered by pbar annihilation become feasible when pbar collection in Penning traps reaches 10^{6} to 10^{8} particles, although 10^{8} to 10^{10} would be preferred. Such thrusters are envisioned as small-scale prototypes of advanced space propulsion systems for sending robotic probes to the Kuiper Belt (3 to 30 light-days) and nearby stellar systems (light-years). With 10^{11} pbars in an argon reaction trap, a 2 milli-Newton thruster is proposed by Smith and Howe. Ultimately pbars may be used to initiate fusion reactions in a deuterium-tritium pellet with the reaction heating a hydrogen plasma for use in advanced rockets with thrust to weight ratios of order 0.1 to 1 (AIMStar concept of G. Smith et al).

To access large numbers of pbars at Fermilab, they must be efficiently decelerated once collected and cooled at 8 GeV in the Antiproton Accumulator. One scheme considered in 1995 was to decelerate pbars back down through the Booster synchrotron, Linac and a 750 keV RFQ decelerator to achieve 18 keV pbars (see articles in the ''Selected Papers'' collection, Aug. 19, 1998, mentioned earlier). The method is feasible but would rely on somewhat expensive modifications to the Booster rf system and not allow for any beam cooling in the low-energy deceleration phase of the Booster. The cost of this option was estimated at \$4M of materials and services (omitting an optional electron accelerator to make positrons) and \$4M in labor. The overall efficiency was estimated at 10^{-3} decelerated pbar per initial 8 GeV pbar. A second scheme, brought up during this meeting by G. Jackson, is to use the new Fermilab Main Injector, now being commissioned, to decelerate pbars below 8 GeV. The Main Injector is designed to accelerate higher intensities of protons and antiprotons from 8 GeV up to 150 GeV for injection into the Tevatron. However the electromagnets that guide and steer the beams can be turned down to produce lower fields, and the rf systems can be used to decelerate the beams. A third alternative suggested by R. Pasquinelli is to decelerate collected pbars in the Antiproton Accumulator. In the past, pbars were decelerated there from 8 to 2 GeV kinetic energy for charmonium experiments . Because the Antiproton source is in nearly constant use during colliding beam operations, this deceleration mode might be restricted in its availability.

G. Jackson plans to do some cursory accelerator experiments between February

and June 1999 in an attempt to decelerate 8 GeV protons down to 1 to 2 GeV/c momentum (430 to 1270 MeV kinetic energy) in the Main Injector. Remnant fields in the magnets which can ruin beam quality and limit the dynamic aperture will determine how far down deceleration can be taken. This would then form the basis of a low-energy pbar program: The roughly 1 GeV/c pbars from Main Injector deceleration are extracted at MI-10 and transported in a relatively inexpensive beamline (perhaps permanent magnets) for 250 m back to the MI-8 service building. There they can be transported up to ground level through the equipment hatch into a shielded area for deceleration in foils and/or gas cells and injection into a Penning trap. Alternately this deceleration could be done at the bottom of the equipment pit at MI-8 if operation below grade were necessitated by radiation considerations.
The expected efficiency in this type of scheme is about 10^{-4}, yielding 10^{6} pbars from an extracted 10^{10} pbar pulse or 10^{7} pbars from a dedicated 10^{11} pbar accumulation. The cost of this initial setup would not be the several million dollars of the Booster-Linac scheme, although the collection efficiency is somewhat lower.
In the future, a dedicated ring can be constructed at MI-8 to decelerate and cool the 1 GeV/c pbars down to MeV kinetic energies for deceleration in an RFQ (to keV energies). This would increase the low-energy collection efficiency to of order 0.1, so that roughly 10^{10} low-energy pbars could be collected from a batch of 10^{11} pbars in the Main Injector. Only a hundred or fewer shots would provide the 10^{12} pbars for the HiPAT trap.

In conclusion, the meeting identified three user groups that are interested in collecting low-energy pbars at intensities as low as 10^{6} initially and ultimately collecting stored populations of order 10^{12}.
In 1995 the basic motivation for low-energy pbars in the Duke University proposal to Fermilab was fundamental anti-matter physics. Much of the funding for the beamline and accelerator modifications would have had to come from Fermilab in that case. In this meeting it was pointed out there are pbar applications in medicine and engineering as well as fundamental physics. G. Smith and S. Howe noted that there are indications of new interest at NASA to fund advanced propulsion research. A low-energy pbar facility might be funded jointly by NASA and DOE if it served the missions of both these agencies. The Fermilab complex was found to be quite flexible for producing low energy pbars with at least three methods available to decelerate them for injection into a Penning trap: \\
(1) Deceleration from 8 GeV through the Booster, Linac and an RFQ to keV kinetic energies at an efficiency of order 10^{-3}.\\
(2) Deceleration in the Antiproton Ring when not in use for pbar stacking. Extraction of the 1 to 2 GeV kinetic-energy beam would be followed by deceleration to keV energies in foils/gas cells with the usual 10^{-4} overall efficiency. \\
(3) Deceleration from 8 GeV in the Main Injector down to about 1 GeV/c momentum, extraction at MI-10, transport to MI-8 service building and deceleration to keV energies in foils/gas cells at 10^{-4} overall efficiency.
This initial setup could be upgraded in the future by adding a dedicated decelerator ring and RFQ decelerator to achieve efficiencies of order 0.1 per initial 8 GeV pbar.

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APPENDIX II

1998

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

PRELIMINARY DESIGN FOR THE HIGH PERFORMANCE ANTIMATTER TRAP (HiPAT)

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ABSTRACT

Portable electromagnetic antiproton traps are now in a state of realization. This allows facilities such as NASA Marshall Space Flight Center the ability to conduct antimatter research remote to production sites. MSFC has begun development of such a trap that will store 10^{12} antiprotons for a ten-day lifetime, to be used in future experiments such as antimatter plasma guns, antimatter-initiated microfusion experiments for space propulsion, and the synthesis of antihydrogen.

Design, safety, and transportation issues were considered for the MSFC High Performance Antimatter Trap (HiPAT). Radial diffusion and annihilation losses prompted the use of a 3 T superconducting magnet and a 20 kV electrostatic potential at 10^{-12} Torr pressure. Cryogenic fluids used to maintain a trap temperature of 4K were sized accordingly to provide four days of stand-alone storage time, which could be brought to the ten-day requirement by refilling the dewars or by addition of a cryo-cooler. Radiation associated with antiproton annihilation required adequate shielding of a proposed transport truck.

Procurement of a cryogenic confinement unit has proceeded, with fabrication of extraction/injection apparatus to proceed in the near future. Initial testing of HiPAT will begin in one year, with actual antiproton transport occurring shortly afterwards.

INTRODUCTION

For decades it has been speculated that antimatter could be used to enable very high specific impulse (I_{sp}) missions into deep-space (Forward, 1988). The specific energy of antimatter is ten orders of magnitude larger than chemical sources and three orders of magnitude larger than nuclear fission and fusion sources.

However, three problems have impeded the development of antimatter rockets. First, production of antimatter falls far short of requirements for most antimatter engines. Second, until recently no means were available for storing large amounts of antimatter. Lastly, the coupling of the release of annihilation energy to propellants has been proven to be relatively inefficient (Huber, 1994).

In the past few years, scientists and engineers at the Pennsylvania State University have found means of resolving these three key issues. Although annual production of antiprotons is presently limited to ten nanograms, conversion efficiencies of approximately 10% have been realized due to the discovery of radiationless, antiproton-induced fission. Furthermore, confinement of antiprotons in electromagnetic traps has developed dramatically over the past ten years (Holzscheiter, 1996).

In view of these recent developments, the Pennsylvania State University group has embarked upon a program of developing a *portable* antiproton trap, capable of holding up to 10^{10} antiprotons for a period of four days. This trap is in its final stages of testing using stores of hydrogen ions and electrons. It is planned that it will be filled with antiprotons from a source in the U.S. within the next two years. Applications, not only to space propulsion, but also to medicine and plasma physics, are being explored (Lewis,1997). In view of the potential of such devices, the NASA Marshall Space Flight Center proposed in 1997 to build a trap of larger capacity (10^{12} antiprotons) and extended antiproton lifetime of ten days. This trap is dubbed the High Performance Antimatter Trap (HiPAT).

Research conducted at MSFC on HiPAT to date has emphasized critical conceptual design issues on the superconducting magnet and cryogenic dewar, attainment of long lifetimes and large stores of antiprotons, radiation safety-related matters, and transportation. The following sections provide a detailed overview of these studies, in anticipation of procurement, assembly, and testing of the trap within two years. Estimates will be provided on projected shielding requirements and antiproton lifetimes. Means of transportation will also be discussed.

DESIGN OVERVIEW

The design of HiPAT stemmed from the antiproton storage trap developed at Penn State University. This trap consisted of a series of electrodes to confine antiprotons in a potential well, while a set of rare earth magnets surrounded the electrodes to provide electromagnetic confinement. Vertical helium and nitrogen dewars surrounded the trap and magnet to reduce the internal temperature to 4°K. Finally, external pumps and extraction gauges were mounted onto the system to provide a high vacuum trap region, as well as providing the means for measuring the activity inside the trap itself.

To increase the maximum level of antiprotons and their confinement periods in HiPAT, several design changes were implemented. Using 20 kV to electrostatically confine 10^{12} antiprotons, calculations have shown the antiproton cloud to be approximately 29 cm in length. The magnet was sized 40 cm in length in order to accommodate the cloud length easily. Due to

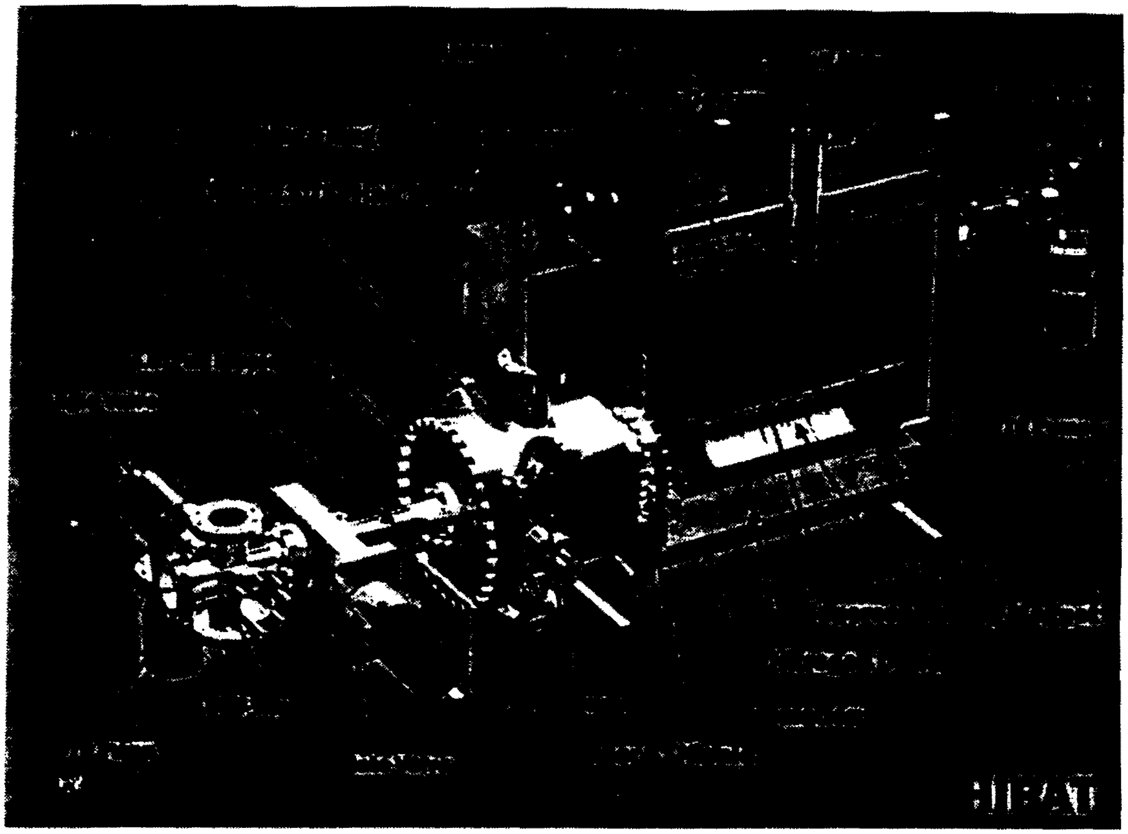

Figure 1. Conceptual layout of the High Performance Antimatter Trap.

radial diffusion losses of antiprotons, the required magnetic field for a storage half-life of ten days must be considered:

$$\left(\tau_{1/2}\right)_{dif} = \frac{1}{n\sigma v}\cdot\left(\frac{\omega_c}{\omega_z}\right)^2. \qquad (1)$$

It was previously determined that the Penn State trap, with an internal pressure of 10^{-10} Torr, 0.4 T field, and 1 MHz axial frequency, had a radial diffusive half-life of 640 sec (Lewis, 1998). State-of-the-art pumping equipment was also purchased for HiPAT, which would lower the internal pressure from 10^{-10} Torr to 10^{-12} Torr. This reduces the number of background particles n by a factor of 100. Using a fixed axial frequency of the antiprotons (ω_z) of 2 MHz, and assuming the cyclotron frequency (ω_c) varies linearly with the magnetic field, scaling HiPAT using Eq.(1) for an assumed 10-day lifetime results in a required 3 T magnetic field. Beyond 1 T, dry, rare-earth magnets became very massive; hence, focus was therefore shifted towards the use of superconducting magnets. In a separate analysis, it was determined that the lifetime against annihilation of antiprotons with residual background gas under these conditions is about 17 days.

Like the Penn State trap, HiPAT will have the ability to ship antiprotons between loading and testing facilities. To enhance the portability of HiPAT, other physical design issues were implemented. For example, the helium and nitrogen dewars were arranged horizontally, as opposed to a vertical orientation. This would allow better access to transport vehicles that have a limited height. Certain elements found in the extraction system and external pumping system located to the front and aft of the cryostat unit were "engineered" for possible detachment during transport.

Through the use of the solid modeling package TrueSpace, a preliminary image of HiPAT is shown in Figure 1. A current, detailed design of the cryostat unit (dewars and SC magnet), required for commercial bids, is illustrated in Figure 2. A diameter of 10 cm is proposed for the inner bore (trap region). Directly inside the inner wall of the proposed 50 L liquid helium dewar (kept at 4K) lies the superconducting magnet. Surrounding the helium dewar lies a thin thermal shield to offset heat radiation losses from the helium dewar, followed by several layers of superinsulation such as Mylar. A 7 L liquid nitrogen dewar surrounds the above items in the form of an annulus, with approximately a 2 cm low-vacuum gap in-between. Finally, beyond a second low-vacuum gap, more superinsulation completely encloses the described network, followed in turn with an aluminum shroud used for structural support. Four fiberglass fill tubes are inserted into the system, two of which (one not shown) are inserted into the N_2 dewar to allow proper fill conditions. The remaining two are inserted into the helium dewar. Aluminum flanges on each end of the cryostat allow for easier maintenance.

Figure 2 includes the recommended addition of a two-stage cryo-cooler, shown thermally shorting the nitrogen dewar and the heat shield surrounding the helium dewar. Without the cooler, the LHe and LN2 would survive for only four days, adequate only for transport, but inadequate for a ten-day storage time. Also in Figure 2, heat conductive end plates were added to the ends of the nitrogen annulus to allow for complete thermal enclosure of the helium dewar.

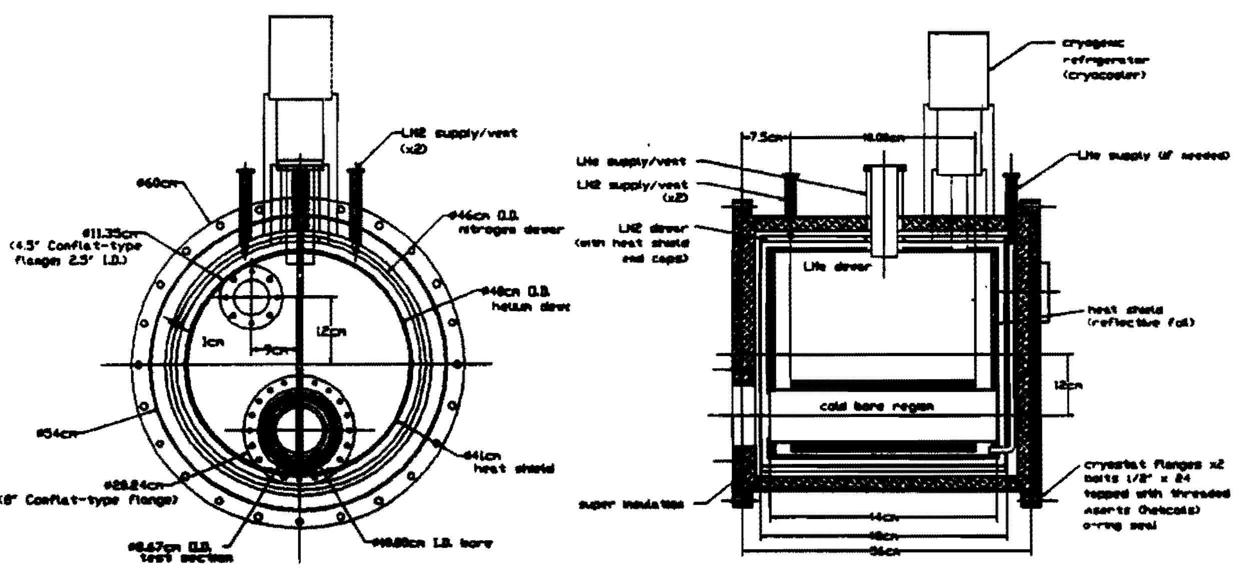

Figure 2. CAD detailed illustrations of HiPAT cryostat.

OTHER CONSIDERATIONS

A. Containment of Radiation Emissions from Antiproton Annihilations

When an antiproton annihilates with matter, it emits a burst of three charged pi mesons and three gamma rays. The average energies of the pions and gamma rays are 243 MeV and 196

MeV, respectively. The pions and gamma rays lose energy by ionizing collisions with atoms and interactions with nuclei. In the quantities to be stored in HiPAT (~10^{12} antiprotons), the collective radiation effects of such numbers can be serious. Shielding is required to protect workers near the trap during utilization, as well as the general public while in transit between loading and testing sites.

Detailed computations have been made to assess shielding requirements. In 1987, a group at the Los Alamos National Laboratory, utilizing an accurate code named Monte Carlo Nuclear Physics (MCNP), produced numbers that defined radiation dose as a function of standoff distance and shielding (Howe, 1987). For reference, Figure 3 shows the radiation dose, immediate to the annihilation site, to be 30 Rads. Since the annual allowable radiation dose for human beings per year is approximately a factor of 100 less than this value, the need for shielding becomes apparent. For a worker located 2 m from the source, Figure 3 shows that about four inches of lead would be required to meet acceptable standards. It is also seen that a composite of borate/graphite/lead, weighing but 60% that of lead, would meet the same requirements. As will be discussed in the next subsection, it is planned to transport the trap in a shielded truck, which would protect the public. Since the distance from the source to the public in this instance is greater, roughly a factor of 10 less shielding on the trailer side walls is necessary.

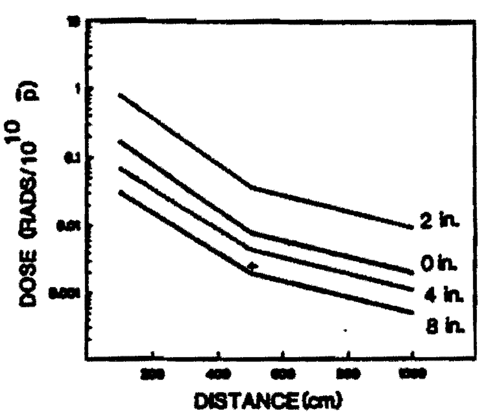

Figure 3. Radiation emissions from antiproton annihilation (Howe, 1987). (lead shield, '+' indicates borate/graphite/lead composite with 60% mass of lead for equivalent dose)

B. Transportation

It is envisioned that the superconducting magnet with its dewars, major vacuum system components, and beam injection/ejection system, will be transported from the loading site to the experimental test site in a specially designed truck. As mentioned above, the vertical walls will be outfitted with shielding to prevent radiation exposure to the driver and general public in the event of an accidental release of radiation. These components, along with support electronics, cryogenic support equipment (e.g. the cryo-cooler), and a portable power system, make up the portable antiproton source. The total weight of the source is approximately 200 kg. The support equipment is estimated to weigh roughly 400 kg. Shielding is estimated at 2 Tonnes, giving a total system weight of about 2.6 Tonnes. The horizontal bore of the trap will be at beamline elevation as determined at the source. At the time of filling, the rear doors of the truck will be opened, and the bore connected via a vacuum pipe to the source beamline (i.e. a real "antiproton filling station", offering premium hi-octane fuel only!).

CONCLUSIONS

Important design and conceptual issues concerning confinement of large numbers of antiprotons for extended periods of time have been addressed. A detailed design of the superconducting magnet and its dewars has been completed; procurement activities for these devices are now underway. Separate studies of antiproton lifetimes of at least 10 days have led to a set of require trap conditions, e.g. vacuum of 10^{-12} Torr, 3 T magnetic field, and a trap length of 40 cm. Shielding required for radiation safety for workers and the general public was considered, leading to approximate specifications for shields. Finally, the transportation of antiprotons from production site to testing site was evaluated.

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