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TITLE: Excitation of Lasing Media Using Antiproton - Annihilation Products

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Excitation of Lasing Media Using Antiproton-Annihilation Products

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Abstract.

Lasing has been achieved in many different media using a wide variety of excitation mechanisms including low-energy electron or proton beams and recoiling fission products. In all cases the power density produced in the medium has been the critical parameter. Recent calculations indicate that a region of high]-power dcnsity can be achieved in high-densityl lasing media by allowing antiprotons to annihilate in the material with an intense magnetic field present. Because of the long range of the energetic annihilation products, the media can be gaseous, liquid, or solid. The thermalization time is the critical parameter for this is excitation mechanism which for liquid-density media, such as Ar-Xe mixtures. is about 2. 1 ns. Based on these calculations power densities of about 100 MW/cm^2 can be achieved using a level of antiprotons that is currently available today. Development o,f an antipron pumping source may allow fundamental reaction kinetics in a wide- varietv of lasing systems to be performed in a university environment. Tile results of the ca]cu]ations in a liquid medium and at, different, magnetic field strengths will be presented. In addition, the. design of an ongoing experiment using an 800 MeV proton beam to puImp a liquid density excimer cavity will be discussed. These preliminary experiments intend t o focus on fuudamental kinetics and on the effects of a strong magnetic field on reactions.

1 Introduction

Ant.iprotons are produced at a variety' of accelerator facilities around the world for basic research in nuclear and particle physics. The advent of the nev cooling technology}' [1] which has opened many. new areas for high-energy physics. also can open new research opportunist in in other areas that. can use a source of very low-energy antiprotons. The Low Energy Antiproton Ring (LEAR) at CERN can provide beams of antiprotom (10^6/sec) at energies down to 2 MeV [2] which have been used for a wide variety of measurements in low-ellergy antiproton physics.

Recently there havee been a number of experiments at LEAR that propose to capture and store significant numbers of these particles for the measurement of fundamental properties [3]. All of these proposals rely on the well established ion-trap technology that is in coommon use in atomic physics [4] Briefly ion traps achieve storage of charged particles using a combination of electric and magnetic fields. Although this technology will never be able to store enough antiprotons to be of interest in a prime power application. (there will always be more energy in the magnetic field than in the rest mass energy [5]) it does offer unique opportunities to investigate specialized applications that can take advantage of the unique way in which antiprotons convert their rest mass into energy. One such application is to use the annihilation products to excite a large-volume. liquicl-excimer lasing medium.

During the last fifteen years many researchers have used energetic particle beams to excite lassing media [6]. In general, these beams have been composed of either electrons with kinetic energies of up t o 1-2 MeV. or of protons with energies up to -150 kc\'. These particles will produce a very high specific ionization due to their relativlely short range in most lasing media. Power densities of about 100 MW/cm^3 can easily be achieved. However. these low-energy particles can excite only very small volumes. Moreover, again because of their short range, the volume that they can excite in a typical experiment is never coaxial with the cavity.

Until very recently, the use of much higher energy charged particle beams for laser excitation has not been very. attractive because of the low peak-current available at most high-energy- accelerator facilities. Even the highest current proton accelerator in the world. LAMPF at Los Alamos. could not produce suffcient power density in a medium to lase. However. the addition of the Proton Storage Ring (PSR) at LAMPF allows for the time compression of a beam burst and the resulting increase in instantaneous current. Thus, it is now possible to obtain a burst of 2×10^{13} protons in 270 ns at 800 MeV with spot sizes of about 0.5 cm. This is more than enough power and energy density to achieve lasing in liquid or high density media. Although the majority of recent work on excimer lasers has been based 011 gaseous phase media. the first excimer laser work was with liquid phase systems [7. 8]. The most recent work in liquid phase excimers is from a Los Alamos group who have investigated a wide variety of such systems [9. 10]. This work has focused on rare gas dimers and rare gas halogen mixtures in a liquid argon host.

Antiproton annihilation leads to the production of very high-energy charged particles. However. there is a central physics question that needs to be resolved: Do these high-energy particles lead to the same excitation modes of the medium that. result in lasing action? The proton beam available at the PSR can simulate the specific energy loss of these annihilation) particles (on the average). Thus. this question can be resolved without using ant protons.

We have designed and built a cavity that could be installed in a PSR beam line. Of the possible liquid excimer systems that our pumping method and cavity could test, we hope to study the XeO system in our initial runs. Our design can easily change optics for investigating other systems.

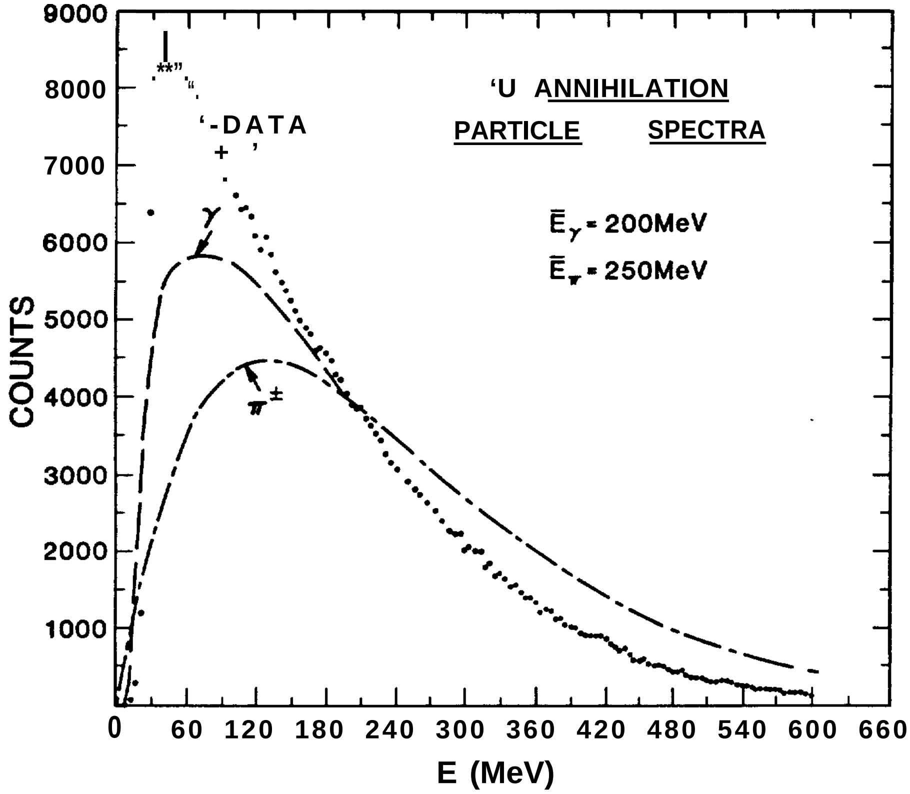

Figure 1: Cualculated kinetic-energy spectra of charged pions and gamma rays resulting from antiproton-proton annillilation at rest. All final states not involvillg kaons are included. Data for gamma production is also shown (see text). These spectra result from 93,000 events which produced and average of 3.12 pions/ event and 3.08 gamma/ event.

The eventual use of antiprotons to pump laser media has the advantage that relatively compact devices can be built for exploring a wide variety of samples on a university laboratory scale.

2 The Antiproton-Pumped Laser Concept

Currently, efforts are underway at the Los Alamos National Lahoratory to develop a modified Penning trap which can contain up to 10^{10} antiprotons at relatively low energies (a few keV) for long periods of time. The trap design allows for the accumulation of antiprotons produced at the modest rate of about 10^6-10^7 per second. once accumulated the antiprotons can be extracted all at once. or in short bunches a few 10.s of ns long.

The spectra of the reaction products from a proton-antiproton annihilation event at rest are shown in Fig. 1. Over half of the annihilation energy is produced in the form of charged pions with an average energv of 250 MeV. Because the range of such particles is several many g/cm^2 the annihilation can occur in a solid medium with most of the energy deposition well removed from the reaction point. Consequent?”. the pion’s energy can be used to excite a lasing medium even if the material is external to the annihilation point.

The problem with the very long range of the particles produced in the altiproton-annihilation reaction and with the deposit ion of their energy over a dilute region can be solved in part by allowing the annihilation to take place in a strong magnetic field. Such a field would be present anyway due to the storage of the antiprotons in an ion-trap configuration. Thus, the idea for the laser is simply

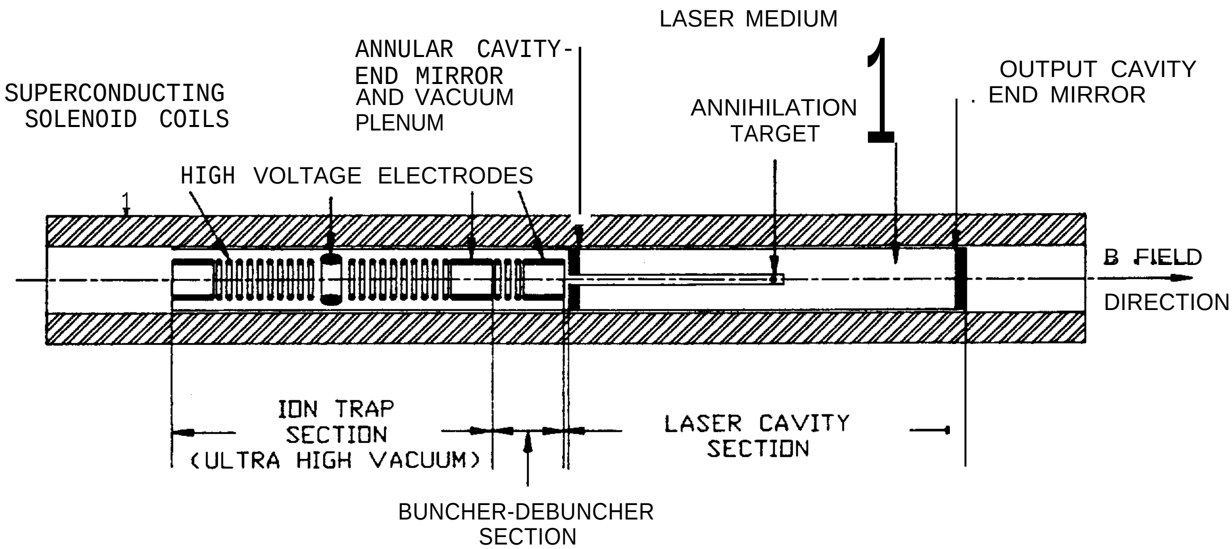

Figure 2: Schematic cross.sectional view of the antiproton pumped laser concept.

to have a suitable laser cavity with an annihilation target at. its center located in the same solenoid that provides the magnetic field for storing the antiprotons. The resulting annihilation particles will be bent into overlaping orbits. thus confiniug the region over which the energy is deposited.

A schematic cross-sectional view of our proposed concept is shown n Fig. 2. In the figure the overall solenoid providing both the storage field for the antiprotons and the guiding field for the annihilation products is shown on the outside of the azimuthally symmetric device. On the left. inside the solenoid is the multiring ion trap that is used to store tile particles. By adjusting the potentials on the electrodes the shape of the charge cloud can be adjusted prior to ejection to the right into the laser cavity. Between the trap and the cavity is located a series of electrodes that are used as a buncher section for the antiproton cloud as it approaches the annihilation target located in the center of the laser cavity. Everything up to the annihilation target is at very high vacuum (10^{-13}-Torr). The resonant cavity itself is annular in configuration with a fully reflective mirror on the ion-trap side and a partially transmitting mirror on the output side. Tile interior annulus is filled with a cryogenic lasing media in liquid form. The liquid form is preferred in our application due to the much higher density over gas. This higher density leads to more rapid energy loss and thermalization of the annihilation products and thus to higher peak-power density. An added advantage of the cryogenic operation is that higher vacuums are possible in such systems.

Preliminary calculations show that the antiprotons stored in the trap can be ejected and subsequently bunched at the target so that all the particles annihilate in about, 50 m. The emerging annihilation products would spread into 4~ if the magnetic field were not present. With this field present the charged particles go into orbits whose radii are determined by the magnitude of the field and the momentum of the particles. Because the particles loose energy as they transit the lasing media the particle momentum is continuous} being degraded. Thus. the resulting orbits are spirals. For the gamma rays the maglnetic field has no effect until they shower into electron-positron pairs. These charged particles will also be bent in the field into orbit. However, the electrons and positrons will generate further gamma rays in the classic shower process that these light particles generate in matter. Thus, some of the gamma rays energy will simply escape the lasing media and not lead to excitation. We are at present modeling this effect. For the purpose of this design concept. We assume that the gamma ray energy which amount.s to about half of the annihilation energy is simply lost to lasing action. As the charged pions decelerate in the lasing media they will finally decay into a muon and a neutrino. The muon will continue to orbit in the magnetic field losing energy and finally decay into an elmtron and two neutrinos. The energy contained in the neutrinos is lost to the excitation of tile lasing media whereas the muons and electrons will deposit their kinetic energy just as tile charged pions did before decay. The energy lost in the neutrinos is about 80 - 100 MeV 011 the average and is thus only about 5% of the total energy available.

We have simulated the orbits of these particles in a typical cryogenic lasing media. liquid argon with t rat-e amounts of xenon. Particles with the spectrum of energies shown in Fig.1 are released at the center of a semi-infinite solenoidal field in the horiziontal direct ion as shown in Fig. 2. Particles that emerge from the annihilation target exactly v'ertical in the figure will simply spiral around in the central plane of the figure as they loose energy. Particles that have a component of momentum parallel to tile magnetic field direction will naturally propagate in this direction as well as spiraling. There will be some particles that have no momentum transverse to the magnetic field or such a small componet that they propagate outside the cavity leaving little or no energy. From these simulations we hav'e determined that the energy lost due to particles lost out the ends of the cavity could be as high as 40% for a 15 Tesla field. By increasing the field strength to 40 Tesla or by adding azimuthal field components using Jaffe coils. the losses may be reduced to 25% - 30%. Naturally this figure depends strong]:- on the specific configuration of the cavity and some steps can be taken to prevent this occurrence by further tailoring the fields near the ends of the cavity. Nevertheless, we will assume that 30% of the annihilation energy is lost due to end effects. The average time for the particles to thermalize is calculated to be about 2.1 ns. Thus. the annihilation energy- is deposited in about .32 ns t eta]. Finally. we have determined how large a volume of lasinq media can be fully excited by the particles. This depends on the size of the magnetic field. For 15 Tesla this vollume is about 200 cm^3. With 10^{13} stored antiprotons we release about 3000 joules of energv. The annihilation and thermalization time being about 52 ns total means that 5 > 10^{10} watls of power have been released. Tile azimuthally averaged spatial distribution of the energy deposition is shown in Fig. 3 for a variety of magnetic field strengths. The peak energy and power densities involved are 1.5 J / Cm^3 and 28 MW' /cm^3. respectively. for the 15 Tesla example, but are 6 J/cm^3 and 115 MW/cm^3 for the 25 Tesla case. These densities are very near those required for achieving lasing action in liquid eximer systems.

Previous work [9] - [11] has shown that either low-energy protons or relativistic electrons can excite excimer systems above the lasing threshold. Because of the short range of these particles however, very small volumes of liquid- or low-density gas targets have been used. Consequently. the power density thresholds, reaction rates, and large-sca]e col]ective effects have not, been fully characterized. By utilizing the results of these experiments as a measure of the efficiency}' of conversion together with the calculated deposition from the antiproton model an estimate for the energy conversion to laser output can be made. Thus. we estimate that around 10^{12} – 10^{12} amtiprotons would be required to produce about a 300 J laser pulse. This quantity. of antiprotons is within current, production levels and will soon be within ion-trap storage capabilities as well. Thus, an

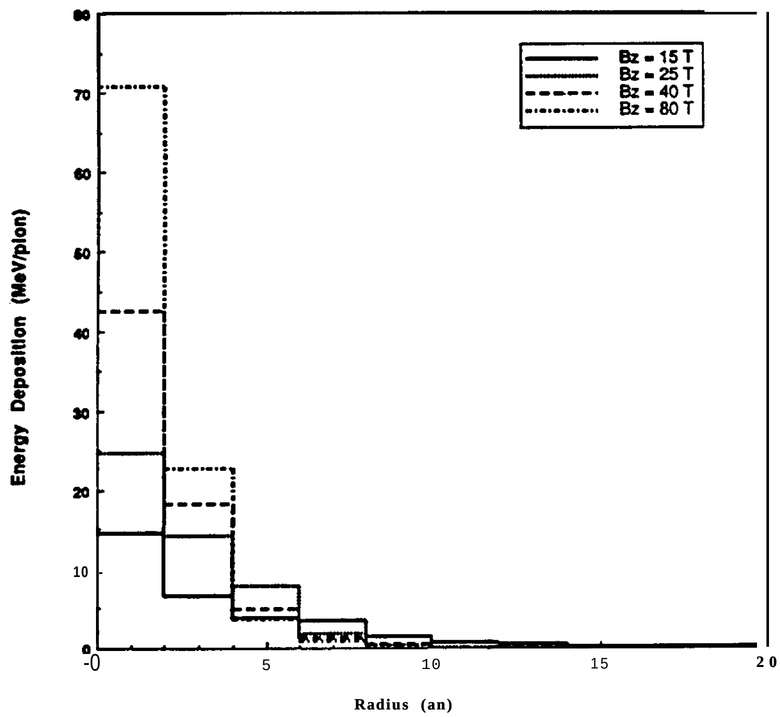

Figure 3: Azimuthally averaged energy deposition plotted as a function of radial distance from the laser axis.

experiment using antiprotons could be executed within the next few years.

However. there are two outstanding physics questions that remain: Do high-energy ionizing particles excite the lasing media in modes that are similar to those achieved by more conventiond charged partic1e excitations? I)oes the presence of a large magnetic field disrupt the lasing kinetics? Both these questions can be answered using high-energy protons and a specially designed cavity.

3 The Proton-Pumped Laser Experiment

Liquid excimer systems have achieved lasing using about 100 MW/cm^3 power densities with about 4 J/CM^3 total energy density to achieve these quantities with a high-energy proton beam. the PSR facility at L.AMPF is an ideal candidate. Beam bursts at 800 MeV with ~ 2 x 10^{13} particles in 270 ns can be delivered in spot sizes of a few millimeters. The 800 MeV protons (1463 MeV/c) will loose energy in a material at nearly the same rate as pions of about 250 MeV. Thus. the beam energy is ideal for our simulation of the antiproton-annihilation product excitation. Additionally. with an energy loss of 1.7 $MeV/g/cm^2$ in liquid argon (p = 1.4 g $/cm^3$) and a spot size of 0.5-cm a single beam burst will deposit about 38 J / Cm^3 at a power density of 140 MW/ cm^3. These numbers are above those required for achieving lasing action using conventional pumping methods.

3.1 The PSR Facility at LAMPF

The Proton Storage Ring (PSR) at LAMPF delivers very intense beans of protons for a wide variety of basic research experiments /12]. An overview of this facilitv is shown in Fig. 4. The LAMPF accelerator delivers a single macropulse. 800-microseconds long. at 800 MeV. to the PSR on demand.

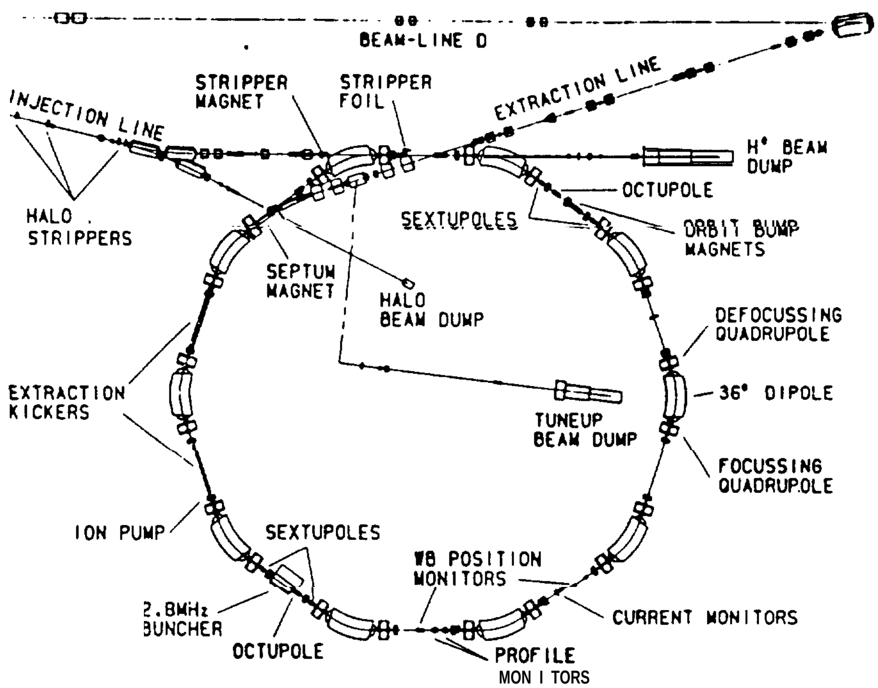

Figure 4.: Schematic overview of the PSRfacility at LAMPF

The P'SR is designed to compact this macropulse, or any subset of it, in time to achieve a much higher peak current (49 A. designed) in a correspondingly shorter lime. .After msny circulations the compacted burst is ejected from the ring structure for experiments. At present the burst can only be delivered at full intensity to the neutron production target . Tile difficulty for our experiment is to find a suitable location at the facility that does not interfere with conventional beam operations and that can accommodate tile equipment needed for our experiment. The 7' beam dump line in the main ring area is tile only location that meets these requirements. This beam line exits the main ring at a 7" donward slope and proceeds through a 48-inch-wide trench to a beam stop somewhat removed from the ring area (see figure). Spot sizes in this beam line are about 1 cm. However. additicnal optics in the beam line preceding our experiment can bring the focus of the beam to about O.5-cm over about a lo-cm-long region. These criteria drive many of the design choices that we made in our experiment..

3.2 Experimental Design

3.2.I The Cavity

Because of the eventUaL focus that. can be achieved iN tHe beam line the natural length for the c.aVity is 10 cm. In principle the cavity could be mych longer due to extremely long range for 800 MeV protons in liquid argon (-- 70 cm). This points to one of the advantages for using the PSR beam to pump a lasing medium: very large volumes can be excited. However. only relatively dense materials such as liquids or solids can be considered due to the dependence of the dE/dx on material density, Naturally. if a given gaseous system has a particularly low lasing threshold, it too can be considered. Fluorescence measurements are possible 011 any system.

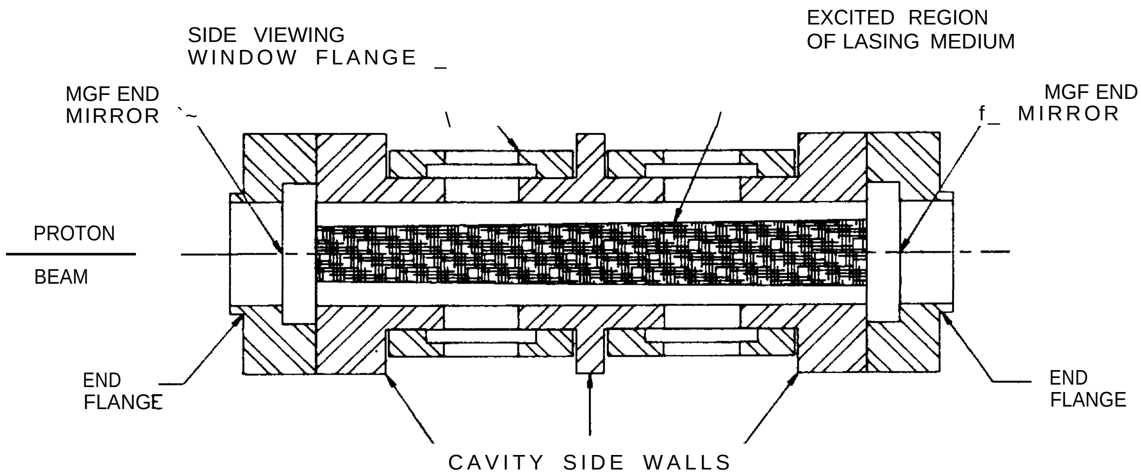

Figure 5: Schematic view of the lasing cavity with the region excited by the beam burst indicated.

For the cavity diameter, the design is driven by activation considerations. The beam spot without the additional optics will be about 1-cm across. Because every beam bunt has a low intensity halo of larger diameter surrounding it. and because the collision of this halo with the casing material of the cavity itself will lead to induced radioactivity. this casing should be well outside of the beam halo area. Based on estimates of this halo. the diameter of the cavity was chosen to be about ‘2 cm (0.750 in.). A schematic cross-sectional view of tile cavity’ volume is show in Fig. 5. Also shownı in the figure is the volume of the medium excited by the beam burst. Because of multiple scattering in tile medium. the beam spot will spread as it transits the material which we assume to be liquid argon. Thus. the cross section of the excited volume is shown as slight l?’ conical. For a 10-cm-lcng cavity the multiple scattering angle is about 9.6 mrad. With an intial spot size of 1 -cm and taking 95% of the beam] this increases the excited volume over a simple cylindrical shape by about 17%. This increase of the spot size due to multiple scattering is within the design sizing for the diameter of the cavity.

We considered at the out set designing the cavity for other excitation geometries. In more conventional excitation experiments the excitation is done from the side of the cavity and not clown its length as we have planned. However, excit.ing the cavity from the sick puts the excited region of the medium off the center of the cavity. The only sections of the medium that are going to resonate are those that fall within the gaussian envelope of the resonance set up by the mirrors at the cavity ends. By exciting the medium directly’ along its centra axis all the excited medium is exactly where it is supposed to be. This is the reason for the axial excitation in our design. It could be that we will measure even lower lasing thresholds for a given power input due to the more efficient coupling that our design has over otber systems.

The cavity design also includes four side-viewing windows that will be used to measure the size of the beam envelope in the lasing medium both on entrance. center. and exit from the caviy, and to measure side fluorescence in the same configuration. Measuring the beam spot size in the cavity during the experiment is important for the normalization of t.he results in terms of volume. Measuring the side-light fluorescence will be one of the diagnostics that we will use to determine if lasing action has occurred. The additional window allows for another detector arrangement and could be easily accommodated in the design.

The cavity and feed lines will be operating at cryogenic temperatures near liquid argon (B.P. = 87.25 k). Because of tile sensitivity of the index of refraction of the cryogenic media to temperature gradients, special consideration to thermal isolation had to be incorporated in the design. Our first line of defense in the design against the thermal problems was to simply make the thermal mass of the cavity itself as large as possible. 'This was consistent with the mechanica1 requirements of mounting the side-viewing w'indow flanges. The limitation in the thickness of the sidevall of the cavit} comes from fitting it inside the bore of the superconducting solenoid. The next design step was t o isolate the cavity from its surroundings in a vacuum. With a vacuum of 10^{-6}-Torr convection is eliminated leaving only radiational heat flow as the only loss remaining [13]. To defeat this process we gold coated (0.0001 in t hick) all parts of the cavity as associated feed lines in the vacuum including the inside of the vacuum pipe. The emissivity of gold is the key operating feature in this approach. Because the feed lines themselves will penetrate the vacuum wall at some point we used thin wall stainless tubing. taking advantage of the poor thermal conductivity of stainless steel and the reduced cross-sectional area to minimize the thermal conductive path t o the vacuum Wall .

3.2.2 The Tuning Beam Line

At any' accelerator facility sometimes hours with beam on target. are used to tune the beam for the experimental requirements. For our laser experiment this means that the laser cavity would be subject to substantial heating due to the beam tuninig. Consequently we have incorporated in our system design a beam line mounted below the laser cavity beam line expressly' for the purpose of tuning the beam. A schematic view of this beam line is shown in Fig. 6. In the figure the tuning beam line is shown tc be the same length as the cavity beam line with tuning screens located in the same posit ion along its length as the entrance and e.xit of the cavity. These screens are made of beryllium-oxide ceramic and glow in the area where the beam strikes them. The image is viewecl from the side as show-n using a conventional video camera. The screens are tilted at 45° with respect to the viewing camera so that a true image of the beam spot size can be read. Each screen is ruled in 0.5-cm marks along both axes. These targets will allow the machine operator to tune the beam for the optimum focus and spot size in the region of the cavrity. The thickness of the screens was chosen to simulate the multiple scattering in the lasing material and end mirrors of the cavity'. This will allow us to get a measure of the spot. size before the cavity is put in place for checking against the fast video camera image of the excited lasing media as the beam passes through.

The tuning beam line is not connected to the vacuum of the laser cavity beam line. Because at only. 10^{-3}-Torr the multiple scattering from air is extremely small this beam line is con.met.ed to the roughing pump. The entrance and exit windows of this beam line are the same as for the cavity beam line.

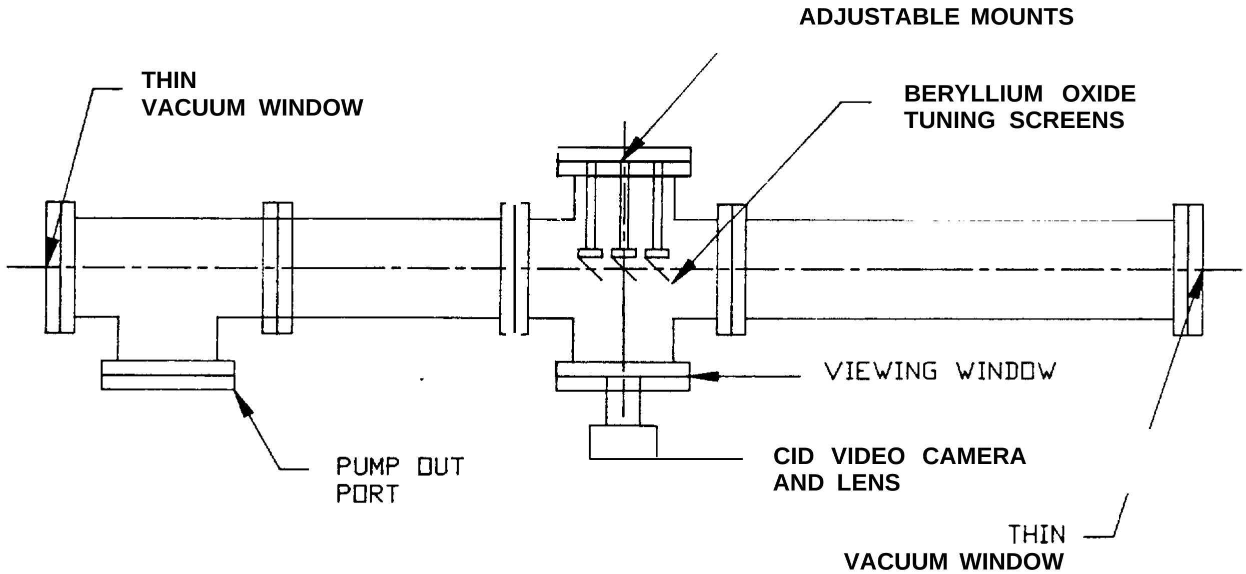

Figure 6: Schematic view of the tuning beam line.

3.2.3 system Mounting Structure

The cavlity and tuning beam lines will be mov'ed in and out of the beam with some regularity during a given run. Each beam line must be repositioned with respect to the beam itself to within about 0.020 in. The cavity beam line ancl all its associated optical equipment has t o move as a unit with the tuning beam line slung beneath. When the cryostat becomes available the same support strucure and motion assembly should be able to support and move this device as well. In addition, the entire structure must fit inside the 4-foot-w-ide t.rench that is available at the PSR. To meet all these requirements. we have designed a four-point lifting system using ball jacks. The ov'erall mounting system is shown in Fig. 7. T'he cavity beam line without the solenoid and cryostat in place is shown in the center of the figure with the tuning beam line slung beneath from the aluminum box-beams that provride tile structural support for the mounting platform. The proton beam enters from the left. The mounting system is shown in the position with the cavity in the proton beam. At each end of the box beams is located a precision ball screw with a gear box on t op. 'Through these gear boxes and two 90° miter gear hexes, torque is transmitted to the ball screws through hardenecl steel shafts so that all screws turn at the same time and rate. The torque for the system is provided from a ½ hp DC motor that can be computer controlled.

Moving tile cavity beam line requires that. all the associated optical equipment has to be movecl as well. in thr figure the optical tables left and right are mounted 011 the box beams. Inside the v'acuum a mirror relay system directs the beams from the sicle-viewing windows and the laser output beam up to the top of the optical tables. In our design we take two windows each upstrealm and downstream with the laser output being readout downstream. The spectrometer shown on the downstream optical table has a movable grating allowing for the input to be read either from the side or the front. The laser output and one of the side windows is directed into these ports on

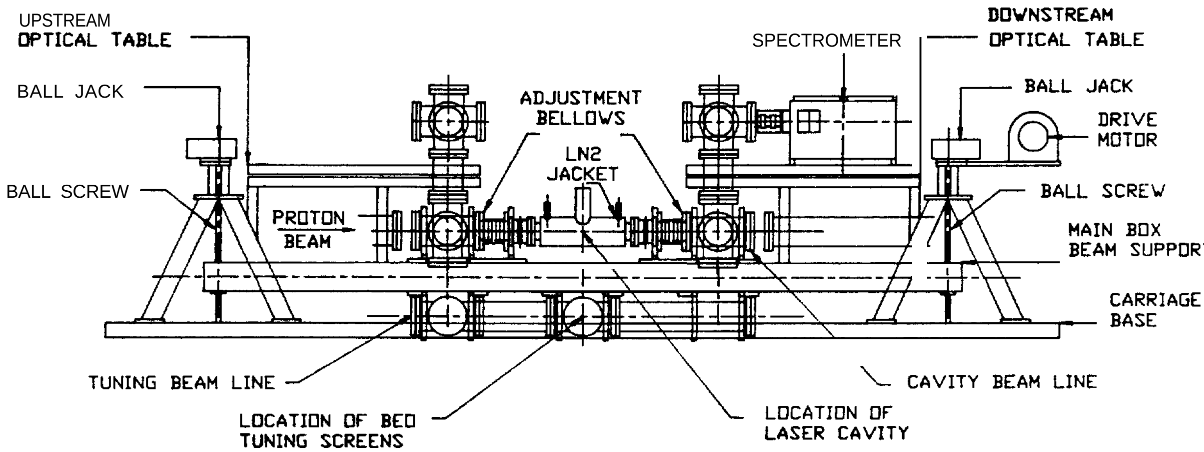

Figure 7: Schematic view of the overall mounting system for both the cavity and tuning beam lines.

this device. Tile other window dowmstream is directed into a video imaging camera for excitation volume measurements. Upstream one of the window's is also directed into a video-imaging system whereas the 0ther is directed to a photodiode for normalization purposes.

The vacuum required for the deep ultraviolet measurements we envision is about 10^{-3}-Torr. Because of this and that probably' frequent entries into the optical table vacuum svstem will facilitate the setup and alignment we have provided for a set of MgF windov's in an intermediate flange (see Fig. 7) to isolate the high vacuum in the cavity beam line. The optical table vacuum is provided by its own roughing pump.

4 Summary

We have designed. fabricated and tested a laser cavity that is suitable for insertion at the PSR facility at LAMPF. Using the high-energy proton beam from this facility, large volumes of liquid or other high-density lasing media can be excited at levels of energy and power density that are beyoncl those currently, known to result in lasing action. This cavity and beam line system was originally designed to answer the physics questions that need t o be resolved before a proof-of-concept demonstration of pumping lasing-media using antiprotons. Because of the growing interest in nuclear and reactor pumped laser systems and the difficulty in testing the lasing media, Our system can serve as a test bench for these investigations. In addition. because of the long range of high-energl protons lasing media that could not be pumped using conventional techniques Can now be studied.

5 Acknowledgements

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