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THE PILAC PROJECT AT LAMPF

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ABSTRACT

Plans for a new pion linear accelerator (PILAC) facility at LAMPF are discussed. A reference design to take intense pion beams produced at LAMPF and to accelerate them up to 1.2 GeV/c in a new superconducting linac is reported. A new experimental facility is planned to utilize the high intensity (10^9 π^+/sec), high-resolution (200-keV) beams provided by PILAC. The major components of the scientific program made possible by this new facility are discussed.

1. Introduction

Plans are being considered to build a superconducting pion linear accelerator (PILAC) at LAMPF to provide high-intensity (10^9 π^+/sec), high-resolution (200-keV) pion beams in the energy range of 0.5 - 1.1 GeV (0.6 - 1.2 GeV/c). Exciting new areas of pion physics become possible with such new capabilities. In particular, 1.05 GeV/c is optimal to produce lambda-hypernuclei through the (π^+,K^+) reaction and for investigation of lambda-nucleon scattering near the Σ threshold or cusp region. More than a dozen baryon resonances can be produced in this energy range above the (3,3) resonance, as well as copious eta production through the $\pi^- p \rightarrow \eta n$ reaction for rare-decay studies. High-energy pion-nucleus reactions make a marked change owing to important differences in the elementary two-body πN interaction as compared to lower energies. A very active user community has formed to provide guidance on the scientific program and performance criteria. An overview of their activities utilizing these new capabilities is given in section 2.

The energy of PILAC was chosen as a logical first step in expanding the frontiers of pion physics. In particular, 1.05 GeV/c is optimal to produce lambda hypernuclei through the (π^+,K^+) reaction and for investigation of lambda-nucleon scattering near the Σ threshold or cusp region. More than a dozen baryon resonances can be produced in this energy range above the (3,3) resonance, as well as copious eta production through the $\pi^- p \rightarrow \eta n$ reaction for rare-decay studies. High-energy pion-nucleus reactions undergo a marked change owing to important differences in the elementary two-body πN interaction as compared to lower energies. An overview of these areas of research utilizing the new capabilities offered by PILAC is given in section 2.

Cutting-edge technology is required to achieve the required performance. An aggressive research and development effort is now underway at the Los Alamos National Laboratory to address these challenging problems. The PILAC reference design, together with research and development activities, is discussed in section 3.

2. The Scientific Program

The energy range up to 1 GeV is rich in opportunities for pion physics. Guidance as to the optimum pion energy for PILAC can be found in Fig. 1. Shown is the present range of energies at LAMPF. The highest energies are achieved in the P^3 channel but with rapidly decreasing intensity (10^6 π/sec at 550 MeV). Also indicated in Fig. 1 is the proposed range of energies deliverable by PILAC. The flux is optimized at 1.05 GeV/c (10^9 π^+/sec). The π^- flux is typically a factor of 20 less than that for π^+. A possible future upgrade to yet higher energies is also shown. This section highlights the PILAC scientific program as developed by the PILAC Users Group. Their full report will serve as the basis of the scientific motivation for the PILAC proposal.

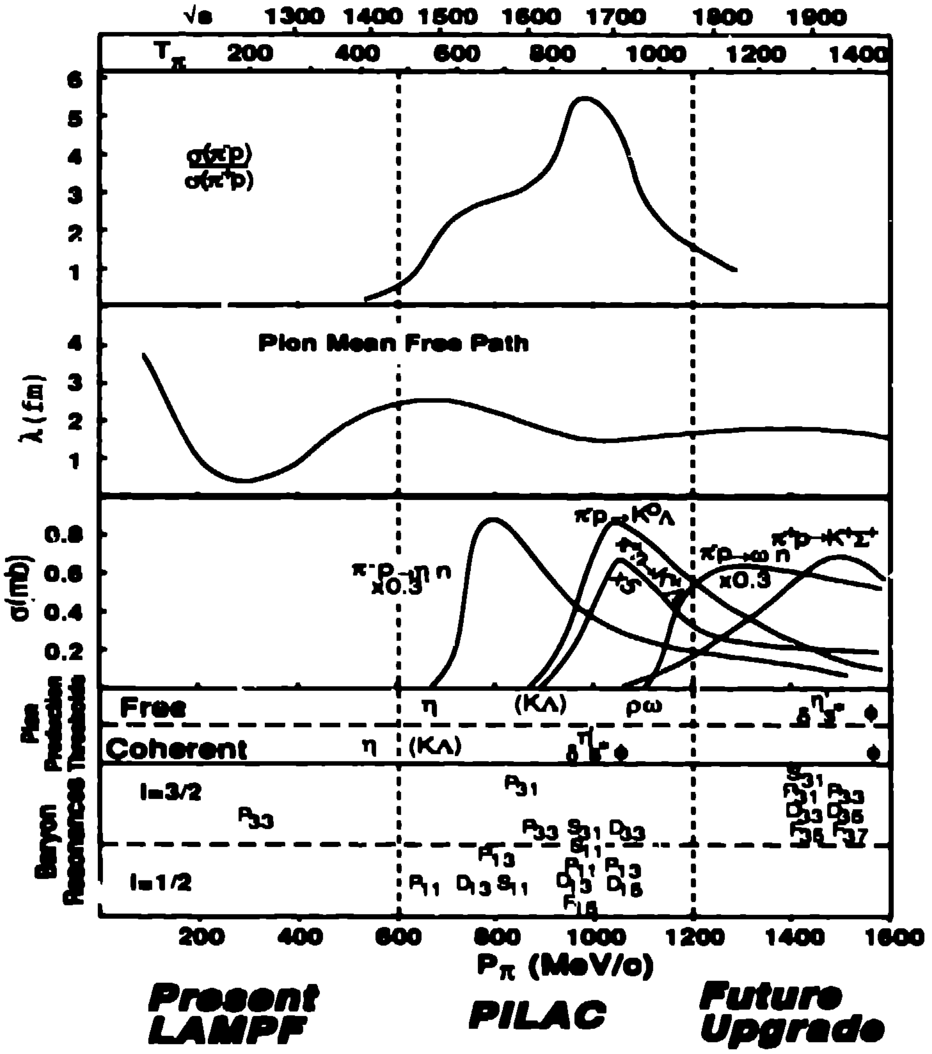


Fig. 1. Energy dependence of the two-body πN interaction

2.1 Lambda-Hypernuclei

The investigation of hypernuclei is driven by our desire to understand the strangeness degree of freedom in the nuclear medium: to explore the many body spectroscopy of a Λ in the nucleus, to discover new dynamical symmetries when a nucleon is replaced by a Λ, to comprehend the initial step in building multi-strange nuclei, to probe nuclear structure by modifying the magnetic and quadrupole moments of the nucleus in the presence of a Λ, and to explore the weak mesonic and nonmesonic decay modes of hypernuclei.[1]

The characteristic differences of the (K,π), (π,K), and (γ,K) hypernuclear production modes[2] means that PILAC has a unique role to play in these investigations. The (K,π) reaction at small angles preferentially populates the low-spin substitutional states. In contrast, the (γ,K) and (π,K) reactions select the largest ΔL. The (π,K) reaction probes the natural-parity, high-spin states as well as the ground state, whereas the (γ,K) reaction also excites the unnatural parity, spin-flip transitions[3]. Furthermore, the complementarity of the (π^-,K^0) and (π^+,K^+) reactions permits one to separate the isospin structure of the hypernuclear states produced.

PILAC would provide unprecedented intensity and resolution for hypernuclear investigations using energetic pion beams.[4] Its high-flux pion beams of 10^9 π^+/sec and resolutions of 200 keV will represent a major breakthrough in capability for this exciting field. It has been optimized at the peak of the elementary reaction $\pi^+ n \rightarrow K^+ \Lambda$ which drives the (π^+,K^+) reaction occurring at 1.05 GeV/c. Fig. 2 presents a calculated spectra for the the (π^+,K^+) reaction using a pure particle-hole interaction with no residual mixing for a medium-mass target using the PILAC system resolutions as compared to what is possible today. Although the single-particle levels are clearly seen in the low-resolution spectrum, no fine structure such as spin-orbit splitting or spin-spin effects can be seen due to the resolution. This is typical of what is measured at the present time. The high-intensity aspect of PILAC provides for more than 30 counts per day in the weakest of the states shown in Fig. 2. PILAC therefore would provide an order of magnitude improvement in resolution and two orders of magnitude more flux than that which is available today.

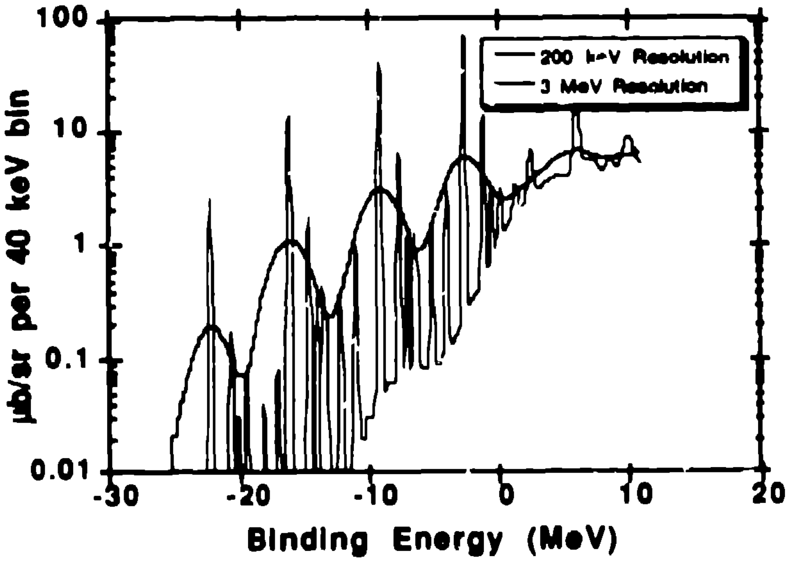


Fig. 2. Calculated (π^+,K^+) spectrum for medium-mass target with the PILAC resolution of 200 keV compared with the 3 MeV resolution available at present

The (π,K) and (π,Kγ) experiments possible at PILAC will provide new information about the structure of hypernuclear spectra which is required to define the properties of the ΛN interaction — the spin-spin, Λ spin-orbit, induced nucleon spin-orbit, tensor, and central terms.[5] The 3-MeV resolution available in present (K,π) and (π,K) experiments is inadequate to constrain the theoretical models to the degree required to define these two-body terms, to see dispersive effects due to ΛN-ΣN coupling, or to understand the size or spin dependence of ΛNN three-body forces. The selectivity of the (π,K) reaction is an essential ingredient, and resolution of the order of 200 keV is required to adequately define the level structure.[3] Additionally, at nonzero angles the (π,K) reaction produces polarized hypernuclei, negligible for unnatural parity states, and substantial for natural parity states. This new information offers a promising spectroscopic tool with which to improve the definition of the ΛN interaction.

The nonmesonic weak decay of Λ-hypernuclei provides our highest momentum transfer (shortest range) probe of the ΛN interaction. If quark-gluon aspects of QCD are to manifest themselves in hypernuclei, such decay studies will be at the forefront.[6] Regardless of that possibility, the production of ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ and study of their subsequent weak decays using the high statistics capability of PILAC provides our best means of exploring the detailed nature of both Λ+N→N+N and Λ→N+π decays in the same nucleus[7]. (Pauli blocking quickly suppresses the mesonic decay mode as A increases.) In particular, precision measurements of neutron-stimulated decay rates Λ+n→n+n could provide our most definitive test of nonmesonic decay calculations, helping to answer such questions as whether the $\Delta I = 1/2$ rule, which holds for hyperon and kaon decay, also applies to the Λ+N→N+N process.

2.2 Baryon Resonances

The study of the baryon resonances occupies a unique place in the field of hadronic physics. It provides our most direct link between our description of the nucleus (and hadronic reactions) in terms of nucleons and mesons with the underlying fundamental theories. Theories take on various forms generally based on (or inspired by) QCD. Some of the most common are the non-relativistic quark model, the collective model, string and flux-tube models, bag models, and Skyrmion models. There are also attempts to relate properties of the lowest-lying baryon resonances to QCD through QCD sum rules.

As seen in Fig. 1, the PILAC energy range also includes more than a dozen baryon resonances (N^*s and Δs) above the (3,3) resonance. Many of these resonances are poorly characterized, as little data or data of poor quality dominate this energy range. As noted by the Particle Data Group on baryon resonances, virtually all information on resonance masses, widths, and elasticities comes from pion-nucleon data. Inasmuch as the resonances above the P_{33} are highly overlapping, the parameters for these states would be obtained by partial-wave analysis of extensive PILAC scattering data over this energy range. Some of the states have unique signatures, such as the S_{11} which decays a large fraction of the time into two η's. This information will be essential to the CEBAF program, which proposes to measure form factors for many of these resonances. PILAC would provide the necessary pion beam energy, purity, and quality for the precision data needed to clearly define this region of resonances.

2.3 High-Energy Pion-Nucleus Reactions

The little work that has been done at LAMPF and BNL in the high-energy region has been with low-intensity low-resolution beams. At energies above 300 MeV, the qualitatively different properties of the elementary pion-nucleon interaction and the much shorter wavelength of the pion alter the character and type of physics questions that can be addressed. The energy and momentum transfers available for nuclear studies with pions at PILAC complements the work with electrons at CEBAF, with the pion adding the isospin degree of freedom to the reaction as well as unique properties of the pion such as double charge exchange.

Due to the much weaker two-body pion-nucleon interaction, the pion acquires a much longer mean free path in nuclei, second only to the K^+ in this energy range. At 1 GeV the pion wavelength is about one Fermi, about the size of a single nucleon, as compared to more than four Fermis at 180 MeV. These aspects of high-energy pions will provide sensitivity to the details of the spatial dependence of the ground-state and transition densities, as well as sensitivity to the modifications of the nucleon properties in the nuclear medium. To fully exploit the short-wavelength features of high-energy pions, measurements need to be carried out to substantial momentum transfer. Since the cross sections are quite small at large momentum transfer, the high intensity provided by PILAC will be essential.

Pion double charge exchange (DCX) is unique in that it is the only reaction of a non-composite particle that requires the participation of two nucleons in all of its manifestations. DCX will clearly benefit from the shorter wavelength of the higher energy pions. Just as the longer-range shell-model correlation sensitivity of low-energy DCX has been clearly demonstrated, the higher energies at PILAC will allow for a detailed study of the short-range behavior of nucleons in the nucleus. The distance scale being probed at PILAC may not be adequately described in terms of only nucleon degrees of freedom, and the transition to mesonic or other sub-nucleonic degrees of freedom could be investigated. Recent calculations indicate that an even more dramatic reduction in the DCX cross section over what is seen at 50 MeV occurs at these higher energies. Sensitivity to more exotic reaction mechanisms will therefore be enhanced.

The isospin dependence of the two-body interaction is also quite different from lower energies. As seen in Fig. 1, the ratio of π^+p to π^+n cross sections on resonance is reversed near 1 GeV. This feature can be exploited to test our understanding of the isospin dependence of the pion-nucleus interaction and the isotopic composition of various nuclear transitions.

The increased energy of pions opens the possibility of a broad program in quasi-elastic scattering. At 1 GeV, the momentum transfer to the nucleon exceeds the Fermi momentum for angles greater than 25 degrees. Under these conditions, the pion will scatter incoherently from the individual nucleons. This reaction provides an independent and complimentary probe of pion dynamics in the nucleus and of that of the nucleon in the nuclear medium, analogous to nucleon and electron scattering. The possibility of "tagging" the S_{11} resonance in the nuclear medium through its decay into eta final states now becomes possible. This would provide a method of investigating the interaction of this highly-excited hadron with the nuclear medium.

The decreasing two-body interaction strength and smooth energy dependence also has important implications for theoretical analysis and interpretation. Perturbation theory becomes increasingly more convergent, making theoretical analysis simpler and more reliable. The relative size of unconventional mechanisms, such as meson exchange currents, to the conventional pion-nucleon interaction is therefore enhanced.

2.4 Elementary Processes

As noted earlier, 1.05 GeV/c is the peak of the lambda-production cross section. Lambdas can be produced polarized in a liquid-hydrogen target, tagged by the K_S decay, and allowed to rescatter in the same liquid-hydrogen target. Using this technique, it is possible to make not only cross-section measurements of lambda-proton scattering near threshold, but also spin-transfer measurements, since the lambda is self analyzing. PILAC would provide the necessary beam energy, intensity, and beam quality to make a ±0.05 determination of σ, A_y, D_{NN}, D_{SS} and D_{SL} in 100 angle-momentum bins within a month's running time. Most of the existing data is of total cross sections, derived from a few hundred bubble chamber events. This would therefore represent a major contribution to the determination and understanding of the hyperon-nucleon interaction for which many models and predictions exist but remain untested.

Of considerable interest is the beta decay of the pion. The rate of this decay, $\pi^+ \Rightarrow \pi^0 e^+ \nu_e$, is proportional to the V_{ud} element of the CKM matrix. A precision measurement would provide a test of the standard model, which predicts this rate to 0.1%, as well as providing a check of the unitarity of the CKM matrix. Pion beta decay offers an alternative approach to this information as compared with nuclear beta decay, which now determines these quantities. The corrections in the two processes are quite different and, in the case of pion beta decay, appear to be more manageable. This experiment was performed at LAMPF in 1985 with a 3.8% determination of the rate. PILAC would provide the necessary energy, intensity, and beam quality to push the measurement to 0.2%.

A dominant channel in the total $\pi^- p$ total cross section near 750 MeV is η-production. Almost 7% of the total cross section goes into this channel. As such, PILAC would be able to provide high fluxes of tagged or untagged η's for strong and rare-decay studies. The expected yield on a 30-cm liquid hydrogen target is 10^{10} η/day. A number of very interesting rare and forbidden decays indicating physics outside the standard model would become possible. These include tests of CP violation in the polarization of $\eta \rightarrow \mu^+ \mu^-$, certain classes of pseudoscalar interactions in $\eta \rightarrow e^+ e^-$ and lepton family number violations in $\eta \rightarrow \mu^+ e^-$. A number of "ordinary" decays of the η — 2π, $2\pi\gamma$, $\pi\gamma\gamma$ — provide important probes of the ways in which the chiral symmetry of QCD is manifested. PILAC would open this area of research to precision study.

3. The Facility

A brief overview of the reference design for PILAC will be given. The major subsystems that define performance and have the greatest impact on the scientific program will be described.

3.1 Pion Production and Injection

A new zero-degree target cell will be constructed in the main LAMPF beamline, replacing some of the existing target cells. The zero-degree arrangement offers the advantages of higher pion fluxes and increased source brightness. A much thicker production target (15 cm viewed at 0° compared with the present 4-cm-thick graphite target viewed at 30°) can be used while still maintaining the small source spot size required by PILAC. The new target cell will be designed for 2 mA of proton current. This level has been successfully accelerated at LAMPF; however, the present target cells are not able to accept this power level. Experiments have been performed at HRS to measure zero-degree-pion production cross sections. Based on this information and survival fraction considerations, the optimum injection energy is determined to be 365 MeV. The yield for the target cell at this energy is $3 \bullet 10^{10}\ \pi^+/\mathrm{sec}$. Pion beams of both signs can be extracted in this configuration. By imposing a path length difference into one arm, the possibility exists to simultaneously inject and accelerate $\pi+$ and $\pi-$ beams on alternate phases of the RF. The new injection line is able to accept a large-phase-space beam (230 π-mm-mrad) and transport it to the linac without introducing large chromatic aberrations as is common with existing pion beamlines.

3.2 The Superconducting Pion Linac

A unique feature of pion acceleration is the fact that the beam decays during acceleration. It is therefore critical to perform the acceleration as quickly as possible, while meeting all conditions on beam dynamics. Central to this point is the issue of accelerating gradients and survival fractions. Fig. 3 indicates the calculated π^+ flux per milliampere of primary current for PILAC as a function of accelerating gradient. As can be seen in this figure, the design goal of $10^9\ \pi^+/\mathrm{sec}$ is achieved at an accelerating gradient of 12.5 MeV/m. Also shown in Fig. 3 are the expected yields for the proposed KAON facility under the assumption that the output phase space of the high-resolution beamline is the same in both cases. The yield for the AGS and AGS plus Booster is also shown under similar assumptions.

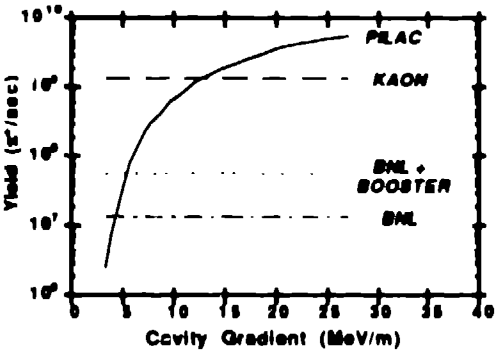


Fig. 3. Calculated π^+ yield for PILAC and other facilities

LAMPF has a long tradition of high-resolution spectrometers, in particular the HRS and EPICS facilities, and unequalled experimental support. PILAC would be a dedicated facility to systematically attack some fundamental questions in nuclear physics with the tools required to make good progress. We would fully expect strong collaborations with other facilities, particularly KAON, CEBAF, and the AGS, to address these issues with a full compliment of probes. This would only serve to strengthen the programs we have discussed.

In section 3.4 a more detailed discussion is given on the research and development activities now in progress to meet the superconducting cavity requirements of PILAC.

As currently envisioned, the linac would be constructed of seven-cell 805-MHz superconducting niobium cavities. There would be 45 of these cavities forming the 100-meter 560-MeV linac. The cavities would be contained in liquid helium cryostats operating at 2° Kelvin with cavity gradients of 25 MV/m, accelerating gradients of 12.5 MeV/m, and a Q of $5 \bullet 10^9$. The beam loading at PILAC is negligible. As such the power requirements are given by the cavities themselves. Power consumption is estimated at 100 watts per cavity, or 4.5 kW total.

All cavities are independently phased. This allows a broader range of tuning parameters that take advantage of individual cavity performance levels. Extensive beam-dynamics studies have been conducted. During the early stages of acceleration, the RF is phased so as to perform a longitudinal phase rotation to provide an output beam minimized in momentum width at the expense of time. This is optimal for injection into the high-resolution beamline.

3.3 Beamlines and Experimental Facilities

Two beamlines are envisioned for PILAC, a high-resolution channel that feeds a high-resolution spectrometer system for hypernuclear and pion-nucleus spectroscopy and a general-purpose beamline for lower resolution and large acceptance detector systems. The general-purpose beamline could also serve as an injection line for a possible future upgrade to yet higher energies. Several beam-sharing schemes are being considered.

The high-resolution system is designed for 200-keV resolution, driven primarily by the requirements of the (π^+,K^+) hypernuclear spectroscopy program. The channel utilizes vertical bends with a momentum dispersion of 25 cm/%. The momentum resolution has been calculated with ion-optic programs up to fourth order. The spectrometer utilizes a superconducting dipole and quadrupoles for increased acceptance. The overall design of the channel and spectrometer are similar to the present EPICS system at LAMPF but with important extensions for the higher energy and acceptance requirements at PILAC.

The present Medium Resolution Spectrometer (MRS) at LAMPF could serve as the lower resolution (2-3 MeV) spectrometer on the general-purpose channel. This would provide sufficient resolution for some pion scattering and DCX experiments up to full energy. Large acceptance detectors based on existing equipment such as the MEGA solenoid and large dipole magnets are also being considered for this channel for light meson decay studies and lambda-proton scattering experiments.

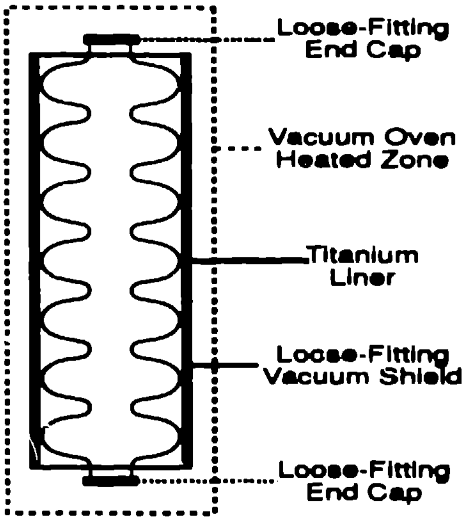
3.4 Research and Development

Research and development (R&D) is underway within the Medium Energy Physics (MP) and Accelerator Technology (AT) Divisions at LANL, supported by Laboratory funds. During FY91 the effort centered around both systems analysis, such as beam transport and dynamics studies, and superconducting-cavity development. A reference design now exists for the overall system as described in the previous sections. A brief overview of the cavity-development program relevant to PILAC will now be given.

In FY92 the R&D effort will concentrate on cavity development, given that high-gradient, high-Q superconducting cavities are central to the pion accelerator R&D plan. The goal is to demonstrate that the necessary gradient (>12 MV/m) and Q ($>2\times10^9$) can be achieved in low-frequency (805 MHz) multi-cell cavities required for the pion linac, and that both the gradient and Q can be preserved in the accelerator environment.

With conventional technologies, accelerating gradients of 5-7 MV/m can be achieved under accelerator conditions. Theoretical limits for the accelerating field for niobium are as high as 50 MV/m, set by the critical magnetic field. Several important limitations have prevented realization of these high fields. Although significant progress has been made in cavity performance over the past several years by overcoming limitations associated with multipacting and thermal breakdown, present performance is limited by field emission.

Recent developments at Cornell and Wuppertal Universities, using an apparatus like that shown in figure 4a, have shown that significantly higher fields can be achieved with new processing technologies. As seen in figure 4b, average enhancement factors of 2 in accelerating gradients have been obtained by special processes involving heat treating pure niobium cavities to temperatures of 1500° C under high vacuum over chemical treatment only. Field emission has been shown to be drastically reduced with this process, thus allowing operation at much higher electric fields. This appears to be the only process which has reproducibly achieved average accelerating fields greater than 10 MeV/m. Other processes, however, will also be investigated, such as ultra-pure rinsing techniques, improved chemical polishing techniques, and high-power RF processing. Since all tests to date have been on small samples or higher-frequency (smaller surface area) cavities, a pion accelerator will require a scaling up of this technology to lower-frequency (larger surface area) multi-cell cavities. A major milestone for the R&D plan is a demonstration of improvements realized by the heat treatment process for larger cavities.



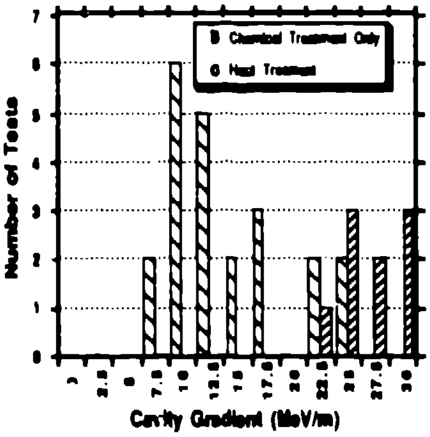


Fig. 4a (left). Heat treatment schematic used in heat-treatment cavity development.
Fig. 4b (right). Maximum peak electric field reached in cavity tests, comparing standard chemical treatment and 1500° C heat treatment.

4. Summary

PILAC is being designed to provide beams of 10^9 pions per second at energies up to 1.1 GeV, capable of upgrading to higher energies in the future. An overall system resolution of 200 keV can be achieved with a high-resolution beamline and spectrometer system defined as part of the PILAC reference design. An aggressive R&D program is now underway to demonstrate the required superconducting cavity performance for the linac in order to achieve the desired goals. PILAC will offer two orders of magnitude more flux and an order of magnitude better resolution than other 1-GeV pion beams available today. Additionally, the PILAC beam will be of extraordinary good quality and purity due to the acceleration process. A broad range of scientific studies therefore become possible with PILAC of interest to many areas of nuclear physics. In particular, the upper end of the PILAC energy range is optimal for production of lambda hypernuclei through the (π^+,K^+) reaction. More than a dozen baryon resonances are accessible with PILAC. Significant differences in the elementary two-body πN interaction at high energies will provide qualitatively new areas of investigation in high-energy pion-nucleus reactions. Copious production of pions and eta mesons will allow for precision studies of their decays. PILAC therefore offers a cost-effective approach to a dedicated facility for forefront nuclear physics research in the US.

Acknowledgments

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