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Status of PILAC:

A Pion Linac Facility for 1-GeV Pion Physics at LAMPF

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Abstract

A Pion Linac (PILAC) is being designed for LAMPF. Together with its high resolution beam line and spectrometer, the system is optimized to provide 10^9 pions per second on target and 200-keV resolution for the (π^+, K^+) reaction at 920 MeV. There will also be an achromatic beam line capable of utilizing the maximum energy available, thus opening up the possibility of a broad experimental program as is being discussed at this workshop.

What is PILAC ?

PILAC is a pion linac facility providing access to 1-GeV pions at LAMPF. The PILAC facility is shown in Fig. 1.

Fig.1. Conceptual layout of complete PILAC facility in Area-A at LAMPF.

The complete PILAC facility consists of the following items:

- 1.) proton buncher;
- 2.) new target cell for zero degree pion production;
- 3.) new pion beamline for injection into linac;
- 4.) superconducting pion linac (400-920 MeV);
- 5.) new 1-GeV high-resolution dispersed beam line and spectrometer;
- 6.) new 1.5-GeV achromatic beam line and existing MRS spectrometer;
- 7.) new experimental area and other civil engineering.

The choice of final energy for the linac is made to optimize the yield of the (π^+ , K^+) reaction on hydrogen, which peaks at 920 MeV. Since initial operation of the linac will be possible at energies at 1 GeV and above with a lower yield of pions, the high resolution beam line and spectrometer are designed for 1 GeV. The achromatic beam line and existing MRS spectrometer are designed for 1.5 GeV to allow for future upgrades of the superconducting cavities of PILAC.

Why a Pion Linac Now ?

When D. Nagle⁽¹⁾ first suggested a pion linac for LAMPF, the gradient available was not high enough to give an attractive yield of pions. To see what is required, consider the survival factor for pions in a linac with uniform gradient

$$SF \approx \left(\frac{p_f}{p_i} \right)^{\frac{m_\pi}{Gc\tau}}$$

Where p_i (p_f) is the initial (final) momentum of the accelerated pion, m_π is the pion mass, G is the acceleration gradient, τ is the pion lifetime, and c is the speed of light. If the beam is given by the following 6-vector

$$(x, x', y, y', \phi, \frac{dp}{p})$$

where x' (y') are angles, ϕ is phase with respect to the rf, and dp/p is relative momentum. The brightness of the beam (pions per unit 6-dimensional phase space) increases as the following ratio

$$B = \left(\frac{p_f}{p_i} \right)^{-3}$$

Combining these, the survival factor times brightness becomes

$$SF \times B = \left(\frac{p_i}{p_f} \right)^{\left(\frac{m_\pi}{Gc\tau} - 3 \right)}$$

The exponent becomes negative, i. e., there is a gain in brightness despite decay, if the gradient is greater than

$$G \geq \frac{m_\pi}{3c\tau} = 5.7 \text{ MeV / m}$$

The gradient is the "real estate gradient", i. e., it includes all dead spaces in the linac. The real-estate gradient can be as large as 60% of the "cavity gradient" (E_0T) usually quoted if care is taken to minimize dead spaces. Thus a pion linac can increase the brightness of a pion beam if the cavity gradient is greater than approximately 10 MeV/meter.

The decay of pions in the linac is a critical issue for PILAC as only approximately 17% of the pions survive to the end of the linac. It is therefore essential to maximize the gradient in the cavities. The yield of pions as a function of the cavity gradient is shown in Fig. 2. We have specified that the minimum cavity gradient (E_0T) be 12.5 MeV/m for PILAC.

Fig.2. Yield vs. cavity gradient for PILAC. Also shown is the yield expected if the high-resolution beam line for PILAC were to be built at KAON, at BNL after the Booster comes into operation, or at BNL today.

At the time of Nagle's talk, the cavity gradient ($E_0 T$) available was 1-2 MeV/m. With the technology now available at CEBAF, this increased to 5-10 MeV/m. Only if the titanium-heat-treatment technology (described in a later section) is used, will there be a large enough gradient for PILAC.

Cavity Shape for PILAC

The first step in maximizing the gradient available in a superconducting cavity is to minimize the ratio of peak surface field to cavity gradient ($E_0 T$). The cavity shape tentatively chosen for PILAC is given in Fig. 3. These calculations, performed by George Swain of Los Alamos, were verified independently by calculations performed at Cornell.

Diagram of Cavity Geometry
(all measurements in centimeters)

Ratio of peak surface fields to accelerating field:

$$E_p / E_0 T = 2.03$$

$$H_p / E_0 T = 3772 \text{ A / MV}$$

Shunt resistance over Q:

$$R / Q = 247 \text{ ohms / m}$$

$$R L = 0.5 V^2 / P$$

Cell - to - cell coupling :

$$k = 2.62 \%$$

Fig. 3. Shape and electrical parameters for PILAC 805 MHz 7-cell cavity.

The new cavity shape improves the ratio of peak surface field to accelerating gradient obtained in the existing cavities of CEBAF, CERN, and DESY by a factor of approximately 1.2.

History of Development of Niobium Superconducting rf Cavities

The first superconducting linac was built at Stanford by Schwettman, et al.⁽²⁾ This linac used pillbox shaped niobium cavities. The Stanford linac was limited to cavity gradients of 1-2 MeV/m by single-point multipactoring near the rectangular corners of the cavities.

The first breakthrough occurred when it was discovered that elliptical shaped cavities do not exhibit single-point multipactoring. This discovery was made simultaneously by experimental observation at Genoa⁽³⁾ and by theoretical calculations at Wuppertal.⁽⁴⁾ With elliptical cavities, the limit on field gradient was given by quenching near small defects in the surface. This effect limited cavity gradients to a few MeV/m.

The next discovery was that higher thermal conductivity can make the cavities stable against quenching at a typical small surface imperfection. By increasing the purity of the niobium, especially by reducing the oxygen content, the thermal conductivity can be raised by a large factor. The so-called high RRR (Residual Resistance Ratio) niobium allows for cavity gradients on the order of 5 MeV/m. Recent advances in cleaning and handling techniques have allowed cavity gradients of 5-10 MeV/m. The distribution of gradients achieved is very broad. Approximately 1/3 of the cavities tested to date exhibit a cavity gradient in excess of 10 MeV/m. This technology is used at CERN, DESY, KEK, and CEBAF. The essential limit on the gradient of these cavities is due to field emission. As the field is raised, the Q drops until either the power required exceeds the available cooling power or the cavity quenches.

A series of benchmark experiments was performed at the University of Geneva.⁽⁵⁾ In these experiments, a sample of niobium was examined by a field-emission microscope under high vacuum. A small oven was located in the vacuum system. It was possible to heat-treat the niobium sample without removing it from the vacuum system and subjecting it to contamination. In these experiments, it was shown that a heat treatment of the sample to 1400°C followed by rapid cooling reduced the number of discrete field emitters per unit area to zero. However, this discovery remained a laboratory curiosity for many years because there exist no

large-scale ovens for heat treatment of full-size cavities which can achieve the necessary vacuum (10^{-10} Torr) and necessary cleanliness.

Several years of experiments at Cornell were devoted to the use of a getter (either yttrium or titanium) in a niobium-lined oven in order to improve the vacuum. Although a number of high gradient cavities were achieved, the yield of good cavities was very low.

Fig. 4. Heat Treatment Apparatus

Fig. 5. Comparison of chemical-polish only and heat-treatment of 1.5-GHz single-cell cavities at Cornell.

Recently at Cornell(6), a new geometry of heat treatment was tried. Essentially, the titanium getter was used only on the outside of the niobium cavity, and only in the region of high electric field. This getter was contained by placing the titanium in a loose-fitting can on the high-field region of the cavity as shown in Fig. 4. The titanium vapor was confined in the can because of the diffusion barrier to the oven. The interior of the cavity was protected by a loose-fitting pair of caps on the ends of the cavity. These caps protected the cavity against contamination by dust and further limit the contamination of the interior surface by titanium. After heat treatment to about 1400°C , the exterior of the cavity was etched to remove the titanium-niobium interface.

Our understanding of how the process works is that the titanium sputters onto the cavity outer surface where it can remove oxygen from the niobium because of the elevated mobility of oxygen in niobium at high temperature. The titanium can be removed from the cavity after cooldown by etching without disturbing the critical interior surface because the titanium only sputters onto the outside. On the interior surface, the heat treatment eliminates the

field emission without requiring further cleaning. The results of many titanium heat treatments using the above technique on single-cell 1.5-GHz cavities at Cornell⁽⁷⁾ is shown in Fig. 5. Similar results have been obtained at Wuppertal⁽⁸⁾ using this technique at 3 GHz. All cavities which have been subjected to the titanium heat treatment at Cornell and Wuppertal have achieved gradients in excess of 15 MeV/meter, exceeding the design specification for PILAC.

Proposed Development Plan for Superconducting Cavities for PILAC

In order to establish the gradient and Q which will be achieved in the PILAC cavities, it is necessary to scale up the titanium heat-treatment technology to the larger, lower-frequency cavities needed for PILAC. We propose to carry out this work in two parallel efforts carried out simultaneously. In one effort, we will enlarge the superconducting rf laboratory to handle 805-MHz cavities. This requires a large oven, a large acid-polish system, and upgrades to numerous existing systems. Upgrading the facilities will take more than one year before multi-cell cavities can be tried. In a parallel effort during the intervening year, we propose to learn the technology using existing equipment at 3 GHz. In this year, we will also take an existing 805-MHz single-cell cavity and heat-treat it in the Cornell oven. In the second year, we will fabricate three multi-cell cavities and test these before and after heat treatment.

In approximately three years there will be three cavities available for test. We plan to take one of these cavities to the P^3 beam line at LAMPF and prove that we can use it to accelerate pions. With additional funds, it would be possible to use these three cavities as a "Super SCRUNCHER" or " η -Factory" at the P^3 beam line of LAMPF. The physics which can be addressed at this interim step is a topic of discussion at this workshop.

Injection Beam Line

The injection beam line proposed for PILAC begins with a matching section to transform the small, high-divergence pion beam produced at the production target into the larger, more parallel beam required for optimum transport through the linac. The matching section is followed by a second-order achromat consisting of four identical cells of DQQ structure. The injection beam-line layout is presented in Fig. 6. Four families of sextupoles and two octupoles correct the chromatic and geometric aberrations of the system. In an initial version of this beam line, 80% of the output beam was contained within the initial phase space

for 10-msr solid angle and 10% dp/p. More work is required to better match the beam into the linac. It is also necessary to study the target cell heating and determine the thickness of the required heat shield between the pion production target and the first quadrupole of the Injection beam line. Because of the need for a heat shield, it may be necessary to move the first quadrupole of this beam line farther downstream. This may reduce the solid-angle acceptance. Further study is required. Barbara Blind of AT-3 is responsible for the injection beam-line-options design study.

Fig. 6. Injection beam line layout for PILAC. The inset shows the pion-production target and the front-end quadrupoles.

Optimum Pion Injection into PILAC

We have addressed the question of the optimum energy and pion production angle for injection into PILAC. The maximum cross section for pion production occurs at zero degrees in the laboratory. This choice of angle also minimizes the phase space of the pion beam and allows a thicker target. However, no data are presently available for π^+ produced at zero degrees by 800-MeV protons.

A pion production experiment was carried out using HRS at LAMPF in collaboration with the University of Houston group during the summer of 1990. In this experiment, the angular distribution of π^+ and π^- were measured from 0 to 20 degrees. Electron and positron contamination were measured and various target materials were explored. Thin- vs. thick-target comparisons were made.

Fig.7. Yield of pions vs. pion energy measured at HRS. These data have been multiplied by the survival in a linac accelerating to a fixed output energy of 920 MeV.

At the present time, only "on-line" results are available. One of the on-line results is presented in Fig.7. It can clearly be seen from these data that the optimum energy for injection into PILAC is 400 MeV. An additional result of these data is a measurement showing that the ratio of π^+ at 400 MeV and 0° to those produced at 20° is 2.4. The injection beam line can tolerate up to a 16-cm-thick target. The result is that the number of pions available can be increased by a factor of 10 over the existing P^3 pion channel at LAMPF. More results will be available when the replay of these data has been completed by Mohamed Barakat of the University of Houston.

Linac Design

We propose to use 7-cell 805 MHz cavities. The number of cells was chosen to give the largest cavity which can be handled comfortably in the existing superconducting cavity lab. Six cavities will be mounted in a single cryostat as a module. A quadrupole doublet is required after each module in order to contain the 225 pi mm-mrad beam in the 12.5 cm diameter bore of the cavities. Six modules are combined to make the full linac. The total length of the linac is approximately 76 meters. The survival factor for pions in the linac is 17%.

The linac beam dynamics have been studied with program SIMILAC. The longitudinal phase space of the beam at several points in the linac is presented in Fig. 8. From this figure it can be seen that there is a 3/4-turn rotation of the longitudinal phase space between linac input and output. The output beam lies within a total momentum spread of 1.5%. The non-linearities of the linac do not distort the output phase-space diagram significantly.

The design gradient for the linac is 12.5 MeV/m and the design Q is 5×10^9 . At the design gradient and Q, the required cooling is ~4 kilowatts at 2°K . A refrigeration system of this size is being installed at CEBAF. Because of the refrigerator's large cost, it is important that Q be maximized.

Fig. 8. Beam dynamics of the PILAC Linac as computed with program SIMILAC.

Further study of the linac beam dynamics is needed to assure that we have the largest possible longitudinal acceptance. We also need to study the tuneup procedure and the operating point modifications needed for higher or lower output energy. George Swain is responsible for the linac beam-dynamics studies for PILAC.

Proton Buncher

In order for the pion linac to accelerate pions, the pions must be bunched within the longitudinal acceptance of the linac. Typically, the time spread of pions accepted by the linac designs under consideration is approximately 60 picoseconds. The bunch width of protons at the end of the LAMPF linac is approximately 20 picoseconds. But, due to the energy spread of the proton beam, the proton bunch width is greater than 100 picoseconds at the A-2 target. The proton bunch can be restored to the bunch width at the end of the linac if a bunching cavity is located at the mid-point of the distance between the linac and the pion production target.

A bunching cavity of 12 MV and 800 MHz located in the thin-target region satisfies this requirement. The required bunching voltage is large, but substantially less than that of one LAMPF module. Thus it could be run with one standard LAMPF klystron and modulator. A feasibility study for such a buncher is being undertaken by Rod Smythe at the University of Colorado.

High-Resolution Beam Line and Spectrometer

A high-resolution beam line has been designed using program MOTER⁽⁹⁾. This beam line, a QDQDMDQDQ design, has a momentum dispersion of 25 cm/% and a horizontal dispersion of 5 mrad. a layout of the proposed high-resolution beam line is presented in Fig. 9. The resolution of this beam line calculated by MOTER for 113- π -mm-mrad by 1.5% dp/p phase space is one part in 10⁴.

Fig.9. Schematic layout of the proposed high-resolution beam line for PILAC.

A spectrometer with acceptance matched to this beam line has also been designed. The design is very similar to that of the existing EPICS spectrometer at LAMPF except that the bending magnet has been made from a single unit in order to minimize the flight path of kaons in the spectrometer. Using superconducting quadrupoles and dipoles patterned after the Hall-C spectrometer under construction at CEBAF, it has been possible to raise the acceptance of this

spectrometer to 30 mrad for the full 40-cm-high beam spot of the high-resolution beam line. This spectrometer has a four-times larger acceptance than the existing EPICS spectrometer. For a front drift chamber package providing 0.07 mm x 0.7 mrad fwhm resolution, the resolution of the entire system of beam line and spectrometer is calculated to be 170 keV using program MOTER. A layout of the proposed high-acceptance, high-resolution spectrometer is shown in Fig. 10.

Fig.10. Schematic layout of the high-acceptance 1-GeV spectrometer for PILAC.

A calculated spectrum for (π^+, K^+) on ^{90}Zr is shown in Fig. 11. In this figure, the spectrum is shown with 3 MeV resolution, similar to that available today, and with 200 keV resolution as specified for PILAC. PILAC will have a sufficient counting rate to obtain 30 or more counts in every state shown in Fig.11 in a 10 day run on a 100 mgm/cm² ^{90}Zr target.

The beam-line design is a collaborative effort among Harald Enge of MIT and Zenghai Li and Arch Thiessen of Los Alamos. Zenghai Li and Arch Thiessen have been responsible for the spectrometer design calculations. Further study of options to reduce the length of the beam line and spectrometer need to be undertaken before proceeding to design the magnets.

Fig. 11. Calculated spectrum for (π^+, K^+) on ^{90}Zr at 10° in the laboratory with 200-keV and 3-MeV resolution. The cross section calculations were performed by John Millener of BNL. H. A. Thiessen estimated the linewidth of the states shown.

Achromatic Beam Line

Fig.12. Schematic layout of Achromatic Beam Line for PILAC. Achromatic line bends in horizontal plane. High-resolution line bends in vertical plane.

A beam line capable of providing a 1-cm-radius achromatic beam spot and also 2-3 cm/% horizontal dispersion (for use with the existing MRS spectrometer) is being designed by Naifeng Mao. At the present time, we are working on a design that switches pions between the high-resolution beam line and the achromatic line by turning off the first bending magnet of the high-resolution line. A layout for the achromatic line is shown in Fig.12. We will next turn our attention to the problem of retuning this line to obtain a dispersed beam for MRS.

Detector Package for the PILAC High-Resolution Spectrometer

At this early stage in the design, we are considering front and rear drift-chamber packages similar to those now in use in the EPICS spectrometer at LAMPF. The resolution of the existing detectors extrapolated to 0.7 GeV/c is 0.07 mm by 0.7 mrad fwhm including multiple scattering in the windows, etc. This detector resolution has been used in the resolution calculations for the spectrometer.

In addition to the drift chambers, there needs to be a front "start" detector for the time-of-flight measurement in order to distinguish pions from kaons. The time separation is approximately 5 nanoseconds. It may be possible to develop a special drift chamber optimized for time resolution and use the inverse of the usual position-time correlation to measure time. If this does not prove to be possible, then we will need to use a thin plastic scintillator for a start signal for the time-of-flight system. The energy straggling in such a scintillator may limit the resolution of the spectrometer.

Summary and Conclusions

PILAC is being designed to provide a beam of 10^9 pions per second at 920 MeV, with a future upgrade to 1500 MeV. We have demonstrated that the required system resolution of 200 keV can be achieved in a high-resolution beam line and spectrometer. In order to provide the necessary flux, the linac requires superconducting cavities which achieve 12.5 MeV/meter. Although no linac presently operates at this high a gradient, tests at laboratories around the world have shown that this gradient can be achieved by titanium heat treatment of the cavities. An r&d program is proposed to scale up the results from single-cell 1.5-3 GHz cavities to the necessary 7-cell 805-MHz cavities. Feasibility studies are underway on the target cell and front-end magnets to provide the necessary injection beam line for PILAC. We are optimistic that these studies will show that the required intensity can be achieved with reasonable components in the target cell.

In its initial stage, PILAC will provide an energy of 920 MeV with operation possible up to 1100 MeV at reduced intensity. This energy is sufficient to optimize the yield of the (π^+, K^+) reaction and to access a broad range of interesting physics. The PILAC energy resolution, 200 keV, is more than an order-of-magnitude better than that which is available today and will give access to a wealth of information on hypernuclear physics. PILAC is cost-effective since it is by far the least expensive upgrade to LAMPF which gives access to this physics. The new superconducting cavities represent a new technology which will open up applications in other fields. Finally, PILAC is feasible only at LAMPF, since only LAMPF has the necessary tightly bunched proton beam to produce pions which can then be accelerated in a superconducting linac.

References

- 1.) D. E. Nagle, Proc. Int. Accel. Conf, Novosibirsk (1967).
- 2.) C. M. Lyness, M. S. McAshan, R. E. Rand, H. A. Schwettman, T. I. Smith, and J. P. Turmeaure, IEEE Trans. Nucl. Sci, NS-28, 3445(1981).
- 3.) V. Lagorrsino, G. Manuzio, R. Parodi, R. Vaccerone, IEEE Trans. Mag-15,25(1979).
- 4.) U. Klein and D. Proch, Proc. of the Conf. on Future Possibilities for Electron Accelerators, Charlottesville, p. N1-17(1979).
- 5.) Ph. Niedermann, N. Sankarraman, R. J. Noer, O. Fischer, J. Appl. Phys. 59,3851-60(1986).
- 6.) H. Padamsee, IEEE Cat. No. 87CH2387-9,1691(1987).
- 7.) Q. S. Shu, W. Hartung, A. Leibovich, J. Kirchgessner, D. Moffat, R. Noer, H. Padamsee, D. Rubin, and J. Sears, Proc. Appl. Sup. Conf. , Snowmass, Sept. 24-28, 1990(to be published).
- 8.) R. W. Roth, H. Heinrichs, V. G. Kurakin, G. Muller, H. Piel, and J. Pouryamort, Proc. 2nd European Particle Accelerator Conference (EPAC), Nizza, 1990(to be published).
- 9.) H. A. Thiessen and M. M. Klein, Proceedings of the 4th International Conference on Magnet Technology, Brookhaven, N.Y., 8-17(1972).

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