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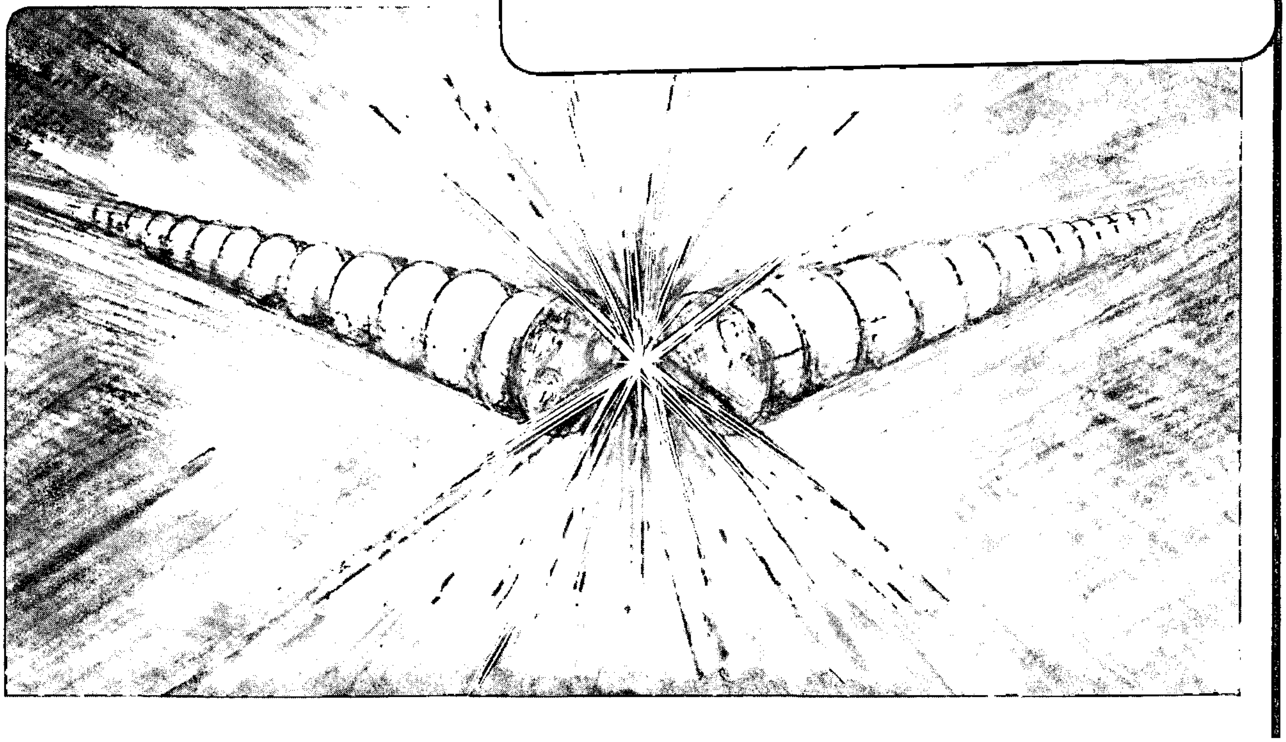

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Abstract

Phase probes have been placed in several external beam lines at the LBL heavy ion linear accelerator (SuperHILAC) to provide non-destructive velocity measurements independent of the ion being accelerated.[1] The system uses three probes in each line to obtain accurate velocity measurements at all beam energies. Automatic gain control and signal analysis are performed so that the energy/nucleon along with up to three probe signals are displayed on a vector graphics display with a refresh rate better than twice per second. The system uses a sensitive pseudo-correlation technique to pick out the signal from the noise, features simultaneous measurements of up to four ion velocities when more than one beam is being accelerated, and is controlled by a touch-screen operator interface. It is accurate to within +/-0.25% and has provisions for on-line calibration tests. The phase probes thus provide a velocity measurement independent of the mass defect associated with the use of crystal detectors, which can become significant for heavy elements. They are now used as a routine tuning aid to ensure proper bunch structure, and as a beam velocity monitor.

Introduction

The SuperHILAC is capable of accelerating elements ranging in mass from hydrogen to uranium. As the linac can accelerate ions to different velocities ranging from 1.2 MeV/AMU to 8.5 MeV/AMU it is essential to have an unambiguous measurement of the beam velocity to satisfy the experimental requirements. Under normal operation as many as three different ions are accelerated on a pulse to pulse basis with a maximum repetition rate of 36 Hz, so the measurements must be made during the appropriate machine pulse.

A system of capacitive electrodes called phase probes has been installed at the SuperHILAC to provide unambiguous velocity measurements for all ion beams irrespective of their masses. These phase probes are similar to those in use at GSI,[2] but with a considerably more elaborate control and analysis system. The phase probes were briefly described at the 1985 Particle Accelerator Conference,[1] and a summary of the improvements made to the system to enable it to be used as a real-time tuning aid and non-destructive velocity monitor was presented at the 1987 Particle Accelerator Conference.[3] This paper will provide a detailed description of the entire system.

Principles of Operation

Six phase probe systems have been set up in the SuperHILAC experimental area, as can be seen in figure 1. Each system consists of three capacitive pick-up electrodes coaxial with the beamline. The probe, shown in figure 2, forms the center conductor of a coaxial 50 ohm line. The 70 MHz beam bunch generates a signal by capacitively coupling to each cylindrical probe as it passes along the probe axis. This signal is sampled at a sampling rate of about 2 MHz resulting in an alias frequency of 2 kHz. The aliased signal, which looks like the original phase probe signal but has a duration $(70 \times 10^6)/(2 \times 10^3)$ times as long, is amplified, digitized, and transmitted to a microcomputer where analysis takes place.

The three electrodes are spaced apart unequally, with a short distance between two of the electrodes and a longer distance to the third electrode. The short distance provides a coarse estimate of the beam velocity while the long distance is used for an accurate velocity measurement. All times are referenced to the RF period, so that probe signals separated by an integral number of RF periods appear identical. The short distance is such that the beam transit time is between 0.5 and 1.5 RF periods for velocities between 1.2 and 10 MeV/AMU. The energy calculation makes use of this coarse velocity to determine the correct number of integral RF periods to add to the fractional period obtained from the time difference between the signals of probes 1 and 3, the longest separation in a system. This procedure results in an accurate, unambiguous determination of the beam velocity. Since the long distance is about eight times the short distance, and the fractional period can be read to about one part in fifty, the system accuracy is +/-0.25%. Other sources of error, such as long term drift of delay lines, are ruled out since the system calibration is checked automatically whenever a new beamline is chosen, as is described below.

The system is fully computerized, with all controls accessible from a console in the main control room. During normal operation the beam energy/nucleon is displayed on a vector graphics display in the control room along with the three probe signals, and updated twice per second. This rapid update rate is essential for using the phase probes as a real-time tuning aid. The operator has the option of choosing which set of probes to use and which of the 36 pulses/sec to observe, and can change the gain of individual probe amplifiers to match the beam intensity, or take advantage of the autogain option.

Hardware

The distribution of the phase probe hardware is illustrated in figure 3. There are four major components. The probes themselves are located in the experimental areas. The sampling heads are also located in the experimental area, within easy cabling distance of all six probe systems. High quality semi-rigid cable connects the sampling head to each probe since it is essential that the cable length be stable and accurately known. The input probe cables are connected to a PIN diode array. During "idle" time the heads are locked on a low level 70 MHz reference signal sent directly from the accelerator RF system. The sampling heads use an approximately 2 MHz sampling rate to alias the 70 MHz signal to a 2 kHz representation. A 2 kHz oscillator provides a reference square wave which is compared to the aliased signal using a phase lock loop for each probe. If the alias signal drifts from the 2 kHz reference, an error signal is sent to voltage controlled oscillators which adjust the sampling frequency for the sampling heads.

During the desired beam pulse a control signal from the beamline select module causes the PIN diode assembly in each sampling head to connect the appropriate probes to the sampling heads. The 2 kHz sample waveform is built up from repetitive probe signals over a 2 msec (minimum) pulse length. Aliased signals from all three probes are collected and brought to a camac crate. This crate contains three amplifiers (one for each probe signal) capable of auto-ranging locally or of having the gain controlled by a signal sent from the computer. In addition, the Analog to Digital Converter, a four channel LeCroy 8210 10-bit digitizer with an 8800/10 memory module, is in this rack. All four channels, three probe signals and the reference square wave, are simultaneously digitized at a 1 sample/microsecond rate. The reference signal is used by the analysis program to mark the endpoints of the aliased 70 MHz frames.

The digitized waveforms are then read using a parallel connection into a multibus-based controller called an Input/Output Micro-Module (IOMM) where the processing and data reduction is performed. This module contains two 8086 based single-board computers and a camac interface. One computer, which contains the phase probe programs in EPROM, performs the data reduction with the aid of a math coprocessor. The other is used for communication to the control room. A 38.4 kbaud serial link is used to send the reduced data to the control room where the Display Micro-Module (DMM) receives it and displays the waveforms and the measured velocity on a vector graphics display (HP1350 and HP1340). The operator makes selections and controls the displays from a touch-screen. The DMM, vector graphics display, touch-screen, and IOMM hardware are all part of the existing control system for the SuperHILAC, so the phase probe system was easily integrated.

Before the latest modifications the signal analysis was performed by an Intel Development Microcomputer in the control room. Extensive testing showed that the accuracy of the measurement decreased when less than 500 time points were used to represent one RF period. In addition, since we skip the first RF frame to allow the electronics some settling time and then average the next three RF frames, 2,000 points are used for each probe signal. Since there are three probe signals and one square wave reference signal, four times 2,000, or 8,000 points are needed for the analysis. Shipping the 8,000 data points from the digitizer to the control room by means of the serial link requires about seven seconds. To reduce this time all signal analysis is now performed in the IOMM, which is connected to the camac crate by a parallel link. Only the 150 points needed for the three phase probe signal displays, the reference time for each display (marked by an "X"), and the calculated beam velocity need to be transmitted to the control room. This reduces the transit time to a small fraction of a second, so that the calculation time (to be discussed in the next section) becomes the primary impediment to increasing the update rate of the system.

A calibration chassis is located in the experimental area to provide reference signals to check out the system. This chassis sends mock beam signals, generated from the 70 MHz accelerator RF, to the phase probes each time a new phase probe line is chosen, or whenever a calibration of the system is desired by the operator. Figure 2 shows that each probe has two connectors, one for signal output and one for input of the calibration signal. By sending the calibration signal directly to the probes, to be treated exactly like a beam signal from that point on, the entire system is tested. When the calibration signal is not being used the input is terminated in 50 ohms through a PIN diode in the calibration chassis. Precisely cut delay lines are used to send the calibration signals to the probes, three lines for each of set of three probes. The lines are cut to simulate the arrival times of an 8.3 MeV/AMU beam at each probe, with different delays needed for each set of probes since the probe separations are not the same. The simulated signal from the calibration chassis that is sent to the phase probes is analyzed by the standard data acquisition system and the system is considered to be functioning correctly if the result is between 8.27 and 8.33 MeV/AMU. During the initialization of a new beamline the system remains in the calibration mode so that the problem can be diagnosed by the operator if the result is outside the acceptable range. If the result is within specifications the system automatically switches out of the calibration mode and into operational mode.

The control console is shown in figure 4. This console allows the operator to determine which of the phase probe systems is active. Up to four systems can be active at a time, with the beam velocity displayed on the console for each active system. Each probe's gain can be set from the console or an autoranging option can be chosen. The operator can decide which of the three probe signals is to be displayed on the vector graphics display, or can display all three signals at one time. In addition, since there are two sets of vector graphics displays, signals from two probe systems can be displayed simultaneously. A sample signal display is shown in figure 5. In addition to the phase probe signal, the velocity, beamline name, and the timeshare mode are displayed, where the timeshare mode shows which of the 36 pulses per second are being displayed.

It is important to note that the touch-screen control console is extremely simple to use. Rather than typing in the various parameters needed for a computer program to run the system the entire system can be run with a few touches of the console. This ease of operation ensures that the program is used routinely as a velocity monitor, and also as a diagnostic to monitor the bunch structure both while tuning up the beam and during normal operation. In addition the phase probe system is used to monitor changes in the energy as requested by the experimenter.

Data Analysis

An ideal phase probe signal is similar to one full period of a sine wave. The function of the data processing program is to pick out a reference time from the signal of each of the three probes. Originally the signal was integrated to pick out the zero crossing, using the maximum value of the integrated signal. This method worked well when the signal to noise ratio was large. However, this method tended to amplify the contribution of low frequency noise, rendering the results erroneous when the beam current was low. A pseudo-correlation technique is now used to pull out the signal from the noise. Conceptually the technique works as follows. The actual phase probe signal is multiplied by an ideal phase probe signal at each point in time, and the sum is taken. The idealized signal is then stepped in time and the process is repeated until the idealized signal is swept through the entire probe signal. When the signals are coincident in time, the sum will be a maximum, so the time step where the sum is maximized represents the needed reference time. This pseudo-correlation is performed for each of the three probe signals and the reference times are compared. Noise contributions are minimized since only that part of the noise which falls under the ideal signal contributes to the sum.

In practice, doing the requisite number of floating point multiplications takes about two seconds of computer time for each of the three, 500 point, probe signals. The sine wave used as an idealized signal has a period of 150 points out of the 500 point RF frame. Since multiplications only need to be performed where both signals are non-zero, the number of multiplications were already reduced by 70% to obtain the two second calculation time. Therefore a number of techniques were used to reduce the calculation time. It was recognized that the two-fold symmetry of the sine wave could be used to reduce the number of multiplications by a factor of two, using only the positive part of the idealized signal and subtracting the appropriate half sum representing the negative part. Normalizing the signals allowed us to achieve sufficient accuracy using integer arithmetic instead of floating point multiplications, greatly reducing the time. The idealized signal was digitized in steps to allow the calculations to be accomplished by shifting binary bits in the actual signal, further reducing the calculation time. Finally, since the idealized signal consists of a series of small plateaus, only the end points of which need to be changed as the signal is stepped in time, the number of points which need to be calculated for each step of the half-wave correlation is reduced to sixteen. This combination of improvements has allowed us to calculate the velocity in less than 0.3 seconds, compared with the initial time of six seconds.

Conclusion

On-line real-time velocity measurements are being routinely performed at the SuperHILAC. The phase probe system provides a convenient means of determining the beam velocity to an accuracy of +/-0.25%. Operators can easily examine both the velocity and the bunch structure of each of the different beams being accelerated at any one time, regardless of the difference in beam intensities, energies, or masses. The phase probe system, with an update rate of two times per second, provides an accurate velocity monitor and tuning aid.

Acknowledgements

We wish to acknowledge the initial design of the phase probe system by B. Leeman and D. Howard, and the early programming work by D. Brodzik. S. Magyary helped us to increase the update rate by programming the correlation routines in assembly language. In addition, this work could not have been accomplished without the support of J. Alonso and H. Syversrud.

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[2] J. Klabunde, V Schaa, E. Schaffner, P. Strehl, H. Vilhjalmsson, D. Wilms, "Measurements of Energy, Energy Spread, and Bunch Width at the Unilac," Proceedings of the 1979 Linear Accelerator Conference, pp. 297-303.

[3] B. Feinberg, D. Meaney, R. Thatcher, C. Timossi, "Superhilac Real-Time Velocity Measurements," Proceedings of the 1987 Particle Accelerator Conference, IEEE #87CH2387-9, 649 (1987).

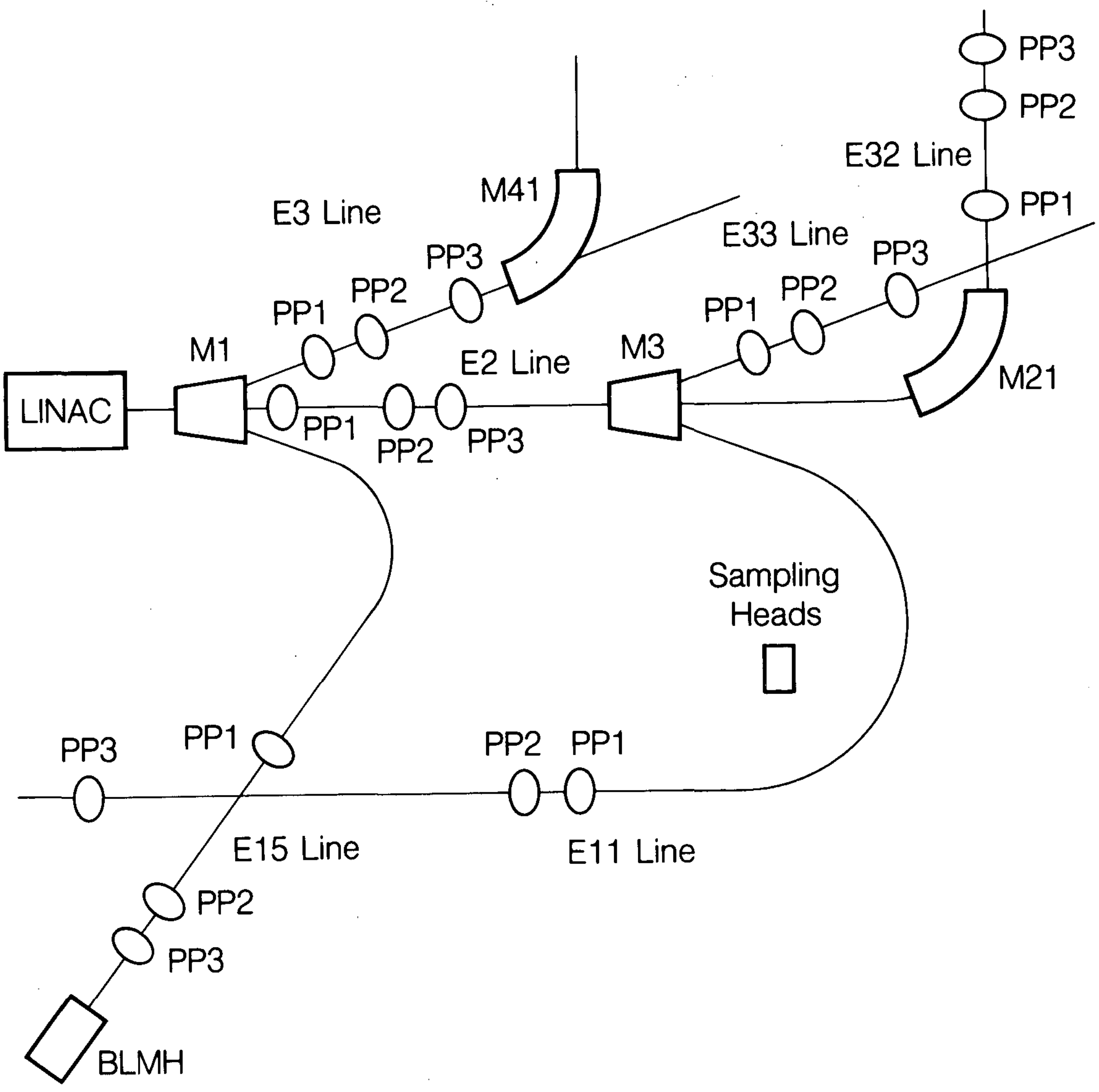

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Figure 1 - Schematic of the phase probe locations in the beamlines leading to the experimental caves.

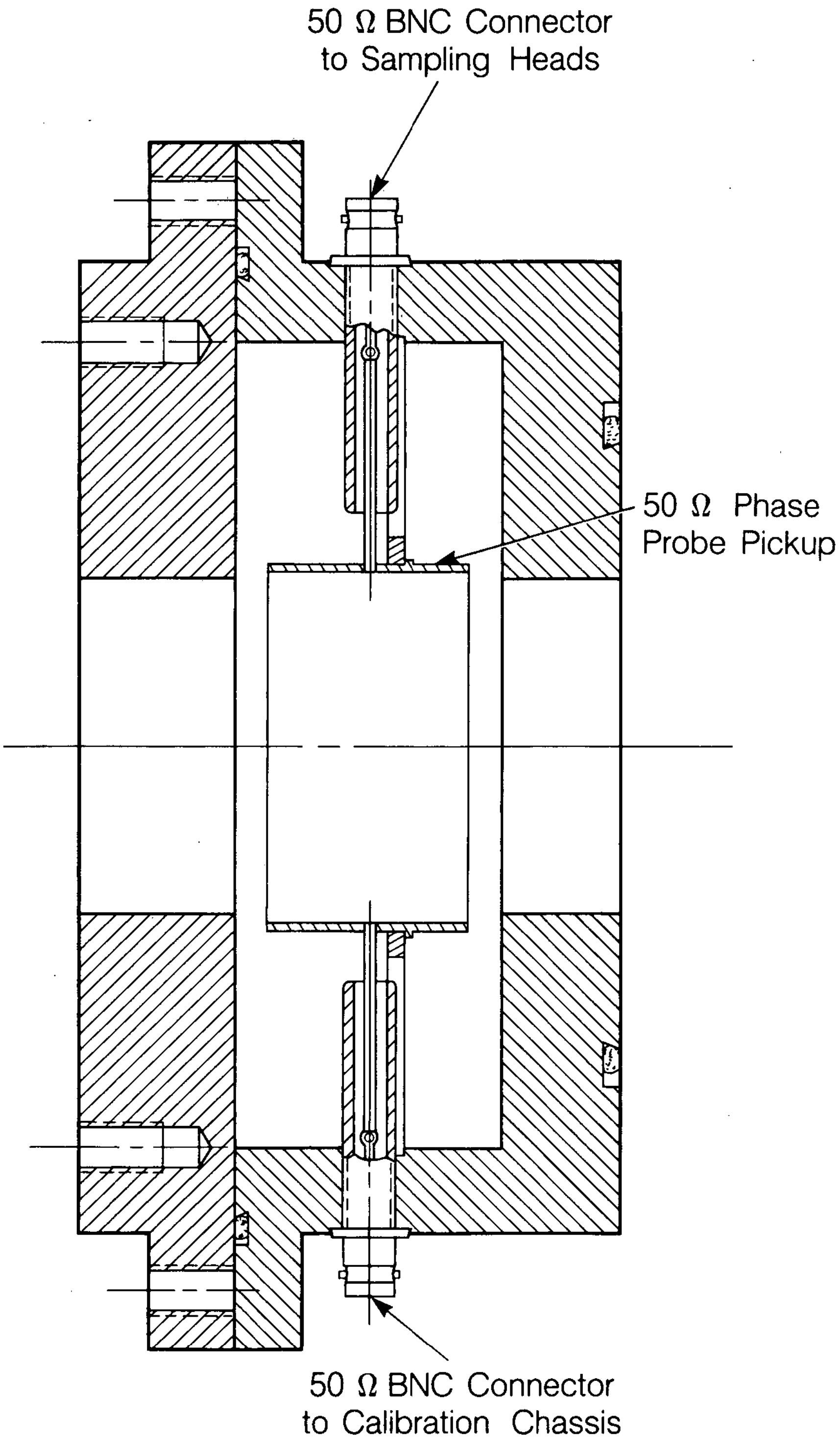

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Figure 2 - Assembly drawing of one phase probe. Note the 50 ohm geometry and the existence of two feedthroughs, one for calibration input and one for signal output.

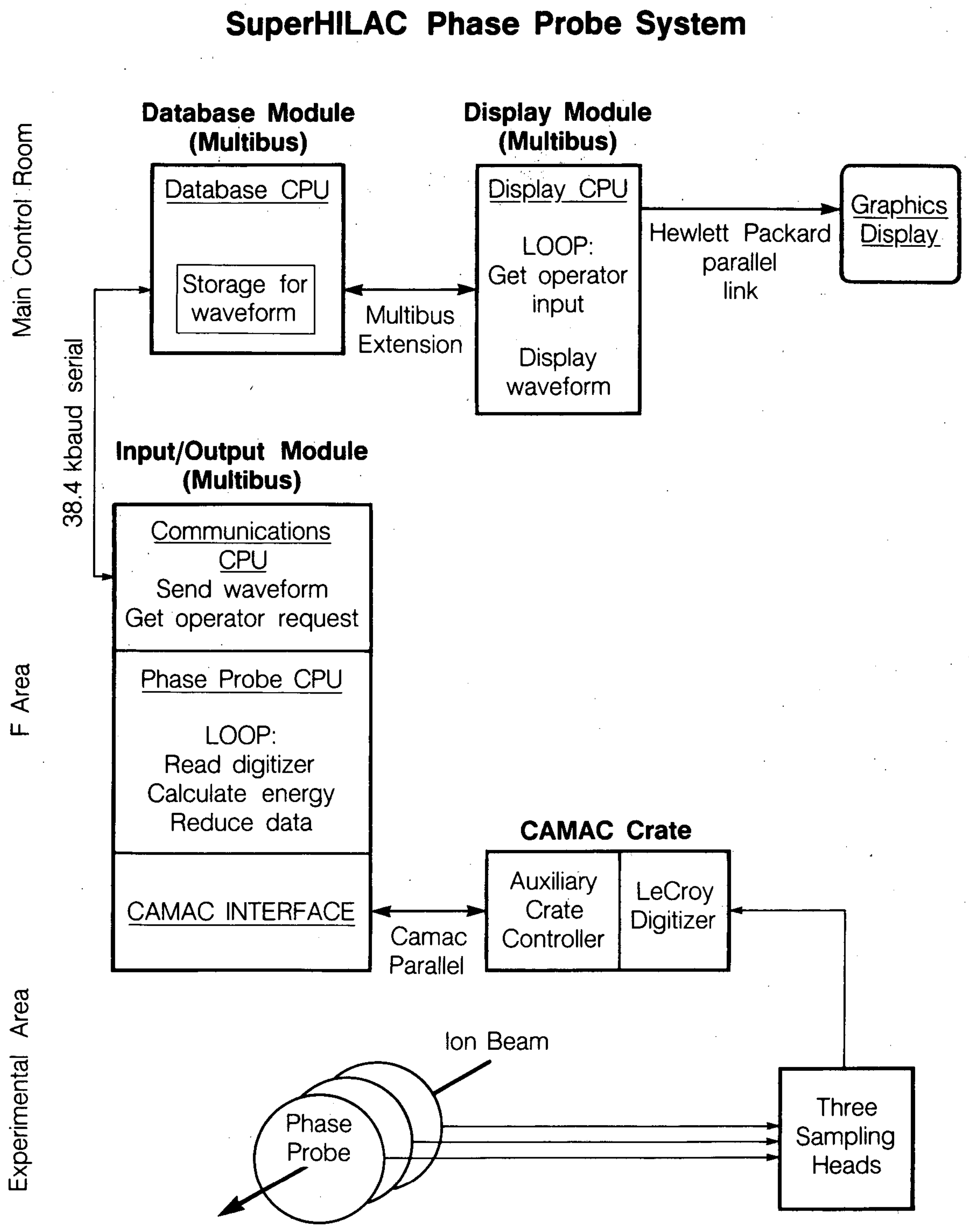

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Figure 3 - Block diagram of the phase probe system, showing the control console and vector graphics display in the control room, the electronics and the microcomputer in the "F" area, and the sampling heads and calibration chassis in the experimental area.

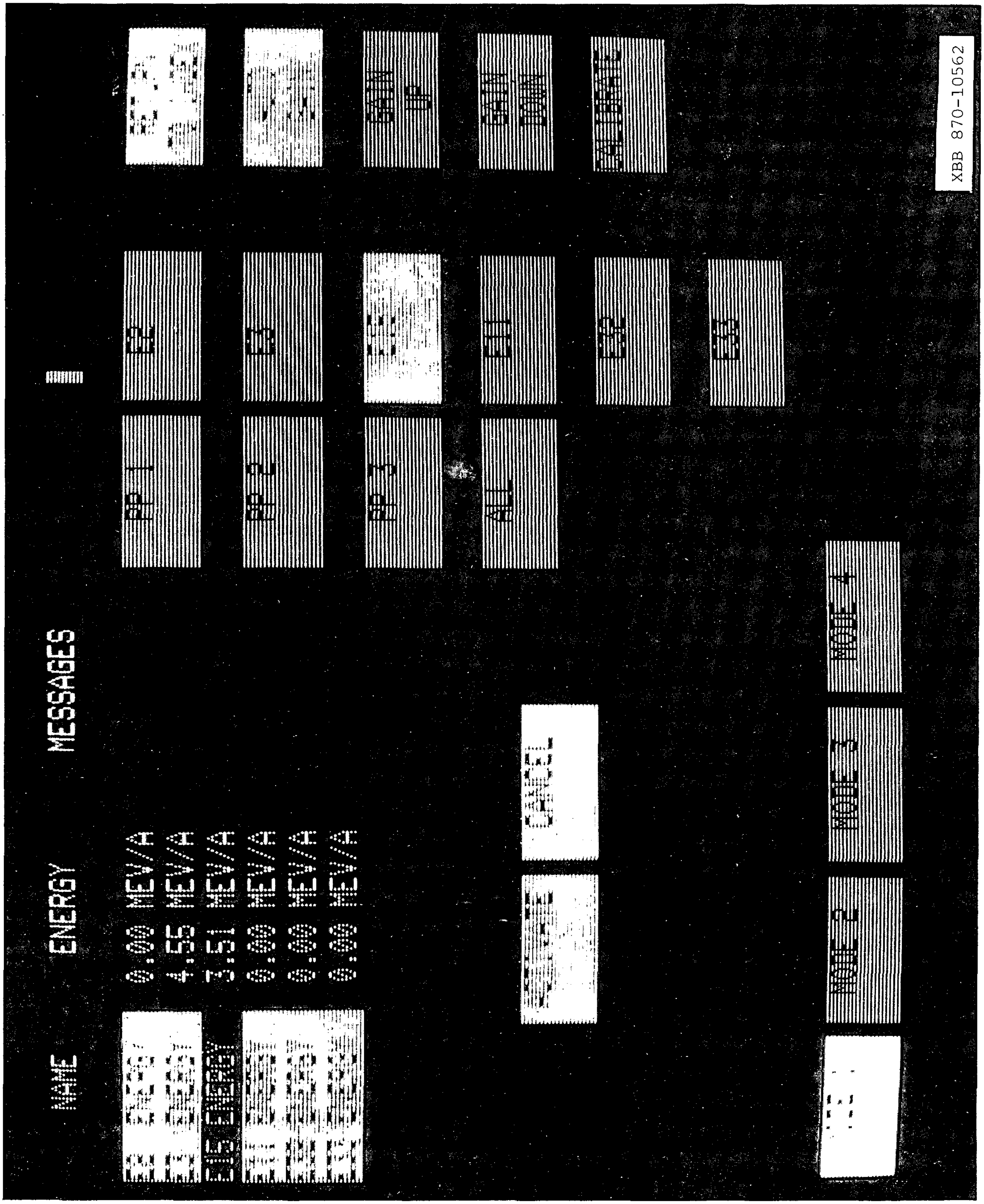

Figure 4 - Photograph of the touch-screen control console in the control room. Note that the individual phase probe systems in operation are highlighted, and that all controls are accessible by means of the touch panel display.

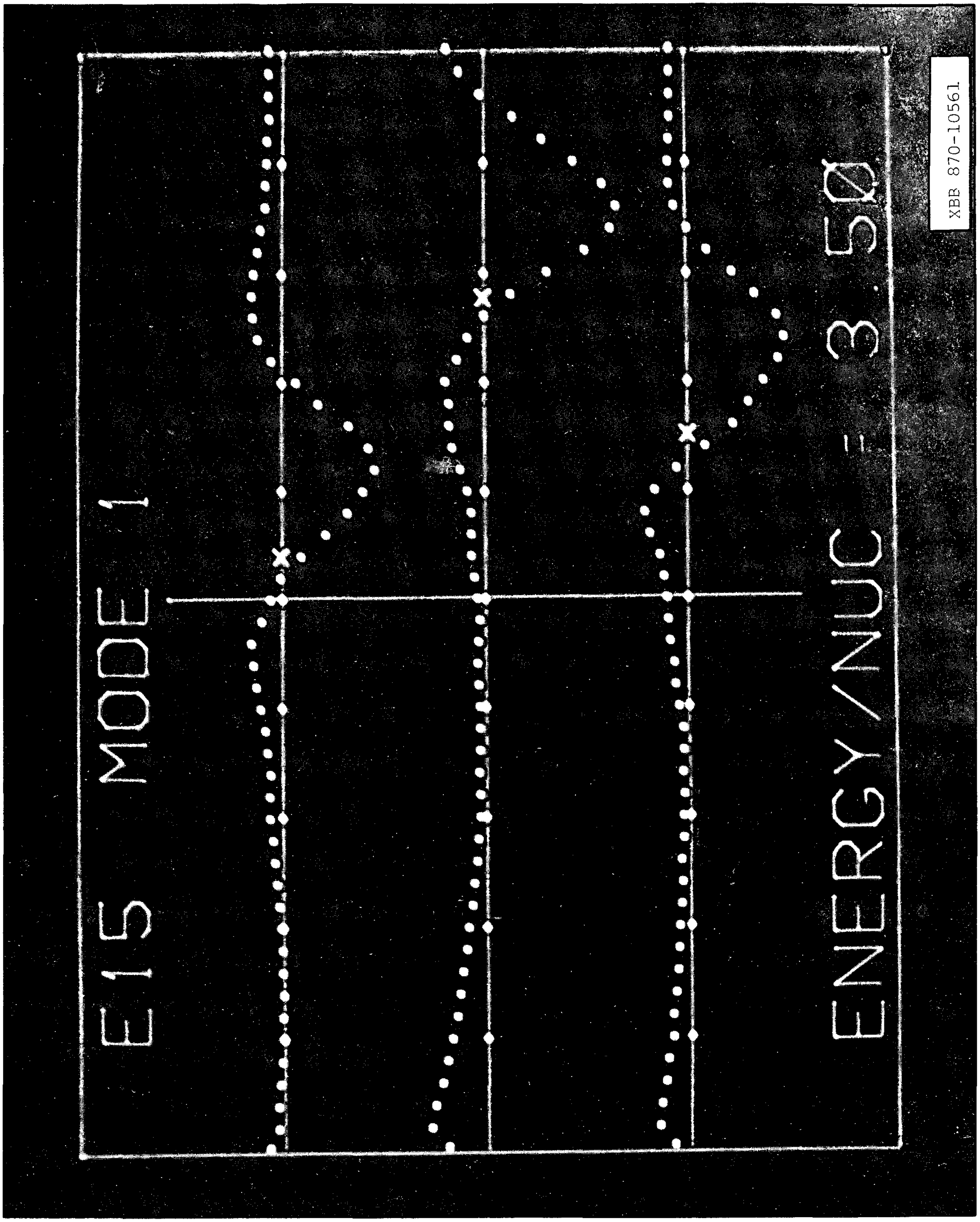

Figure 5 - Photograph of the phase probe signal. The beam velocity (in MeV/AMU) is clearly displayed, along with the mode and beamline name. This display updates about twice per second when only one phase probe system is active.