Conf-830311--104 TIC

ENERGY MEASUREMENT USING A RESONATOR-BASED TIME-OF-FLIGHT SYSTEM

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CONF-830311--104

DE83 010580

I. Introduction

A resonant pickup time-of-flight system has been developed for the precise measurement of beam energy at the Argonne Tandem-Linac Accelerator System (ATLAS). The excellent timing characteristics available with ATLAS beams (time widths of 100 ps FWHM or better on target) make it desirable to design the beam transport system to be isochronous. Therefore, the use of a dispersive magnetic system for energy analysis would require a large amount of building space and be unduly expensive if both energy analysis and isochronous transport were required.

The resonant time-of-flight system which has been developed has the following advantages over other potential approaches.

1. The system is non-interceptive and non-destructive. The beam phase space is preserved.
2. It is non-despersive. Path length variations are not introduced into the beam transport which would reduce the timing resolution.
3. It has a large signal-to-noise ratio when compared to non-resonant beam pick-up techniques.
4. It provides the means to precisely set the linac energy and, potentially, to control the energy in a feedback loop if desired.
5. It is less expensive than an equivalent magnetic system.

II. Implementation

The resonant pickup time-of-flight system consists of two beam-excited resonators, associated electronics to decode the information, a computer interface to the linac PDP 11/34 control computer, and software to analyze the information and deduce the measured beam energy. A schematic overview of the system is shown in Figure 1.

A. Resonators

The resonant pickups chosen for the system are λ/2 helix resonators. These resonators are tuned to the beam pulse frequency of 48.5 MHz and are matched to a synchronous particle velocity of $\beta = 0.1$. Each resonator is 0.32 m long and has an inner diameter of 11.0 cm. The helical structure is constructed of 0.64 cm diameter tubing with a major coil diameter of 5.5 cm and a pitch of 2.31 cm. The resonators are constructed of stainless steel which is plated with silver to a thickness of one mil. This construction approach produces a rugged inexpensive design with excellent vacuum characteristics.

In a resonant detector, the field induced by a beam pulse decays exponentially and is given at time t after the pulse by

$$E(t) = E_o e^{-\omega t/Q}$$

where $\omega = 2\pi f$ and f is the resonant frequency of the

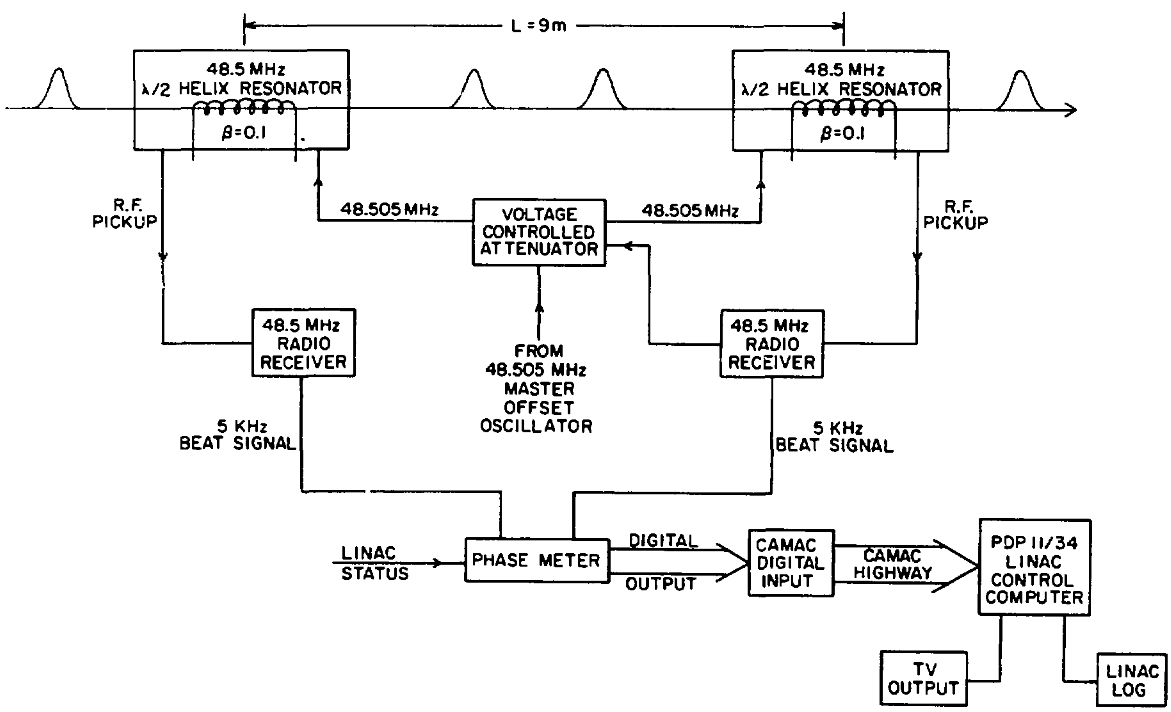

Figure 1. Schematic of Resonant Beam Energy Measurement System.

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detector. For these resonators, the Q is approximately 1900. The induced field at any moment in the resonator is an average of many pulses with an averaging time constant of approximately 6 microseconds (300 beam pulses).

B. Signal Processing

Each resonator is excited by the beam pulses at a frequency of 48.5 MHz and also by a reference signal with a frequency of 48.5 MHz + 5 kHz. The resultant field in the resonator has an amplitude modulated component with a 5 kHz frequency. The phase relationship between the beam induced field and the master oscillator is contained in the phase of the 5 kHz A.M. signal. The relative phase of the beam-induced fields in the two helix detectors is related to the relative phase of the respective 5 kHz signals by

$$\phi^1_{beam} - \phi^2_{beam} = \phi^1_{5KHz} - \phi^2_{5KHz} + \theta,$$

where θ is a constant offset phase.

A schematic of the electronics used in this system is shown in Figure 1. The modulated field in the resonator is sent to a radio receiver which detects the 5 kHz side-band frequency. The phase of that amplified signal is measured with respect to a similarly processed signal from the second helix resonator by a commercial phase meter[1] which is interfaced to the linac control computer via the CAMAC highway.

C. Data Analysis

The range of particle velocity over which the system must function is $0.06c \leq \beta \leq 0.16c$. For detectors separated by 9 meters, the total transit time is much longer than a single 48.5 MHz period of 20.6 ns and will vary from 9 to over 29 periods. This component of the time-of-flight information is lost completely by the phase detection system.

There are a number of methods which could be employed to determine the number of periods in the transit time between detectors. The method being employed presently is to assume that the linac beam energy is known from the tuning data to the accuracy necessary to determine the number of integer periods. A method which is less susceptible to error is to determine the approximate beam energy based on the magnetic field of a bending magnet in the beam transport system. This method will replace the present technique shortly. Present experience indicates that either of these approaches is acceptable to determine the approximate transit time. Of course an unambiguous result would be obtained by installing a third resonator at a distance of less than 1.0 m from the first resonator.

One additional assumption about the estimated time-of-flight is required. For a phase reading to have unambiguous interpretation, the first estimate of the beam time-of-flight must be correct to within ± 180°. This assumption allows a unique sign to the phase error to be determined. Here the phase error, $\delta\theta$, is defined as

$$\delta\theta = \theta_{read} - \theta_{expected}$$

where $\theta_{expected}$ is the phase angle which would be measured for the assumed beam energy.

III. System Operation and Sensitivity

The energy measurement system is installed and functioning on one beam line at the tandem-linac. The system yields phase readings with typical stability of ± 0.2° with an averaging time of 0.1 msec. For particle velocities with $\beta = 0.1$ c, the total flight time between detectors is 300 ns. Therefore the sensitivity to relative energy changes is

$$\delta E/E_0 = 2\delta t/t_0 \approx 1.0 \times 10^{-4}$$

The resonant helix detectors provide a signal strength of approximately 5μV/nA of beam current (electrical) into 50 ohms. For beam currents below 5 nA (electrical), we find an amplitude dependent phase shift with a magnitude of 2.6 degrees at 1 nA of beam current. This reduces the relative energy resolution to 1×10^{-3} for beam currents between 1 and 5 nA. The observed amplitude-dependent phase shift is due to the vector addition of a fixed phase noise source and the actual beam signal. An improved design of the electronics to increase channel separation is planned which is expected to give improved sensitivity to the system. Another improvement which is being pursued is the use of a spiral resonator, which is expected to have better coupling to the beam than the present helix resonators and therefore yield an improved signal-to-noise ratio.

An initial calibration of the system has been performed using beams of known energy from the tandem accelerator operating with the linac. This calibration is based on the calibration of the 90° analyzing magnet of the tandem accelerator. The present absolute calibration is accurate to a value of $\delta E/E \approx 2 \times 10^{-3}$. A more careful absolute calibration will take place in the near future. To obtain an absolute accuracy approaching $1\text{-}2 \times 10^{-4}$ may require the ability to routinely determine the distance between the two detectors on a regular basis. This is due to phenomena such as the thermal expansion of concrete which may cause variations in path length of the order of 10^{-4} over the course of a year.

In operation of the energy-measurement system, the linac computer first reads the phase angle. The number of 48.5 MHz periods and the expected phase angle are computed based on the assumed energy. The difference between the expected phase angle and the read phase angle constitutes a correction to the expected time-of-flight and the corresponding energy for this new flight time is computed. The computer checks that the accelerator system is operating properly and determines that the signal amplitude in the phase detector system is above a minimum value. If all requirements are satisfied, the computed energy is displayed on the color TV monitor of the linac control console. The results are also recorded periodically in the accelerator log.

The system will be expanded with the installation of detecting resonators on other beam lines.

References

1. Model 331, Dranetz Engineering Laboratories, Inc., South Plainfield, NJ.

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*This research was supported by the U. S. Department of Energy under Contract W-31-109-Eng-38.
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