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TIME-RESOLVED BEAM ENERGY MEASUREMENTS AT LAMPF*

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Abstract

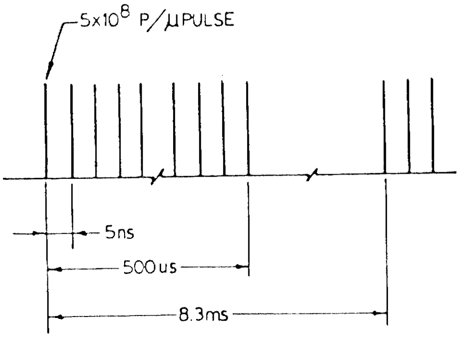
A narrow atomic photodetachment resonance is used to measure the LAMPF beam energy. Energy and time resolution are adequate to permit the use of this method in studying transient changes in accelerated beam energy.

Introduction

The high current proton storage ring (PSR) now being designed[1] at the Los Alamos Scientific Laboratory will accumulate 800-MeV protons from the LAMPF linac and deliver them in very intense short pulses to a heavy metal target at the Weapons Neutron Research (WNR) Facility. Figure 1 shows the LAMPF pulse structure, which consists of macropulses of half millisecond duration repeated at a 120 pulse per second rate. Each macropulse consists of 10^5 micropulses of $<10^{-10}$ second duration containing 5×10^8 protons or negative hydrogen (H^-) ions.

At present, when nanosecond neutron pulses are required at WNR, single micropulses of protons are selected from the LAMPF macropulses and delivered to the neutron production target. Much more intense nanosecond-long pulses (containing 10^{11} protons) will be produced by the PSR operating in the storage mode illustrated in Fig. 2. The (H^-) ion micropulses accelerated at 60 nanosecond intervals by the linac will be accumulated in the PSR as six circulating proton bunches separated in the ring by 60 nanosecond spacings. The H^- ions are injected for 200 turns (72 μs), by means of a two-step charge changing method.[2] The bunches are maintained during the accumulation process by a 500 MHz rf buncher. After full intensity is reached they are ejected towards the WNR target at intervals of 1.4 millisecond.

In this mode of operation the energy acceptance of the PSR is quite small because the proton transit time around the ring must be at or near an integer multiple of the 5 nanosecond† micropulse spacing to properly synchronize newly injected H^- ions with protons already in the ring. This requirement on the circulation period fixes the LAMPF beam energy (and energy spread) for a given ring circumference. If these conditions are not met, the protons will be lost from the 500 MHz rf buckets, which are phase-locked to the LAMPF micropulse repetition frequency. An overall energy acceptance of $\Delta E/E \approx 10^{-3}$ is calculated for the PSR, which includes the stability of the nominal (central) energy. This is in contrast to the operation of a synchrotron, whose rf system typically operates at a low harmonic of the circulation frequency; in this situation the momentum acceptance is usually limited by the growth of the transverse dimensions of the beam.

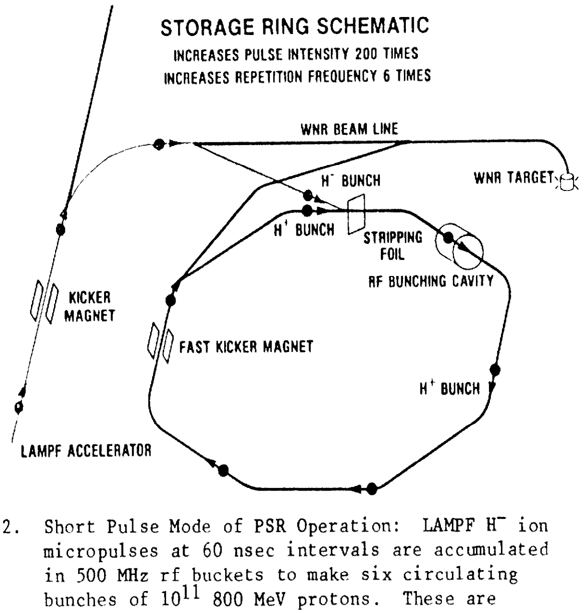


1. LAMPF Beam Pulse Structure: Micropulses of 10^8 particles at 5 nsec intervals make up a 500 microsecond macropulse. Average current during the macropulse is 7 mA. Macropulses occur at a 120 per second rate.

The beam pulse to be delivered by the linac to the PSR/WNR is prepared by means of a chopper in the 750 keV linac injection line.

This device opens a several μs long hole in the macropulse which isolates the PSR/WNR pulse from the main portion. This interval permits the switchyard kicker magnet to turn on without spilling 800 MeV beam on the first magnet in the WNR transport channel. We are concerned about the transient response of the linac rf systems to this sudden removal and replacement of the beam load, and about any consequent slewing of the output beam energy during the PSR/WNR pulse.

Such an effect might put some of the micropulses outside the energy acceptance of the PSR, but not be detectable in time-integrated measurements of the LAMPF beam energy. To assess the importance of this effect it is necessary to measure beam energy variation from micropulse to micropulse within high current macropulses which have been appropriately chopped. This could be done by direct time-resolved measurements of the magnetic rigidity of the beam using electrostatic position sensors to detect small changes in the bending angle or by time of flight measurements using micropulse detection in the 200 meter-long WNR beam line. These techniques would have marginal energy resolution.



2. Short Pulse Mode of PSR Operation: LAMPF H^- ion micropulses at 60 nsec intervals are accumulated in 500 MHz rf buckets to make six circulating bunches of 10^{11} 800 MeV protons. These are ejected at 1.4 msec intervals.

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†This is a nominal value. The actual spacing is 4.969 ns.

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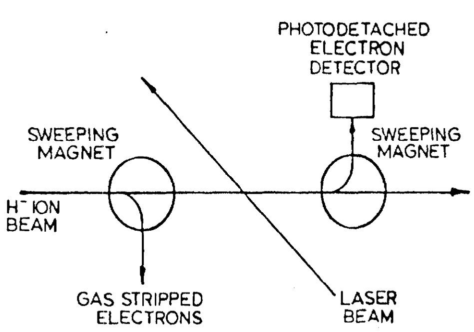
Energy Measurement Technique

A very precise energy measuring technique is now available at LAMPF. It utilizes an atomic resonance line in a manner analogous to the techniques which are conventionally employed in calibrating electrostatic accelerators. The method takes advantage of a very narrow resonance in the photodetachment spectrum of the H^- ion. The low intensity H^- beam which shares the accelerator with the proton beam can thus be used as a probe of the rf system reponse to chopping of the high current proton beam. Any transient droop in accelerating cavity voltage will be reflected by energy variation in the H^- beam, which can be measured with the desired precision.

The H^- beam energy is measured in the following way, using apparatus mounted in the external proton (EP) beam line in LAMPF experimental area B. The beam is directed through a pulsed photon beam from a Nd:YAG laser. By varying the laboratory angle between the ion and photon beams, the photon energy in the ion center-of-mass frame can be continuously adjusted. This method has been used for a number of sensitive atomic physics experiments at LAMPF.[3,4] The H^- ion resonance observed for beam energy measurements is the n = 2 Feshbach photodetachment resonance. An attractive feature of the method is that this resonance, which is at 10.930 eV in the center-of-mass frame, and which is too narrow to measure, can be tuned through with both third (3.494463 eV, 0.7 meV FWHM) and fourth (4.659284 eV, 0.9 meV FWHM) multiples of the laser fundamental frequency. This makes possible an absolute measurement of the H^- beam velocity in terms of the two different laboratory angles (between the ion and photon beams) for resonant photodetachment produced by the different laser harmonics.

Figure 3 shows the essential features of the experimental apparatus. A Q-switched Nd:YAG laser is frequency tripled or quadrupled to generate a 5 nsec long photon pulse which is directed by a series of prisms at a fixed intersection region in the ion beam. The laboratory intersection angle α is set by a stepping motor and measured by a shaft encoder to 30 microradian accuracy.

The H^- ion beam passes through an upstream weak transverse magnetic field which sweeps out any fast electrons liberated by collision with residual gas atoms. Photodetached electrons (463 keV) from the photon-H^- ion interactions are directed onto a silicon detector by a downstream sweeping field having a polarity opposite to the initial one. Pulse height analysis determines the number of photodetached electrons and discriminates against low energy electrons. Coincidence gating with the laser pulse gives a good signal to noise ratio. Although the laser firing jitter is 10 ns and the laser pulse width is 5 ns FWHM, single micropulse timing resolution is obtained by measuring the timing of the laser pulse relative to the ion micropulse.



3. Experimental Schematic Diagram: Laser beam interects ion beam at laboratory angle α. Ion beam is cleared of gas stripped 463 keV electrons by upstream sweeping magnets. Downstream sweeping magnet sends photodetached 463 keV electrons onto the detector.

The following relations are basic to the experiments:

$$E' = \gamma E_{lab} (1 + \beta \cos \alpha) \qquad (1)$$

where E' is the photon energy in the center-of-mass frame, E_{lab} is the photon energy in the laboratory frame, and α is the is the laboratory angle betwen the ion and photon beams, defined so that $\alpha = 0$ for head-on collisions.

For the third harmonic photon beam and 800 MeV ions,

$$dE'/d\alpha = E_{lab}\, \gamma\beta \sin \alpha = 3.09 \text{ meV/ mrad} \qquad (2)$$

$$dE'/dT = (E_{lab}/mc^2)\,(1 + \beta^{-1} \cos\alpha)$$

$$= 7.36 \text{ mev/Mev} \qquad (3)$$

where T is the ion kinetic energy, and

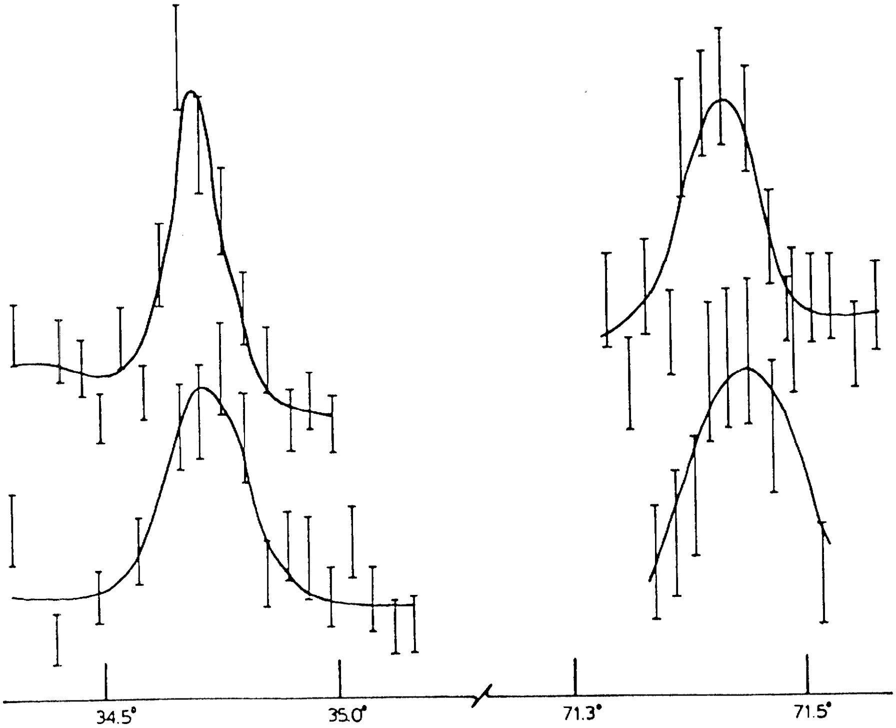
$$dE'/dE_{lab} = \gamma\,(1 + \beta \cos \alpha) = 3.13 \text{ meV/meV} \qquad (4)$$

The angular divergence of the photon beam is 0.5 mrad, and the angular divergence of the H^- ion beam is 0.2 mrad. The energy spread δE_{lab} of the laser beam is 0.75 meV and the intrinsic width of the photodetachment resonance (n = 2 Feshbach) is unknown, but negligible. The beam intrinsic energy spread δT can be determined from the measured resonance line width by the relation

$$(\delta T dE'/dT)^2 = (\delta E_{rms})^2 - (\delta E_{lab}\, dE'/dE_{lab})^2 - (\delta\alpha dE'/d\alpha)^2 \qquad (5)$$

The last two terms on the right hand side contribute a fractional linewidth equivalent to that of an 800 MeV ion beam with a 195 keV energy spread. By careful measurement and control of $\delta\alpha$, determination of δT to ±50 keV is possible. Time-of-flight measurements made at WNR indicate a characteristic intrinsic energy spread within a micropulse of $\Delta E/E \approx \pm 10^{-3}$ FWHM, which is ±800 KeV for an 800 MeV ion beam. Therefore, we can see that the photodetachment energy measurement technique delivers the desired resolution.

The centroid of the resonance lineshape can be determined to ±60 microradians, permitting an absolute measurement of the H^- beam energy centroid to six parts in 10^4 (±480 keV). This is marginal (but sufficient) accuracy if it is desired to use this procedure to tune the linac for a specific energy with an accuracy of a part in 10^3.



4. Preliminary Results. Third multiple resonance at 34.7° and fourth multiple resonance at 71° without time resolution or proton beam chopping.

Results

Figure 4 shows initial results obtained using the third and fourth multiples of the laser fundamental frequency made on an unchopped beam at one point in the macropulse. The photodetachment cross section peaks correspond to ion beam energies of 797.63 MeV ±0.36 MeV and 798.56 MeV ±0.35 MeV respectively, which is consistent with the nominal LAMPF beam energy of 795 MeV to 800 MeV. The linewidths correspond to FWHM energy spreads of 1.4 MeV and 1.8 MeV, in agreement with estimates of the energy spread in the LAMPF beam made from transit time broadening of micropulses in the WNR beamline.

The data for the third and fourth laser frequency multiples were taken a week apart and thus cannot be used to make an absolute measurement. More extensive and detailed measurements, including time-resolution, are being made.

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