# A Real-Time Longitudinal Phase-Space Measurement Technique for H⁻ Beams

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**Abstract**

The longitudinal phase-space distribution of a bunched beam can be determined by selecting short-phase slices of the beam and measuring the energy distribution of each slice. This paper describes a system that should be capable of producing phase-space measurements of an $H^-$ beam at a rate of 2 Hz. The phase is selected by photoneutralization with a mode-locked laser. A deflector magnet downstream of the neutralization point deflects the charged beam, and the neutral particles enter a spectrometer through a slit covered with a stripping foil. During the 20- to 40-μs laser burst, a ramp signal shifts the laser phase with respect to the beam phase. The same ramp signal controls electric deflection plates in the exit beamline of the spectrometer, which bend the beam perpendicular to the dispersion plane. If the spectrometer magnet bends the beam horizontally, then the beam-current distribution at the focal plane is analyzed horizontally in energy and vertically in phase.

## I. Introduction

The Laser-Induced-Neutralization Diagnostic Approach (LINDA)[1], developed at Los Alamos National Laboratory, is a technique that uses light pulses from a laser to select portions of an $H^-$ beam for analysis. Light pulses of the appropriate wavelength to neutralize $H^-$ ions pass through the beam upstream of a deflection magnet. The neutralized beam passes through the magnet and into a detector.

Longitudinal phase-space distributions have been made measured using LINDA by firing single laser pulses through beams and measuring energy spread by time-of-flight. This technique requires several hundred laser pulses for each measurement and is applicable only to beams of less than about 10 MeV with rms bunch lengths of greater than about 30 ps.

This paper describes a system (see fig.1) that should be capable of producing longitudinal phase-space measurements of an $H^-$ beam at a 2-Hz rate. It is applicable to high-brightness beams of energies greater than 100 MeV.

The phase is selected using light from a mode-locked laser whose frequency is locked to a subharmonic of the accelerator rf. A spectrometer is placed downstream of the deflector magnet for energy-spread analysis. During the laser firing, the rf phase of the laser is ramped at the same rate that the ion beam in the image line of the spectrometer is deflected perpendicular to the dispersion plane. The beam current on the spectrometer focal plane is analyzed in both phase and energy.

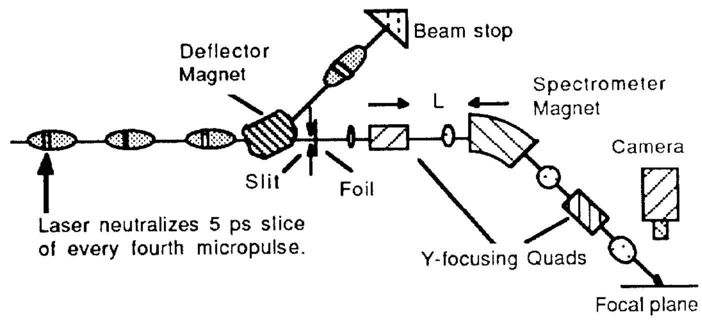


Figure 1. Schematic of measurement technique. The laser-firing frequency is one-fourth the accelerator rf.

## II. Measurement System Requirements

The laser and spectrometer constitute a measurement system with a phase-space window having dimensions θ of rf phase and R of energy. The phase dimension of the window is equal to the time width provided by the laser pulses multiplied by $2\pi/T$ (where T is the rf period). The energy width is equal to the resolution of the spectrometer.

The detector resolution required to measure a particular beam is determined by calculating the effect the detector window size has on the measurement result. The following calculation is based on studies done by Gluckstern[2] and Connolly and Johnson[3].

If a beam of phase-space distribution $\rho(\phi,E)$ and true rms emittance $E_t$ is measured using a detector having a window of dimensions θ of rf phase and R of energy, the measured distribution is $\rho_m(\phi,E)$ where

$$\rho_m(\phi_o,E_o) = \frac{1}{R\theta} \int_{\phi_o-\frac{\theta}{2}}^{\phi_o+\frac{\theta}{2}} \int_{E_o-\frac{R}{2}}^{E_o+\frac{R}{2}} \rho(\phi,E)\, d\phi\, dE. \quad (1)$$

When $\rho(\phi,E)$ is expanded to second order around $\phi_o$ and $E_o$, the result of the integration is

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$$\rho_m(\phi_o,E_o) = \rho(\phi_o,E_o) + \frac{\theta^2}{24}\left[\frac{\partial^2\rho(\phi,E)}{\partial\phi^2}\right]_{\phi o,Eo} + \frac{R^2}{24}\left[\frac{\partial^2\rho(\phi,E)}{\partial E^2}\right]_{\phi o,Eo}. \tag{2}$$

The rms emittance calculated from this measured beam distribution is

$$E_m = \pi\left[\frac{E_t^2}{\pi^2} + \frac{\theta^2}{12}\sigma_E^2 + \frac{R^2}{12}\sigma_\phi^2 + \frac{\theta^2R^2}{144}\right]^{1/2}. \tag{3}$$

where $\sigma_\phi$ and $\sigma_E$ are the rms beam dimensions. Written in terms of the Twiss parameters $\beta$ and $\gamma$, Eqn. 3 becomes

$$E_m = E_t\left[1 + \frac{\pi\gamma\theta^2}{12E_t} + \frac{\pi\beta R^2}{12E_t} + \left(\frac{\pi\theta R}{12E_t}\right)^2\right]^{1/2}. \tag{4}$$

An emittance measured by a detector whose window is small compared to the beam distribution is the true emittance of the beam. If the window size is comparable to the beam distribution, the measured emittance is larger than the true emittance.

Equation 4 shows that the effect of the detector on a measurement depends on the beam parameters. For the case of an upright ellipse, Fig. 2 shows how the ratio of $E_m/E_t$ increases with detector window size. For this example, $\theta/\sigma_\phi=R/\sigma_E=A$. The ratio $E_m/E_t$ is plotted as a function of A. This plot shows that a detector window with dimensions equal to the rms beam dimensions produces a measured emittance that is 1.08 times the true emittance. For most applications, the detector window should be no larger than $\sigma_\phi$ by $\sigma_E$.

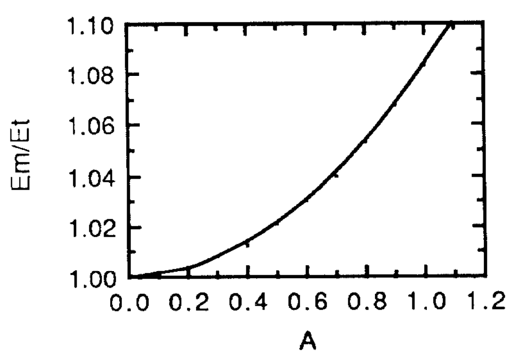


Figure 2. The ratio of measured emittance to true emittance as a function of detector window size for the case of an upright phase ellipse. The detector window dimensions are $\theta$ by R and $A=\theta/\sigma_\phi=R/\sigma_E$.

## III. Measurement System

### A. Mode-locked laser

The laser has to produce short pulses of an appropriate wavelength and photon flux to produce the required neutralization of the $H^-$ beam. The required neutralization fraction depends on the beam current and the sensitivity of the spectrometer detector.

If the laser pulse duration is long compared to the flight time of the ions through the laser beam, the neutralization fraction is

$$P = 1 - \exp(-\sigma F t), \tag{5}$$

where $\sigma$ is the neutralization cross section, F is the photon flux, and t is the time the ions spend in the photon field. The photon flux is given by

$$F = \frac{\varepsilon\lambda}{h c A \tau}, \tag{6}$$

where $\varepsilon$ is the laser-pulse energy, $\lambda$ is the wavelength, h is Planck's constant, c is the speed of light, A is the laser beam cross-sectional area, and $\tau$ is the laser firing time.

The best laser for $H^-$ beams is a CW mode-locked Nd:YLF laser tuned to a subharmonic of the accelerator frequency. This laser produces 50-ps pulses of 1062-nm light, giving a photoneutralization cross section of $3.6 \times 10^{-17}$ $cm^2$[4]. These light pulses are chirped, amplified, and compressed to get pulses as short as 1 ps. The output energy of the pulses is controlled by the number of amplification stages. The amplifier rods limit the output bursts to 20-40 µs.

The laser beam is focused so its width along the ion beam is as narrow as possible. The detector phase window is the quadrature sum of the laser pulse length, the laser firing jitter, and the ion-beam transit time across the laser beam. If the laser-beam dimension is 0.1 mm in Z, a 5-MeV proton takes 3.2 ps to pass through it and a 20-MeV proton takes 1.6 ps. Detector windows of ~3 ps are possible with 20-MeV beams.

Neutralizing the smallest phase window possible requires that the laser beam intersect the $H^-$ beam perpendicularly in the $H^-$ rest frame. This is done by directing the laser beam through the $H^-$ beam at a lab-frame angle of $\cos^{-1}(\beta)$ where $\beta$ is the relativistic parameter v/c. For a 20-MeV $H^-$ beam, the intersection angle is 78°.

An example of a laser system that can produce about 10% neutralization of a 20-MeV $H^-$ beam is one being considered by Los Alamos[5]. It consists of a Quantronix[6], Series 4200 Nd:YLF CW mode-locked laser with an amplification and pulse-compression system from Continuum[7]. The laser is available with frequencies of 50 to 240 MHz. Firing jitter with respect to the rf source is reported to be ±1 ps.

### B. Spectrometer

As with the laser, the spectrometer requirements depend on the specific application. A design that has been studied at Los Alamos[8] is shown in Fig. 1. It is a double-focusing transport line consisting of two y-focusing quads and a dipole with straight, perpendicular entrance and exit edges. One quad is in the middle of the image and object lines. These focus the beam through a waist in y in the center of the dipole [9].

The half length of each leg, L (see fig. 1), is approximately $1.5r/\sin(\alpha)$, where r is the bend radius and $\alpha$ is the bend angle. The momentum resolution is $\Delta P/P = s/6r$, where s is the entrance slit width in the dispersion plane. The spectrometer shown in Fig. 1 bends the beam 45° with r=1.5m and L=3.2m. With a 1-mm entrance slit, the energy resolution for a 20-MeV beam is about 4.5 keV.

The sensitivity of this design to magnet misalignments and vibrations has been studied with TRANSPORT[10]. The only strong sensitivities were found to be the roll angles of the quads and dipole. Errors in the roll angles produce mixing of the X and Y planes which is uncorrectable by focusing. The studies show that quad roll-angle has to be correct to ±5 mr and dipole roll correct to ±1 mr.

Focus sensitivity studies to quad settings and to harmonic contamination of the quad and dipole fields done to third order with GIOS[11] show this design to be extremely robust. The quad fields need to be within ±1% of the design value, and sextupole and octupole components of ±0.1% at the pole-tip radius have little effect on the focus. Similar harmonic components of the dipole field can be tolerated. The only critical field is that of the dipole, which needs to be stable to ±0.004%.

### C. Integrated System

The complete measurement system is shown in fig. 4. A magnet, placed between the neutralization point and the entrance slit, deflects the charged beam into a beam stop. The analyzed beam is neutral, so a stripper foil is placed over the entrance slit. Angle scattering in the foil does not affect the analysis because the system produces a point-to-point focus.

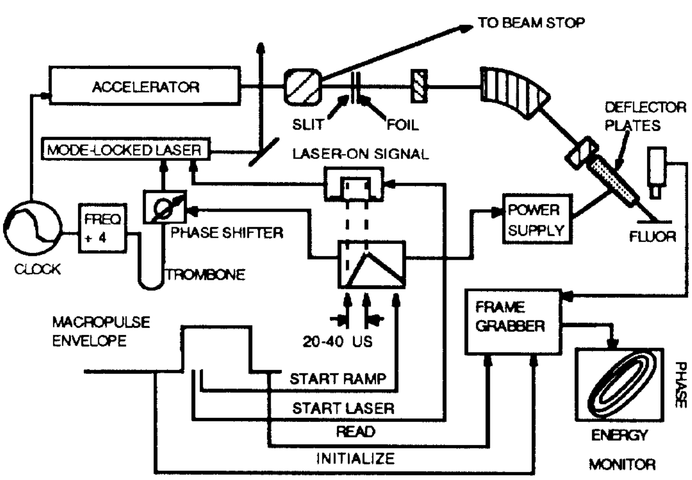


Figure 4. Block diagram of complete measurement system.

Electrostatic deflector plates in the image line deflect the proton beam perpendicular to the dispersion plane. During the overlap of the beam macropulse and the laser-firing time, both the phase of the laser and the deflection of the beam follow a common linear ramp. This produces an integrated current distribution on the image plane; the distribution's energy is analyzed in the dispersion plane and its phase in the perpendicular plane. One possible image-plane detector is a fluorescent screen and CCD camera. The image can be digitized for analysis and displayed on a monitor.

## IV. Discussion

This system should be capable of producing complete longitudinal phase-space measurements of an $H^-$ beam at a rate of 2 Hz. This is the firing rate of the laser amplifiers. Probably this technique can be used for other negative-ion beams, but it has been studied only for $H^-$ beams.

This method is applicable to beams whose rms bunch lengths are as short as a few ps. The spectrometer described will work for beams with rms energy spreads of greater than $\sim 2 \times 10^{-4}$. For a 100-MeV beam the total length is ~12 m, so a more compact design probably is needed for higher-energy beams.

If the electrostatic deflector plate lengths are 0.75 times L and the maximum voltage between them is 20 kV, the total image deflection is 1.3 cm for all beam energies. This image width should probably correspond to $6\sigma$, so the entrance slit height for this case should be ~2 mm.

## V. Acknowledgement


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