Design, Implementation, and Results from a Longitudinal Phase Space Tomography (PST) Monitor in the Fermilab Main Ring

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Abstract

In order to image the longitudinal phase space density distribution of a beam during complicated RF manipulations or during important points in the ramp such as transition, a Phase Space Tomography (PST) monitor has been installed in the Fermilab Main Ring. Based on tomography techniques normally used to image organs inside human beings, a 2-D map of the internal distribution of charge in longitudinal phase space is produced. The detector is simply a resistive wall monitor. Presented are descriptions of the monitor hardware, image reconstruction software, and results when the monitor is used to diagnose problems during the coalescing process.

I. INTRODUCTION

During commissioning and tuning of such longitudinal beam manipulations as coalescing [1], imaging enhancements can save time and allow the diagnosis of problems not readily identifiable by more traditional beam diagnostic techniques. This is especially true in the longitudinal plane where the shape and extent of the beam phase space distribution with respect to the separatrix are especially important parameters. One technique for producing such an image of the longitudinal phase space of the beam is the subject of this paper. The technique is very similar to that of medical CAT scans of human patients.

When a doctor needs to know the 2-dimensional size, shape, and position of an organ in a patient, a now common procedure is to put the person in a special X-ray machine. Instead of exposing a piece of photographic film to a single burst of radiation through the body, an array of X-ray tubes and electronic detectors are rotated around the patient, measuring the attenuation of each X-ray beam as a function of angle. This attenuation data is digitized and acquired by a computer.

In 1917 the Austrian mathematician J. Radon published a paper proving that any two-dimensional object can be reconstructed from the infinite set of its projections. Later mathematicians were able to show that a sufficient number of projections could reconstructed the two dimensional structure using some rather simple mathematical algorithms. Applying these same algorithms to the X-ray data, a computer can generate a 2-dimensional density profile of the person on a grid of pixels. This technique is called tomography.

In the case of a particle beam it is relatively easy to measure only the temporal projection of a longitudinal phase space charge distribution. Sending the signal from a resistive wall monitor [2] into a fast digitizer is analogous to measuring the signals from an array of X-ray detectors from just one angle. But to carry the analogy between medicine and accelerator physics further, imagine that instead of rotating the X-ray tubes, the patient is rotated. This is called a synchrotron oscillation in the world of accelerators! By digitizing the output of the resistive wall monitor periodically during a synchrotron period, enough projections of longitudinal phase space can be accumulated to use the standard tomography reconstruction algorithms to image phase space.

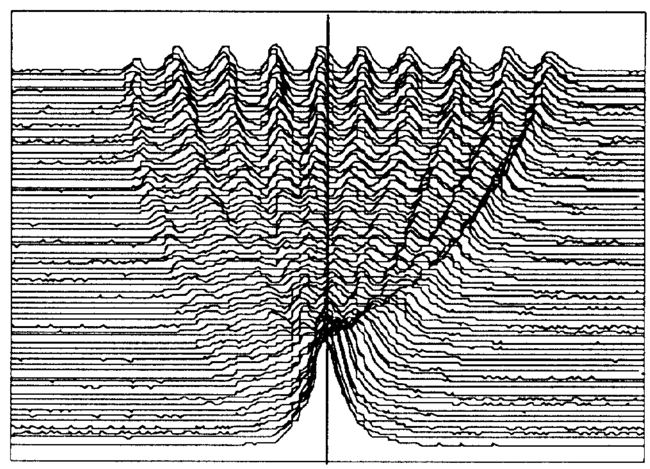

Figure 1: Mountain range plot of high intensity beam during the bunch rotation phase of coalescing. Note that the earlier bunches are debunching while the later ones preserve their shape.

II. SYSTEM DESIGN

The heart of the system is a Tektronix RTD720 transient digitizer linked via GPIB to the Fermilab control system. Capable of digitizing at a peak rate of 2 GS/sec, with a 500 MHz analog bandwidth, and with a segmented memory capable of more than 512 ksamples of storage, this device can be repeatedly triggered, filling a successive portion of memory each time. After acquisition is complete, the data stored in the digitizer memory is downloaded to the control system for processing. In the implementation aimed at diagnosing Main Ring coalescing, two of the channels of the digitizers are

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utilized, each working at a 1 GS/sec sampling rate. While one channel is monitoring the beam signal, the other is digitizing the RF cavity fanback waveform. With a RF period of approximately 19 nsec and bunches which fill the RF buckets, enough resolution is attainable for tuning and diagnosis. With the memory segmented into 512 sample sections, 512 turns of data may be sampled, where the triggering is accomplished via a timing signal synchronized with the beam sent through a programmable ÷N counter.

The data is analyzed using a VAXstation computer, which is the standard console in the Fermilab control system. The first step of the reconstruction is to propagate each ray through the grid at its correct position and angle, adding the value of that digitizer bin to all of the grid squares that it traverses [3]. This summation method is a surprisingly good way to start the process, though for a small number of measured angles the contrast of the image suffers significantly. Given a finite number of colors or gray gradations, a background subtraction where pixels with values at or below zero are not plotted (or are black) can improve the contrast a bit.

A standard method for improving the fidelity of the phase space image relies on the convergence of an iterated algorithm. The resistive wall monitor data represents various projections through the actual longitudinal phase space density distribution. After applying the above summation method to an initially zeroed grid, perform a mock measurement through this distribution at the same positions and angles as the original measurements. For each ray, subtract the actual projection measurement from the grid projection measurement, and then distribute the difference across all of the intercepted grid points equally so that another projection measurement would agree with the original measurement. An optional step after each iteration which improves convergence is to find all pixels less than zero and setting them to zero. Repeat the entire process until the image does not change substantially any more.

III. SAMPLE MEASUREMENTS

As an example of the power of this phase space tomography, a phase space rotation during coalescing of high intensity protons is presented. Figure 1 shows the beam current data from the resistive wall monitor acquired every 80 revolutions of the Main Ring. The rotation RF voltage, which has a wavelength of 21 accelerating RF buckets, clearly changes the alignment of the bunches in phase space from the time axis to the energy axis, at which point the accelerating voltage is turned back on to recapture this new distribution in a single bucket. Calling the starting alignment 0° and assuming that recapture occurs at 90°, the data in figure 1 is used to reconstruct the phase space picture at recapture time. This phase space image is shown in figure 2. By writing a simulation program which creates mountain range images similar to figure 1, various tuning errors and intensity effects can be recognized and corrected. See figure 3.

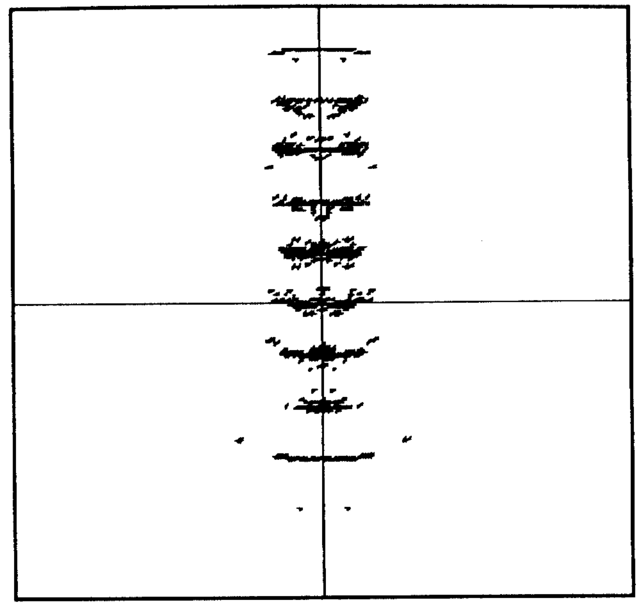

Figure 2: Phase space distribution of the beam reconstructed form the above Main Ring data and imaged at recapture time.

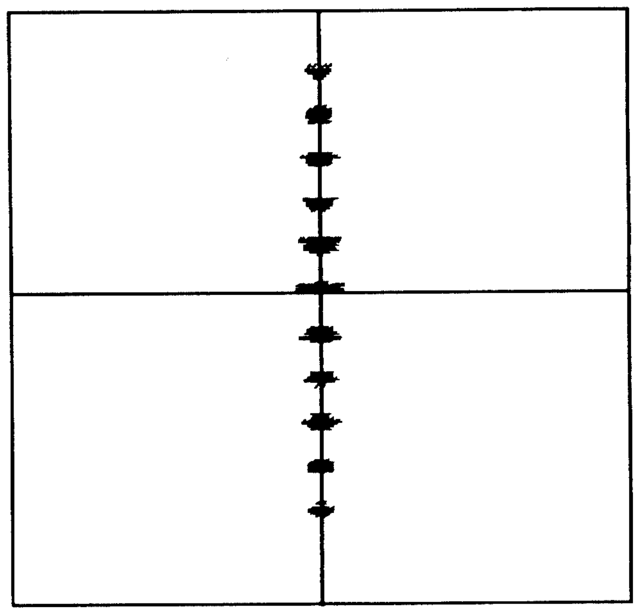

Figure 3: Phase space distribution of a low intensity beam which was coalesced after considerable tuning.

IV. REFERENCES

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