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Publication Date
2003-05-28

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DEVELOPMENT OF A LONGITUDINAL DENSITY MONITOR FOR STORAGE RINGS[*]

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Abstract

We report on development of a new storage ring operations tool for measurement of longitudinal beam density profile. The technique mixes synchrotron light with light from a mode locked solid-state laser oscillator in a non-linear crystal and detects the up-converted radiation with a photo-multiplier. The laser is phase locked to the storage ring RF system. The laser choices available for repetition frequency, pulse length and phase modulation give a very wide range of options for matching the bunch configuration of particular storage rings. Progress in the technology of solid-state lasers ensures this system can be made robust for routine use in storage ring operations. A very large number of important applications are possible including measurement of the fraction of untrapped particles prior to acceleration, the population of particles in the nominally unfilled RF buckets in a bunch train (“ghost bunches”), longitudinal tails, the diffusion of particles into the beam abort gap and the normal bunch parameters of longitudinal shape and intensity. We are currently investigating application to two devices: (1) the 1.9 GeV ALS electron storage ring at LBNL with 328 RF buckets, 2ns bucket spacing, 276 nominally filled bunches, 15-30ps rms bunch length and (2) the 7 TeV LHC proton collider under construction at CERN with 35,640 RF buckets, 2.5 ns bucket spacing, 2,808 nominally filled bunches, 280-620 ps rms bunch length. A proof of principle experiment is being conducted on ALS. The results of the ALS experiment and detailed analyses of the application to LHC and its requirements are described.

INTRODUCTION

The purpose of the work described in this paper is to develop a flexible beam instrument for the measurement of the longitudinal bunch distribution of beam particles in storage rings. The approach that is being developed is indicated schematically in Fig. 1 and has two parts; (1) utilization of the synchrotron and wiggler radiation emitted by highly relativistic beam particles in strong magnetic fields and (2) cross correlation of the synchrotron or wiggler radiation with light from a solid state CW laser that is phase locked to the storage ring radio frequency system. The cross correlation is done by mixing the laser and beam radiation in a non-linear crystal and detecting the sum frequency radiation. When the synchrotron radiation is in the near infrared, this allows shifting the detection wavelength to the optical region where quantum efficiency is high. A prototype system has been assembled and initial data taken in beamline 5.3.1 at the ALS electron storage ring at LBNL.

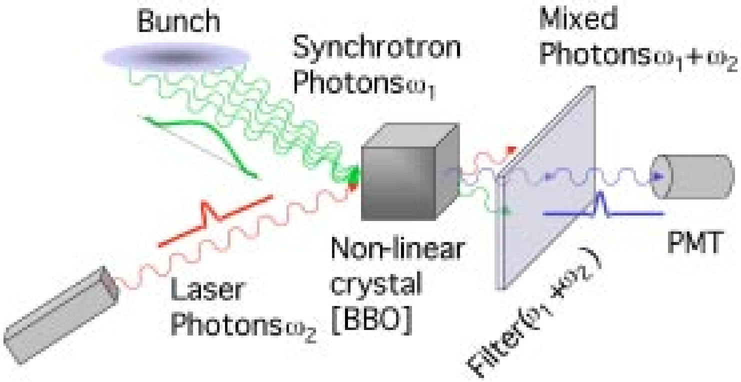

Figure 1. Schematic of the experimental technique for longitudinal beam density measurement by up-conversion of synchrotron radiation with a CW laser.

Owing to the large range of laser pulse lengths and repetition frequencies available it is possible to design a system that can accurately measure bunch shapes with ~1 ps to ~50 ps resolution and with rms lengths from ~10 ps to ~1 ns for any modern day storage ring;

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[*] Work supported by the US Department of Energy under contract DE-AC03-76SF00098.

Tevatron, RHIC, ALS, LHC, APS etc. A longitudinal density monitor will find a wide range of applications that provide essential information for machine operation and longitudinal beam dynamics studies, including measurements of: (1) the untrapped beam fraction, (2) the intensity of ghost bunches, (3) the fraction of particles in the beam abort gap, (4) the longitudinal bunch shape and (5) coherent multi bunch modes. The concept was originally proposed and is being developed at LBNL for the Large Hadron Collider (LHC) under construction at CERN. In this case the stored beam energy is very high ~350 MJ/beam and can cause extensive damage to machine components if some of it diffuses into the beam abort gap. It is therefore clearly necessary for LHC operations to have a good understanding of the longitudinal distribution of protons. In addition, it is desirable to minimize the untrapped beam fraction prior to the energy ramp and to limit the beam population in the ghost bunches which cause background in the detectors. In the LHC context our goal is to develop an instrument with four orders of magnitude dynamic range so diffusion of beam particles into unwanted regions can be detected well before reaching a level that could damage equipment. The idea of building such a system on ALS was to demonstrate the quality of information available and the practicality of such a system for routine use in an accelerator control room.

EQUIPMENT

The synchrotron radiation from the bunched beam of the ALS is mixed in a non-linear crystal with a mode locked Ti:Al_2O_3 laser oscillator and the up-converted radiation is detected with a photo-multiplier tube. The laser operates at 71 MHz (14 ns) with pulse length 50 fs, wavelength 800 nm and power 100-200 mW and has been described previously [1]. The 197 m main ring of the ALS has 328 RF buckets separated by 2 ns so that after 7 revolutions each RF bucket has been sampled once (7x47=328+1). The laser is phase locked to the ALS RF frequency. The laser is phase modulated at 10 Hz with a mirror mounted on a piezo-electric crystal and arranged to sample the profile of each RF bucket with 32 time slices separated by approximately 4.8 ps. Nominally 276 consecutive buckets are filled with ~1.2 mA per bunch and the 52 bucket gap has a single "camshaft" bunch of ~6 mA near the center of the gap.

The electronic hardware and the software necessary to measure the longitudinal density profile of the ALS was developed in 2002. A data acquisition board was designed and fabricated to accumulate the number of photon counts per time slice per bunch passage. The data acquisition board contains an address generator and bunch accumulation memory that keeps the data sorted according to position in the circumference of the ALS. Data accumulation stops and a trigger is generated for readout by a PC after a certain number of revolutions of the ALS. The software that has so far been developed allows for display of (1) electron density profile with 4.8 ps sampling interval over the full circumference of the ALS, (2) peak and integrated intensity per RF bucket versus bucket position and (3) rms pulse length per RF bucket versus bucket position. Examples are given in the following section.

INITIAL RESULTS

The data acquisition board and software described in the previous section have been successfully tested in initial experiments on the ALS.

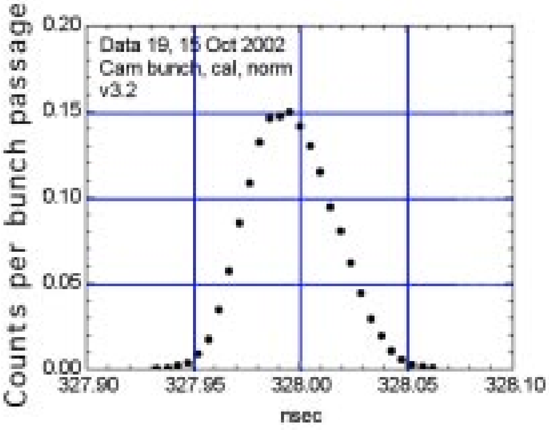

Figure 2. Beam intensity profile of a single bunch in the ALS measured by correlation of synchrotron light emission with a mode locked solid-state laser oscillator.

Fig. 2 shows the density profile of the "camshaft" pulse in photon counts per bunch passage for a typical fill of the ALS (1 count = 4.4 mA). The rms pulse length is approximately 18 ps. The 'camshaft" pulse is quite symmetric and leans forward slightly due to the inductive/resistive impedance of the ALS ring [2]. Similar density profiles of the complete RF bucket train of the ALS were obtained simultaneously.

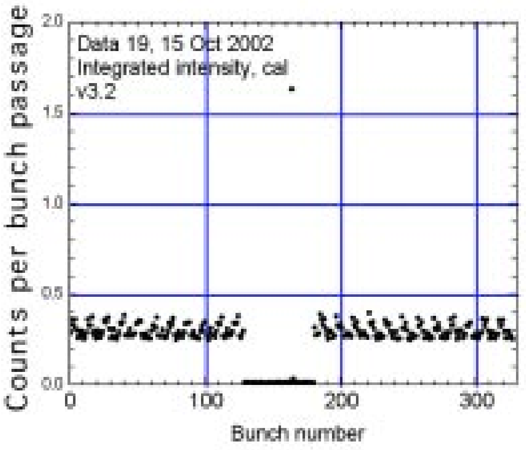

Figure 3. Integrated intensity of all 328 RF buckets in the ALS.

Fig. 3 shows the integrated bunch intensity versus RF bucket number (from 0 to 327). The gap in bunch intensity extends from buckets 129 to 180. The "camshaft" bunch is in the middle of the gap at bucket number 164 and has intensity 1.63 counts.

A low intensity 0.035 counts is visible in the trailing bucket number 165. The average background is 0.014 counts and can be further reduced by inserting a filter to reject second harmonic laser light and decreasing the ambient background radiation from room lights near the photomultiplier. Inspection of the nominally filled RF buckets reveals a nine bucket repeating pattern of bunch intensity variation at the level of ±20%. This is traceable to intensity variation from the booster injecting into the ALS. Fig. 4 shows the rms bunch length versus bunch number. The rms bunch lengths of the nominally filled RF buckets are in the range 16 to 18 ps and show a trend of decreasing linearly from 18 ps adjacent to the gap to 16 ps on the opposite side of the ring due to transient beam loading in the harmonic RF cavities. The approximately 40 ps rms bunch length for the empty gap buckets corresponds to the rms length of a uniform distribution with full duration equal the measurement window per bucket. This can be corrected in software by subtracting the background level. The background level is also responsible for the 28 ps length attributed to the parasite bunch immediately trailing the "camshaft".

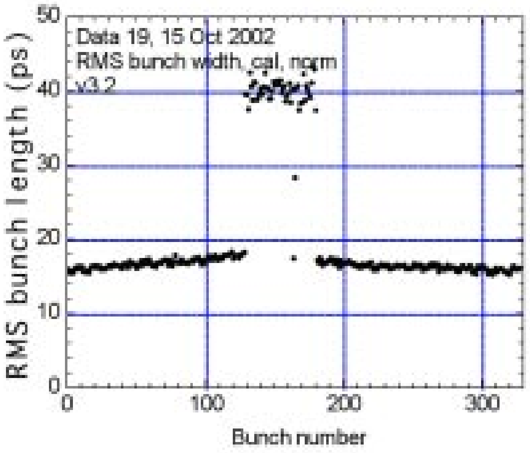

Figure 4: RMS bunch length of the 328 RF buckets in the ALS.

Fig. 5 shows in more detail the leakage from the "camshaft" bunch into the two trailing RF buckets on a logarithmic scale to emphasize the dynamic range of signal detection. The peak of the 'camshaft' bunch is 5x10^{-2} counts whereas the noise level is ~2x10^{-5}, giving a signal to noise ratio of roughly 2.5x10^{3}. The noise is primarily due to fluctuations in ambient background light and can be further improved so 10^{4} dynamic range can be expected.

The power of the experimental method under development is clearly indicated in Figs.2-5. The time resolution exceeds that possible by purely electromagnetic pickup devices. The dynamic range that can be expected is at least four orders of magnitude. The technique is well suited to routine digital signal analysis of a very large number of buckets (328 for ALS and 3,564 for the future LHC).

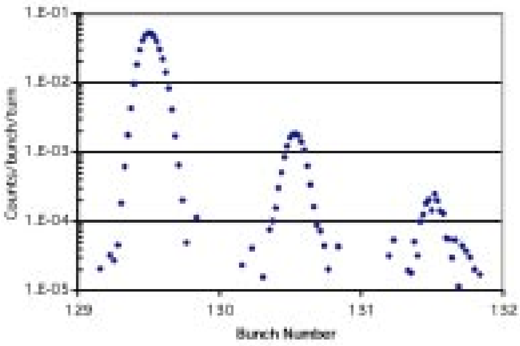

Figure 5: "Camshaft" pulse and two trailing RF buckets. Background has been subtracted.

CONCLUSIONS

In this paper we have presented a summary description of a new tool, based on non-linear mixing of the synchrotron radiation with a mode-locked laser, for measuring the longitudinal beam profile in a storage ring. The non-linear mixing technique allows to detect the beam signal in the optical range with high quantum efficiency, even when the natural synchrotron radiation has longer wavelengths (for example, in lower energy proton rings). Additionally, our instrument has very good time resolution (which depends on the laser parameters) and dynamic range.

We also present the first results of our instrument testing on Berkeley ALS main storage ring. A comparison with other diagnostics available at the ALS shows good agreement with the LDM data, for both the bunch length and phase.

REFERENCES

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