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Publication Date

2004-05-03

Measurement of the Beam Longitudinal Profile in a Storage Ring by Non-Linear Laser Mixing[*]

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Abstract. We report on the development of a new technique for the measurement of the longitudinal beam profile in storage rings. This technique, which has been successfully demonstrated at the Advanced Light Source, mixes the synchrotron radiation with the light from a mode-locked solid state laser oscillator in a non-linear crystal. The up-converted radiation is then detected with a photomultiplier and processed to extract, store, and display the required information. The available choices of laser repetition frequency, pulse width, and phase modulation give a wide range of options for matching the bunch configuration of a particular storage ring. Besides the dynamic measurement of the longitudinal profile of each bunch, the instrument can monitor the evolution of the bunch tails, the presence of untrapped particles and their diffusion into nominally empty RF buckets ("ghost bunches").

INTRODUCTION

We report on the development of 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 utilizes the synchrotron radiation emitted by highly relativistic particles in a strong magnetic field. This radiation is cross correlated with the 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 up-converted radiation at the sum frequency on a photomultiplier tube. When the synchrotron radiation is in the near infrared, this allows shifting the detection wavelength to the optical region where the detectors quantum efficiency is higher. A prototype system has been assembled and initial data taken in Beamline 5.3.1 at the ALS electron storage ring at LBNL.

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; Tevatron, RHIC, ALS, LHC, APS etc. A longitudinal density monitor

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[*] Work supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

would find a wide range of applications that provide essential information for machine operation and longitudinal beam dynamics studies, including measurements of the untrapped beam fraction; the longitudinal bunch shape; and coherent multi bunch modes. Depending on the particular machine, the time required to measure these beam parameters can be substantially shorter than the synchrotron period. The concept was originally proposed and is being developed at LBNL for the Large Hadron Collider (LHC) [1] 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.

NON-LINEAR MIXING TECHNIQUE OUTLINE

The instrument can be seen as an optical sampling scope, with an important difference that we will illustrate later. Figure 1 gives a schematic view of the fundamental functional parts involved.

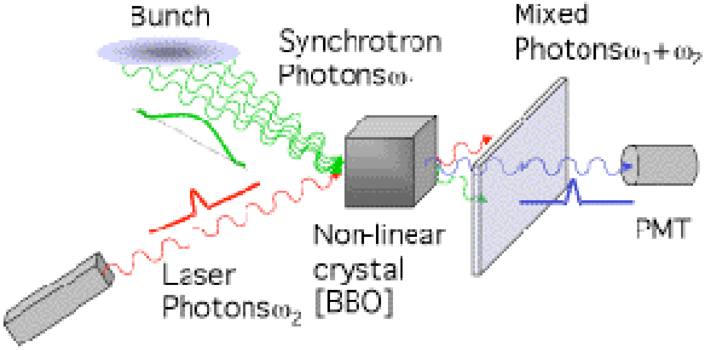

FIGURE 1. Schematics of the experimental technique for longitudinal beam profile measurement by up-conversion of synchrotron radiation with a CW laser.

The synchrotron radiation emitted by a bunch is mixed in a non-linear optical crystal with the light from of a laser pulse. The sum frequency is filtered and detected on a photomultiplier (PMT). The efficiency of the up-conversion process is linearly proportional to the laser power density [2], which we can assume constant from pulse to pulse. Therefore the number of photons detected on the PMT gives a measurement of the number of charged particles in the bunch contained in the duration of the laser pulse. Choosing a laser pulse much shorter than the bunch and sweeping it across the bunch length, we can measure the longitudinal distribution of particles in the bunch. The laser pulse repetition rate is chosen in such a way as to be synchronized with the bunch frequency or a sub-multiple of it (i.e. sampling every n-th bunch). This is done by tuning the laser cavity length. The timing of each laser pulse is then finely changed, at a slower rate, so that the laser pulse samples different longitudinal slices of a given bunch at each bunch revolution. This can be realized by mounting one of the laser cavity mirrors on a piezo-ceramic positioner, which is excited by a sinusoidal signal. This dual sweep procedure allows to concentrate data samples at high time resolution in the region of interest, for instance monitoring the bunch core at a resolution comparable to the laser pulse length, as opposed for instance to a more traditional oscilloscope. The fastest oscilloscopes available today allow to take data at the 10 ps level, which is still slower to what achievable with our technique anyway, but have to map the entire ring uniformly thus generating a huge amount of unnecessary data for many applications.

The non-linear crystal length and cut angle with respect to its optical axis are optimized at a design wavelength, which should be chosen together with the laser wavelength such as to put the detection wavelength at a value where the PMT quantum efficiency is maximum. The physics of the non-linear mixing process naturally selects a bandwidth (usually of the order of a few percent) outside of which the efficiency of the up-conversion process falls sharply.

Depending on the synchrotron photon flux in the bandwidth of interest, the instrument can work in “single-photon counting” or “accumulation” modes. In single-photon counting mode, the probability of two up-converted photons to be generated in a single sample is negligible. The detection circuit, following the photomultiplier, is a simple two-level discriminator and the analysis of a single bunch slice has to be integrated over many passes in order to build a meaningful statistics of the particle distribution in the bunch. In machines with a higher photon flux, where multiple photons can be generated by the mixing process at once, the digitizing of the PMT detected signal has to be carried out on a multiple level basis. In this case, it is possible to measure the bunch distribution taking just one sample per slice, depending on the signal-to-noise and accuracy requirements.

INSTRUMENT SETUP AT THE ALS

In order to test this technique validity, a prototype system has been assembled at Lawrence Berkeley National Laboratory and data was taken during several experimental sessions in Beamline 5.3.1 at the Advanced Light Source (Fig.2).

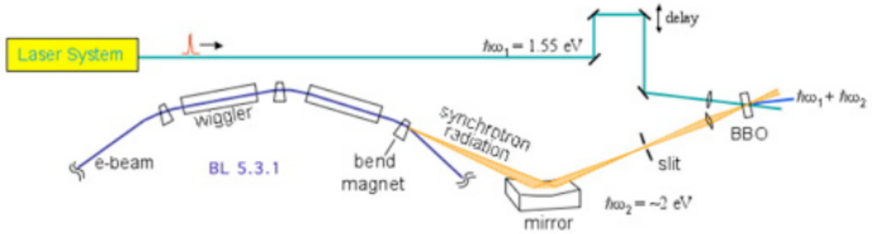

FIGURE 2. Optical layout at ALS's Beamline 5.3.1.

The laser used is a mode locked Ti:Al_2O_3 oscillator, phase locked to a sub-harmonic of storage ring's the main RF system. The laser operates at 71.4 MHz (14 ns repetition period), with a pulse length of 50 fs, wavelength of 800 nm and a 200 mW power.

The 197 m long ALS storage ring 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 modulated at 10 Hz so to sample the longitudinal profile of each RF bucket with 32 time slices (or *bins*) separated by approximately 4.8 ps.

The particular non-linear crystal used is a β-Barium Borate which, as a result of its large thermal acceptance bandwidth, high damage threshold and low absorption, is of common use with laser systems like ours.

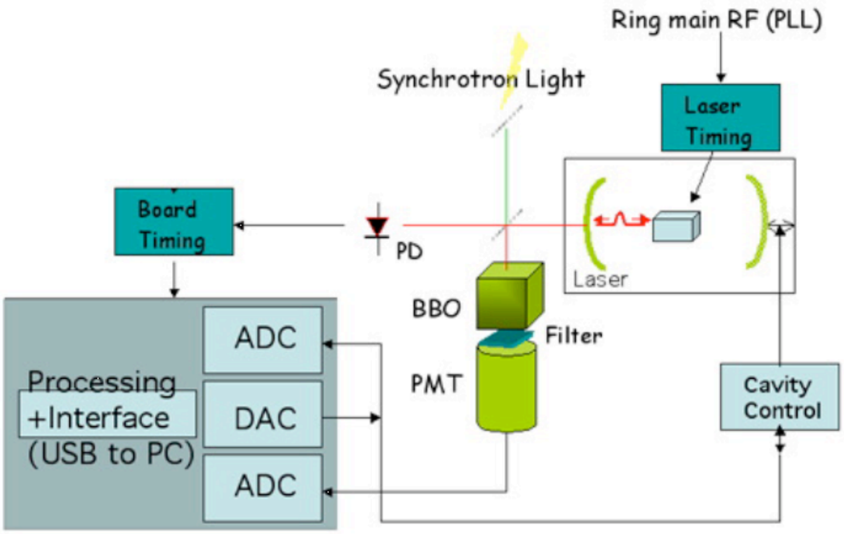

FIGURE 3. Timing scheme for the laser mixing technique used at the Advanced Light Source.

Figure 3 shows the functional units composing the instrument prototype used at the Advanced Light Source. The laser pulse is detected on a photodiode, which triggers the data acquisition board. The time delay between laser and enable signal for the

ADC is adjusted at the beginning of each experimental session. We are currently investigating triggering the board directly from the ring RF so that data taking would be synchronized with the beam rather than with the laser. The cavity control signal is a 10 Hz sinusoid which is slow enough to avoid any problem connected with mechanical vibrations induced in the mirror by faster modulating signals. This sets to 50 ms the theoretically minimum time to sample the entire bunch profile (i.e. the time it takes for a full excursion movement of the mirror). In fact, this is consistent with the photon flux out of the ring which, under typical conditions, yields about 10^6 photons per second detected by the PMT. Simple arithmetic tells us that this is equivalent to some 180 photons from each bunch, spread over the 32 bins. To obtain a better signal-to-noise ratio, especially for the bunch tails, we actually integrate for about 10 s, so that our bunch profile is composed of $3x10^4$ accumulated counts. The non-linearity of the 10 Hz sinusoid can be further used to our advantage: opportunely timed (i.e. with its zero-crossings coinciding with the bunch centre) it allows to take more data point in correspondence of the bunch tails, where a lower photon counts, and therefore a lower S/N, is expected.

Our in-house developed electronics board converts the PMT output into digital format and stores it in a local memory. Each bin has a separate memory register that accumulates the relative photon count. The 10 Hz waveform is also digitized and its value at data acquisition time is stored in a corresponding register, so that the count number for a particular bin is normalized to the number of samples taken.

The accumulated data is eventually dumped into a personal computer via USB interface for data postprocessing and visualization.

EXPERIMENTAL RESULTS

An prototype of the instrument described in the previous section has been successfully tested during several experimental sessions, which allowed to point out and correct bugs in the software for data display and minor problems in the board timing and RF noise rejection.

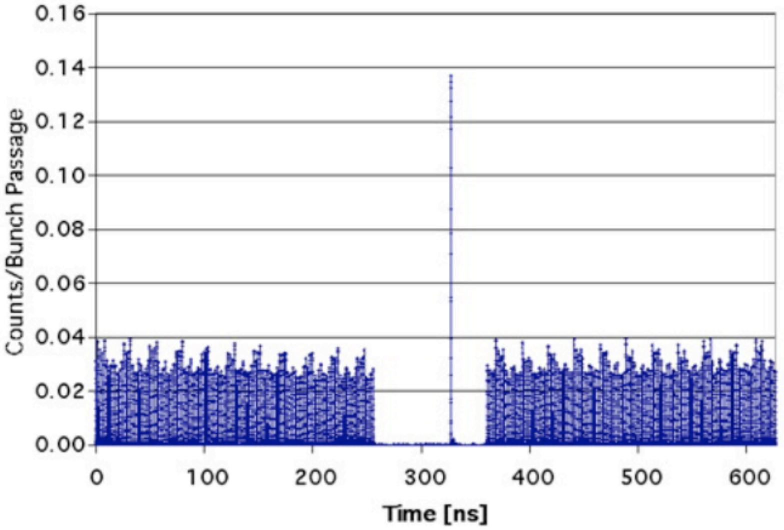

FIGURE 4. Complete ALS fill as measured using the laser mixing technique.

Figure 4 shows the data taken on such an occasion. The 657 ns long ALS fill consists of a single train of 276 bunches, with the remaining 52 RF buckets left empty (referred to as the *gap*). One of such buckets, called *camshaft*, is usually filled separately with a higher than normal current. The total current is in the range 200-400 mA. The periodic structure seen in the bunch train in Fig.4 is caused by the particular injection process used at the ALS, which our technique is able to document.

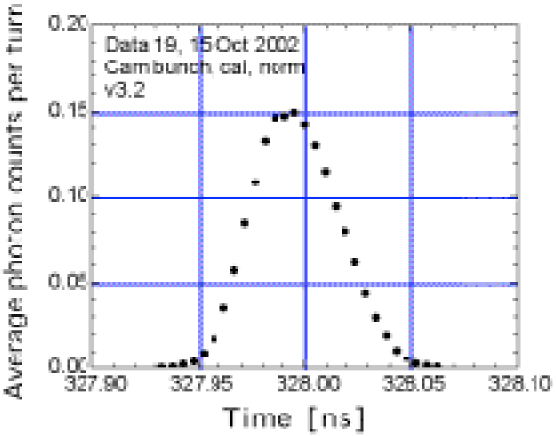

FIGURE 5. Detail of the camshaft longitudinal profile.

Thanks to the very high data throughput, expanding the horizontal time scale is all it takes for examining one of the bunches shown in Fig.4 in much greater detail (Fig.5). As a comparison, a streak camera can generate similar figures after a somewhat lengthier post-processing. The fundamental difference lays in that a streak camera cannot take data at the picosecond level resolution necessary to analyze a single bunch when taking data over a hundreds of nanoseconds long time span. Therefore, generating Fig.4 and 5 would require taking two separate images.

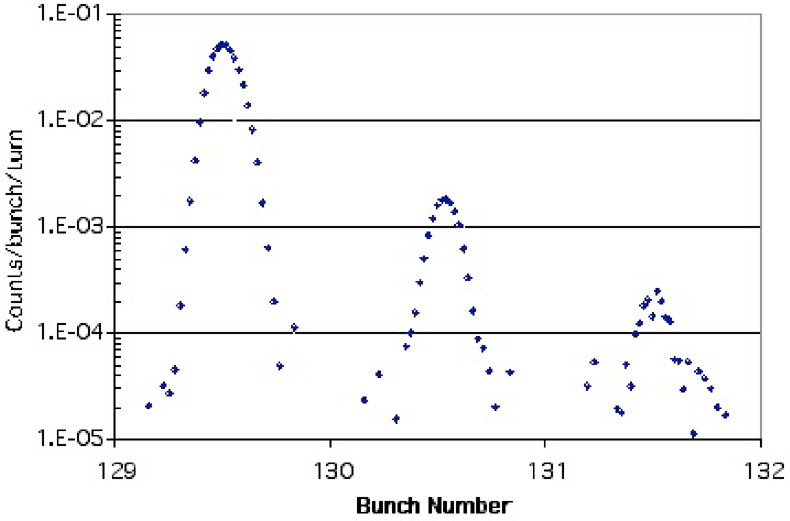

FIGURE 6. Dynamic range and sensitivity: the camshaft and ghost bunches can be measured at the same time. The instrument's noise floor is about three orders of magnitude below the camshaft signal.

Electrons lost from the camshaft can be recaptured by the following RF buckets, which are nominally empty, generating the so called *ghost bunches*. Figure 6 shows such situation: the second ghost bunch has a current of about 1/500-th of the camshaft's (6 mA), which gives an idea of the sensitivity obtainable with this technique.

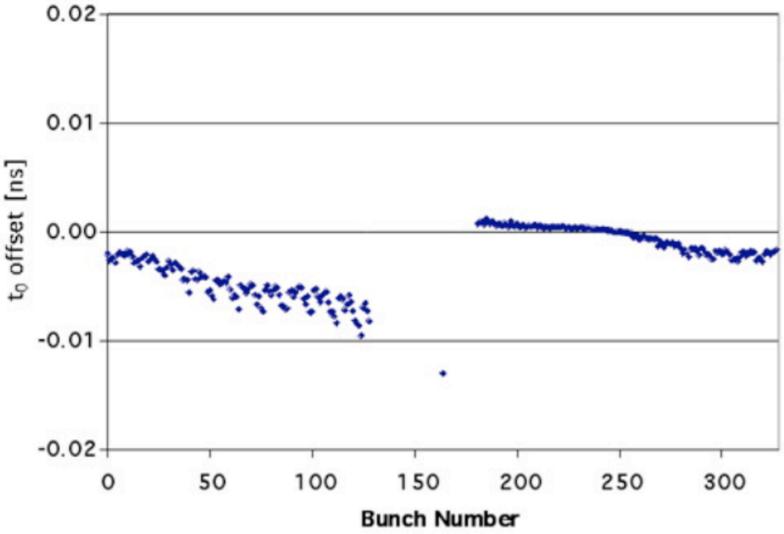

FIGURE 7. Synchronous phase transient along the ALS bunch train.

With a simple post-processing of the accumulated data we were also able to plot others parameters of interest: Fig.7 shows the variation of the synchronous phase along the bunch train, by plotting the position of each bunch centre. Fig.8 shows the bunch length instead. These effects in the ALS are caused by beam loading in the third harmonic cavities system installed to increase the lifetime.

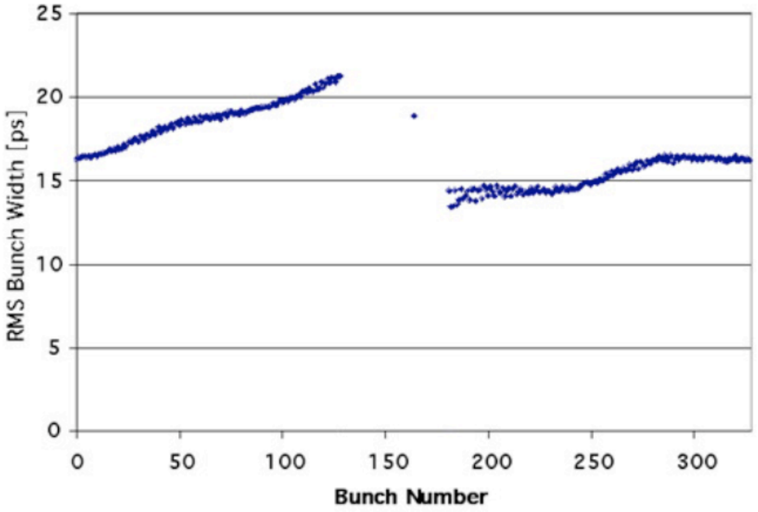

Figure 8. Bunch length variation along the ALS bunch train.

CONCLUSIONS

We believe that the laser mixing technique presented in this paper offers a number of exclusive features, which makes for a powerful instrument for longitudinal dynamics studies in storage rings. In particular, the maximum time resolution achievable is much higher than with other techniques available, and the combination of frequency up-conversion and choice of sampling rate make it a very flexible device. Our experimental results at the ALS well document the range of possible applications. Where a higher photon flux is available, it is possible to study the evolution of several beam parameters in a time scale substantially shorter than the synchrotron period.

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