Streak Camera as a Diagnostic for High Intensity Cooled Bunched Beams

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Abstract

Streak cameras are frequently used in plasma physics for recording processes requiring ns time resolution and high spatial resolution. This technique has been applied to ion beams from the GSI experimental storage ring (ESR) and the heavy ion synchrotron (SIS). First experiences with this application of the streak camera diagnostic are discussed. The method allows for high-resolution quantitative analysis in two dimensions, simutaneously. Its application to studies of beam instabilities appears promising.

1 INTRODUCTION

One of the objectives of the SIS/ESR [1] complex at GSI is to obtain cooled bunched beams with high phase space density and high total density. An application of such beams is the planned plasma physics experiments for the heating of a target with the focused beam. An important tool for achieving the desired high phase space density in the longitudinal and transverse directions is electron cooling in the ESR [2]. For achieving high total density, reinjection into the SIS from the ESR combined with stacking in the SIS will be important.

To study, understand, and optimize the development of these bright beams requires the appropriate beam diagnostics. Such a diagnostic is the optical streak camera which allows for unique observations of a beam bunch with good time and spatial resolution and which complements the existing non-destructive diagnostics in the SIS/ESR system. With a streak camera, measurements are possible simultaneously in the time domain and in one spatial dimension perpendicular to the beam's motion (e.g. horizontal or vertical). The capabilities of the streak camera make it suitable for studies of bunch profiles (temporally and spatially), bunch instabilities, transverse emittance, momentum spread, etc. as a function of various SIS/ESR operating parameters (e.g. those of the ESR electron cooler).

2 EXPERIMENTAL TECHNIQUE

The first implementation of the streak camera diagnostics has been to study the dynamics of bunching and the effects of high intensity (e.g. instabilities) in the ESR ion beams. Since the diagnostic is an interceptive technique it was installed in the reinjection line between the ESR and SIS where the extracted ESR bunches could be observed. Two species of ion beams, C^{6+} and Ne^{10+}, were studied for a variety of ESR operating conditions such as different circulating beam currents. For both species of ions the energy was 250 MeV/u.

The experimental technique was straightforward. The ESR extracted bunches were studied by using the streak camera to observe light emitted by a scintillator that was directly inserted into the beam. The scintillator was oriented at an angle of 45 degrees with respect to the ion beam line-of-flight and the streak camera line-of-sight was at 90 degrees with respect to the beam.

The streak camera used in these measurements was a Hamamatsu C2830 [3]. Briefly, the camera functions by converting the optical image of a thin slit into an electron image. The electron image is accelerated through a time varying deflecting field. The sweep of the electron image (e.g. from top to bottom) is synchronous with the passage of the electron image. The electron image is then reconverted to an light image. This light image is the streak image of the slit swept from top to bottom, thus representing a time axis flow (see Fig. 1).

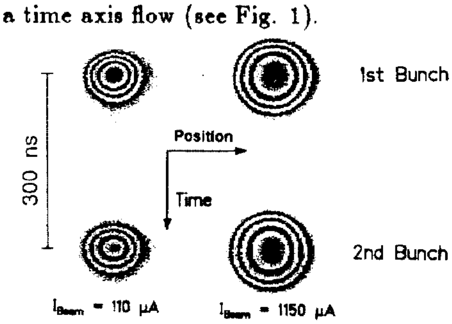

Figure 1: Steak camera images for C^{6+} cooled bunches at two different ESR beam currents. The energy is 250 MeV/u. Each image corresponds to a pair of bunches striking the scintillator.

In our measurements, the light emitted from the scintillator was incident upon a $\approx 100\ \mu m$ wide slit. The slit axis slit was oriented horizontally corresponding to the ESR bend plane. The slit was centered on the scintillator image of the 2-D spatial bunch profile. Because the the horizontal-axis information is the same for the original slit image and the streak image (time is the vertical axis), the streak camera allows for measurements of the time dependence of spatial and intensity distributions.

The choice of scintillation material was a 0.5 mm-thick sheet of NE102A [4] which is a widely used and readily available scintillator. It was chosen because of its high

*Permanent address: LANL, Los Alamos, NM, 87545, USA light output and good temporal resolution (decay constant 2.4 ns). Its principal disadvantage is its response to bright ion beams where saturation of the scintillator light output is observed and where radiation damage is possible. Experimentally this problem is overcome by expanding the beam in the reinjection line to reduce beam brightness.

In typical ESR operation, there are two stored bunches. When extracted they produce two spots in the streak image (Fig. 1). This provides a time calibration for each streak image. In the case of the C^{6+} and Ne^{10+} beams, the beam energy of 250 MeV/u implies a time difference of 300 ns (i.e. half of the ESR period of revolution) between bunch centers in the streak images. To obtain a spatial calibration for the images, the streak camera is operated in a mode which provides a conventional 2-D spatial image of the bunch profiles. From geometrical features of the scintillator (e.g. the scintillator edge or overall width) the spatial calibration is determined. This can be compared and checked for consistency with wire grid measurements of the beam profile which can be made a few cm's downstream from the scintillator. Ultimately, this technique should provide ns time resolution and ≈ 10 μm spatial resolution.

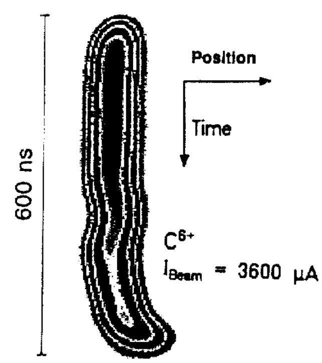

Figure 2: Streak camera image of C^{6+} cooled coasting beam (fast extraction) at 250 MeV/u. The circulating beam current was 3.6 mA. The time from head to tail is 600 ns (i.e. one ESR period of revolution). The horizontal deflections in the image are caused by the kicker pulse.

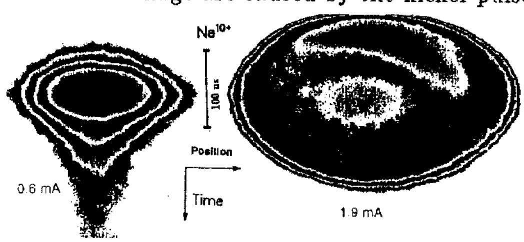

Figure 3: Streak camera images of a stable (left) and a unstable (right) Ne^{10+} bunch at 250 MeV/u. The stable and unstable bunches were for circulating beam currents of 0.6 and 1.9 mA, respectively. Both bunches were for the same rf buncher voltage.

3 EXPERIMENTAL RESULTS

The streak images can be processed in a variety of ways to observe and study various aspects of the ion beams. Figs. 1, 2, and 3 show black and white representations of the streak images for bunched and coasting C^{6+} beams and for bunched Ne^{10+} beams. The vertical-axis represents time flow from top to bottom and the horizontal-axis represents the horizontal spatial extent. Shown are equal intensity contours of scintillator light, which are converted alternatively into black and white.

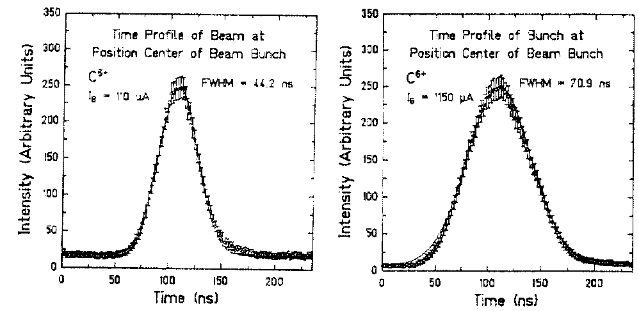

Figure 4: A comparison, at two beam currents, of the position profiles at the bunch centers. The solid lines represent fits to the data by a Gaussian plus a constant.

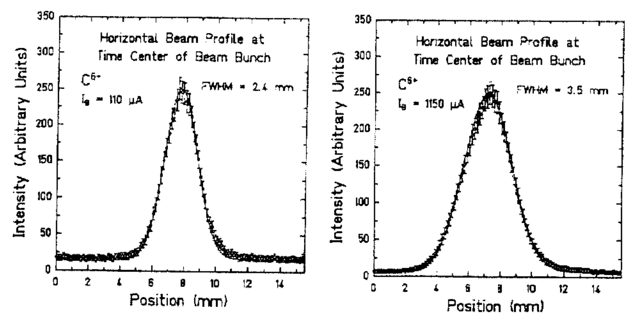

Figure 5: A comparison, at two beam currents, of the time profiles at the horizontal center of the bunches. The solid lines represent fits to the data by a Gaussian plus a constant.

Fig. 1 shows streak images for stable C^{6+} cooled bunches at 250 MeV/u for circulating beam currents of 110 and 1150 μA, respectively. The center-to-center time interval for each pair of bunches is 300 ns. For the first bunch of each pair, the horizontal beam profile at the bunch center and the time profile at the horizontal center of the bunch are shown in Figs. 4 and 5. The solid lines represent fits to the data by a Gaussian plus a constant. The fits and data are in good agreement. At times and positions other than those of the bunch center, the profiles were also determined to be Gaussian. The bunch lengths (FWHM) were ≈ 44 and ≈ 71 ns for the low and high currents, respectively. The corresponding bunch widths (FWHM) were 2.4 and 3.5 mm.

A cut from left to right in a streak image gives the instantaneous horizontal size of the beam in real space (see Fig. 4). The instantaneous horizontal beam emittance is proportional to the square of the instantaneous beam size. In Fig. 6 the dependence of the instantaneous horizontal emittance on time is shown for the high and low circulating beam currents. If the beta-function were known at the position of the scintillator, absolute emittances rather than relative could be determined. The emittance is observed to be constant along the bunch, independent of current. A possible explanation for this has been given by I. Hofmann [5] in terms of a constraint between the beam current and momentum spread along the bunch due to the synchrotron motion.

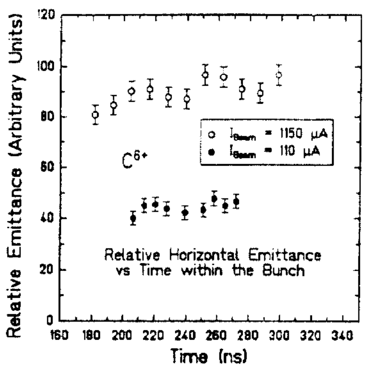

Figure 6: The dependence of the C^{6+} instantaneous horizontal emittance on time within the first of the two ESR beam bunches. The results for two ESR circulating beam currents are shown.

In Fig. 7 the instantaneous emittance dependence on time for a 3.6 mA C^{6+} coasting beam is given. Fig. 2 gives the corresponding streak image. A slow growth in emittance is observed until ≈ 250 ns. In the interval 250 ns to 460 ns the emittance is relatively constant. The point at ≈ 460 ns corresponds to the onset of the horizontal deflection due to the kicker pulse (Fig. 2).

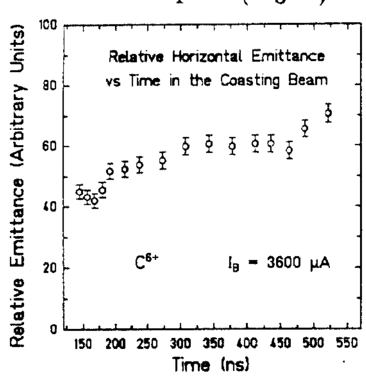

Figure 7: The dependence of the C^{6+} instantaneous horizontal emittance on time within the ESR coasting beam at 250 MeV/u. The results for a beam current of 3.6 mA are shown.

ESR experiments using higher intensity bunches have exhibited instabilities. For circulating currents exceeding ≈ 2 mA (i.e. ≈ 20 % of the maximum stable stored coasting beam currents for C and Ne beams) it was observed that the bunches were not in a stable equilibrium with the electron cooling. An example is shown in Fig. 3 of Ne^{10+} streak images for a stable bunch (left) and an unstable bunch (right) at beam currents of 0.6 and 1.9 mA, respectively. For the high-intensity inage, the bunch exhibits unstable behavior in both the longitudinal and horizontal directions. The peak intensity occurs in the center and in the half-moon shaped area at the head of the bunch. In the low-intensity image the top-bottom asymmetry is due to a scintillator afterglow. These Ne^{10+} images illustrate the sensitivity of the streak camera for studying bunch instabilities.

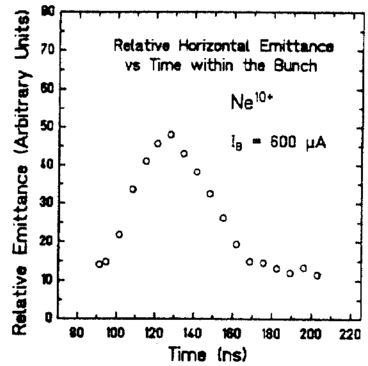

Figure 8: Dependence of the Ne^{10+} instantaneous horizontal emittance on time within the left hand bunch in Figure 7. The ESR circulating beam current was 600 μA and the energy was 250 MeV/u.

In Fig. 8 the measured dependence of the instantaneous emittance on time for the stable Ne^{10+} bunch (left image in Fig. 3). The emittance within the bunch varied strongly with time. This time dependence was quite different from that observed by the C^{6+} bunches.

4 SUMMARY AND CONCLUSIONS

The first results from the use of the streak camera in the ESR/SIS reinjection line shows qualitatively that this diagnostic has a unique capability for observing high-current beam dynamics within a bunch (e.g. the instantaneous horizontal or vertical emittance within a bunch or instabilities in bunched and coasting beams). In the case of the C^{6+} data, the quality of the data allow for an understanding of the observed constant horizontal emittance in time along the bunch [5].

Further work is required to determine and better understand the response of the scintillator to beam intensity per unit area per unit time and to the linearity of the streak camera with respect to light intensity. The possible use of other scintillating material or other light emitting mediums are being considered.

5 REFERENCES

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