INITIAL APPLICATION OF A DUAL-SWEEP STREAK CAMERA TO THE DUKE STORAGE RING OK-4 SOURCE

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Abstract

The visible and UV spontaneous emission radiation (SER) from the Duke OK-4 wiggler has been used with a Hamamatsu C5680 dual-sweep streak camera to characterize the stored electron beams. Particle beam energies of 270 and 500 MeV in the Duke storage ring were used in this initial application with the OK-4 adjusted to generate wavelengths from 500 nm to near 200 nm. The OK-4 magnetic system with its 68 periods provided a much stronger radiation source than a nearby bending magnet source point. Sensitivity to single-bunch, single-turn SER was shown down to 4 μA beam current at λ = 450 nm. The capability of seeing second passes in the FEL resonator at a wavelength near 200 nm was used to assess the cavity length versus orbit length. These tests (besides supporting preparation for UV-visible SR FEL startups) are also relevant to possible diagnostics techniques for single-pass FEL prototype facilities.

1 INTRODUCTION

It is well-established that two critical factors in successfully starting a free-electron laser (FEL) in an oscillator configuration are the gain (strongly dependent on peak current or particle beam charge density) and the synchronism of the orbit length and the resonator cavity length. Recently, in a collaborative effort between Duke University and the Advanced Photon Source (APS), the first dual-sweep streak camera images were taken of the output radiation of the Duke optical klystron version 4 (OK-4) installed in the 1-GeV storage ring [1]. These data were used to address directly the issues of the observed bunch length as a function of single-bunch current and rf cavity gap voltage. For the available rf fields a reasonable operating condition for adequate FEL gain was identified. Additionally, the key aspect of ring orbit length versus the resonator round trip time was actually done with λ = 195 nm radiation outcoupled from the resonator, a wavelength shorter than the existing 240-nm FEL lasing record. The usefulness of these key measurements was confirmed as first lasing experiments were successful a few weeks later, although at 350-400 nm [2]. These experiments in a sense are extensions of techniques demonstrated on a linac-driven visible FEL in the late 1980's [3].

2 EXPERIMENTAL BACKGROUND

The Duke storage ring and OK-4 have been described elsewhere [1,2] and key parameters are listed in Table 1. Operating energies from 0.25 to 1.0 GeV are possible. In this case the linac injection energy was about 270 MeV and beam could be stored there or ramped slowly upward in energy to 500 MeV. A key practical detail involved the rf frequency of 178.547 MHz which is a subharmonic of the linac's s-band at 2856 MHz. To use the synchroscan streak plug-in at 119.0 MHz, the 24th subharmonic of 2856, a special circuit was built at Duke that was phase-locked to the 178.5 MHz [4]. The OK-4 total length of 68 periods was also critical to performing the very low (sub-0.1 mA) current measurements.

Table 1: Summary of Parameters of the Duke Storage Ring and OK-4 (see Ref. 1)

Parameter	Design Value
Storage Ring	
Operating energy (GeV)	0.25-1.0
Ring circumference (m)	107.46
Revolution freq. (MHz)	2.789
rf frequency (MHz)	178.547
Beam current, A	0.1
Peak current, A	80-130
Horizontal emittance (m-rad)	18×10^{-9}
Vertical emittance, m-rad	1×10^{-9}
Bunch length (σ, ps)	33
OK-4 Parameter	
Undulator length (m)	3.40
Period (m)	0.10
Peak magnetic field (kG)	0.0-5.8
Buncher length (m)	0.34
Magnetic field (kG)	0-12

As shown schematically in Fig. 1, the SER was initially picked off by a retractable mirror positioned upstream of the cavity mirror. Mirrors and/or beam splitters were also used to bring the cavity's outcoupled radiation to the APS streak camera. A monochromator that is

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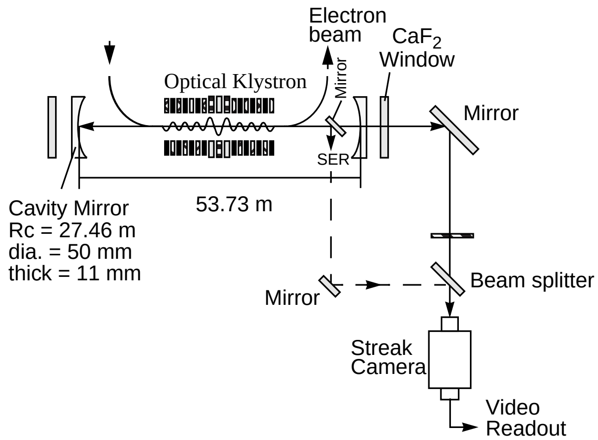

Figure 1: Schematic of the resonator set-up on the Duke OK-4 storage ring FEL. A pick-off mirror inserted just upstream of the cavity mirror allows the sampling of the SER for each pass of the electron beam.

not pictured was used to verify the operational wavelengths generated by the OK-4. The Hamamatsu C5680 dual-sweep streak camera was generally run with the vertical sweep in synchroscan mode and the horizontal sweep time selected for 10 µs, 50 µs, 1 ms, or 50 ms. With the revolution frequency in the ring of 2.78 MHz, single-bunch, turn-by-turn data could readily be attained.

It also should be noted that the nominal operating range of the S-20 photocathode streak tube with the UV-transmitting input optics is from 200 nm to 800 nm [5]. However, there is a rapid decrease in transmission of UV light through this input optics as one approaches and goes below λ = 250 nm. This practical effect in detector sensitivity was a key part of our tests, and why we originally looked at SER in the 400-500 nm regime in dual-sweep and then used synchronous averaging at λ = 200 nm.

3 EXPERIMENTAL RESULTS

3.1 Bunch Length

Initial tests on beam imaging were done with the bending magnet source, but we quickly moved on to the much stronger OK-4 source. A 450 × 40 nm bandpass filter rejected most of the bending magnet's white radiation. A representative example of a dual-sweep streak image at λ = 450 nm, beam energy E_B = 500 MeV, rf gap voltage V_{rf} = 150 kV, and beam current I_B = 1.62 mA is shown in Fig. 2. The vertical axis is the fast time axis with about 800 ps of the 1000-ps range displayed, and the horizontal sweep covers 10 µs. Each vertical image comes from a single pass through the OK-4. The selected fifth image's temporal profile has a calculated duration of 162 ps (FWHM). For comparison purposes, Fig. 3 then shows a similar image but with a higher gap voltage V_{rf} = 500 kV and lower current I_B = 0.19 mA. The measured bunch is much shorter at 60 ps (FWHM) or 25 ps (σ).

Figure 4 summarizes a series of measurements of bunch length with a variation of rf gap voltage and nominally for the low current regime (0.10-0.14 mA) and a ten times higher current regime (1.0-1.8 mA). It is noted that the plotted values are based on the preliminary analysis using the Hamamatsu MAC-TA algorithm which finds the peak intensity and then searches for the two half-maximum intensity points. Generally, there are ten beam images per file and two files were saved per parameter set. We are using the data from a single image, and plan to do further analysis on the actual profile shape as compared to a Gaussian shape. Based on available rf power, the 500 kV gap voltage with a few mA average current resulted in 5-10 A peak current. This latter value was calculated to have adequate gain for lasing experiments [2].

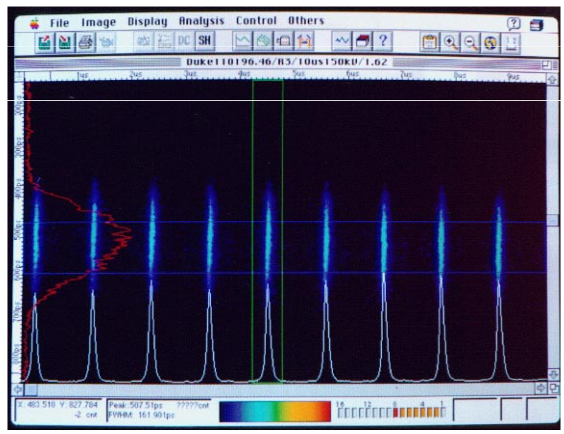

Figure 2: Dual-sweep streak camera image of the SER from the OK-4 at λ = 450 nm and for a beam energy of 500 MeV. The vertical sweep covers 800 ps while the horizontal axis is 10 µs. These are single-bunch data taken turn by turn. The measured bunch length at 150 kV rf gap voltage and I_B = 1.6 ma is 160 ps (FWHM).

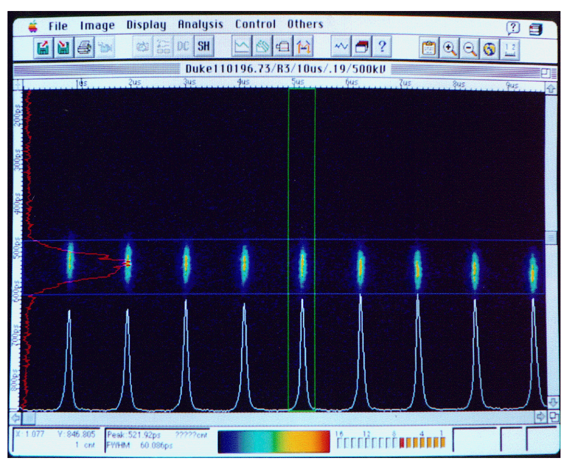

Figure 3: Dual-sweep streak camera image of SER from the OK-4 at λ = 450 nm, a beam energy of 500 MeV, V_{rf} = 500 kV, and I_B = 0.19 mA. The time axes are again 800 ps vertical and 10 µs horizontal. In this case, the bunch length of the selected image is 60 ps (FWHM).

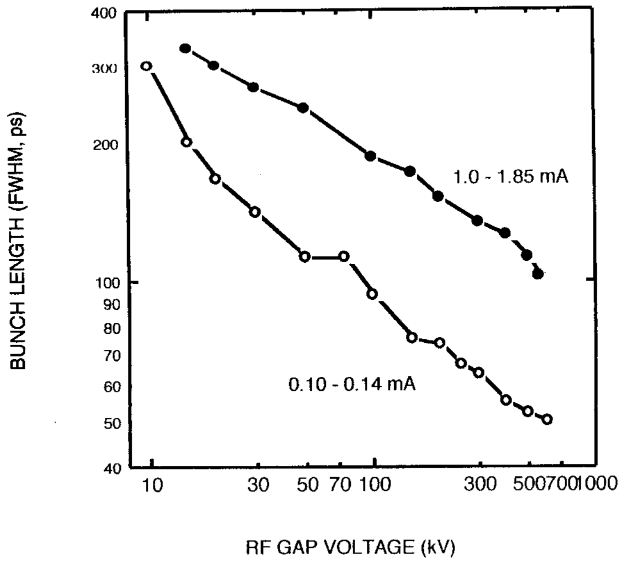

Figure 4: Plot of the variation of beam bunch length with rf gap voltage. The two sets of data are from low current (0.10-0.14 mA) and medium current (1.0-1.85 mA) runs.

3.2 Cavity Length/Orbit Length Synchronism

All measurements in the preceeding section used the retractable pick-off mirror upstream of the resonator cavity mirror. In order to evaluate the feasibility of detecting radiation near 200 nm, we initially used the pick-off mirror for wavelengths down to 220 nm in dual-sweep mode. We then changed to synchroscan sweep only and also changed a relay lens to a 50-mm focal length to provide a smaller focus at the entrance slit of the streak camera. The OK-4 was tuned to about λ = 195 nm, and the 193 nm $\times$ 10 nm band pass filter was put in the path to the streak camera. The radiation outcoupled from the cavity was then transported to the streak camera. At that point manual tweaking of the resonator cavity mirrors was done until the observed signal in the monochromator was reduced by 50% between the resonator mirrors' being tuned and detuned. The rf frequency for the storage ring was then varied to change the beam orbit length relative to the fixed resonator cavity length. As the stored beam current decreased, the bunch length shortened to about 40 ps (FWHM). We could then clearly display the relative arrival time of the second pass in the resonator compared to the first pass of the next e-beam bunch. Figure 5 shows an example where the second pass or lower image is 99.5 ps displaced from synchronism. By tracking the second pass's positions, the cavity and e-beam orbit length were synchronized. This preferred length was then used in subsequent lasing experiments within the next few weeks [2].

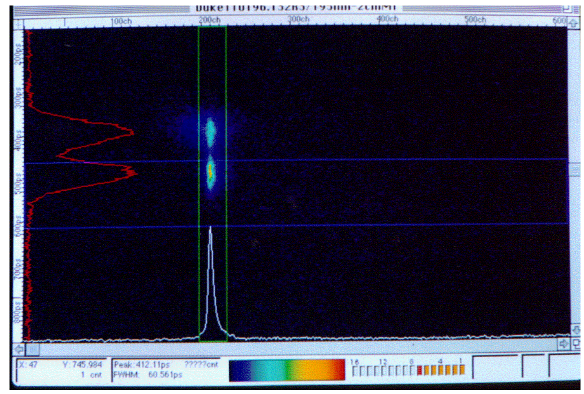

Figure 5: Synchroscan streak image of the SER outcoupled from the resonator cavity at $\lambda \sim$ 195 nm. The very low current of 0.04 mA resulted in a bunch length of 44 ps (FWHM). The cavity length is different from the orbit length by 99.5 ps as shown by the vertical displacement of the two images.

4 SUMMARY

In summary, both the dual-sweep and synchroscan options of the streak camera were used to provide key information for the operation of this SR FEL. The source strength of the OK-4 SER was exploited to measure the electron beam bunch lengths at very low currents (<10 μA) and to detect radiation in the deep UV at λ = 195 nm. These results extend the range over which the techniques have been demonstrated on a FEL facility.

5 ACKNOWLEDGMENTS

The authors acknowledge John Galayda (ANL/APS/ASD) and John Madey (Duke FEL Laboratory) for their support of this collaboration. APS work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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