# SUCCESSFUL COMPLETION OF THE FEMTOSECOND SLICING UPGRADE AT THE ALS*

C. Steier†, P. Heimann, S. Marks, D. Robin, R. Schoenlein, W. Wan, W. Wittmer,
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA


## *Abstract*

An upgraded femtosecond slicing facility has been commissioned successfully at the Advanced Light Source. In contrast to the original facility at the ALS which pioneered the concept, the new beamline uses an undulator (the first in-vacuum undulator at the ALS) as the radiator producing the user photon beam. To spatially separate the femtosecond slices in the radiator, a local vertical dispersion bump produced with 12 skew quadrupoles is used. The facility was successfully commissioned during the last 1.5 years and is now used in routine operation.


## INTRODUCTION

The ALS is one of the earliest third generation synchrotron light sources located at Lawrence Berkeley National Laboratory and is serving more than 2200 users every year. To generate short pulses of x-rays with durations of $100-200$ femtoseconds, an innovative technique to slice the longer electron bunches was proposed and successfully demonstrated several years ago [1]. The technique uses a femtosecond laser beam copropagating within an undulator or wiggler to energy-modulate a short section of a bunch. Using spatial or angular dispersion downstream of the interaction with the laser combined with apertures in the beamline to block the light of the unsliced part of the bunch one can then produce fs x-ray pulses. A sketch of the main accelerator components of the new undulator fs-slicing beamline is shown in Fig. 1.

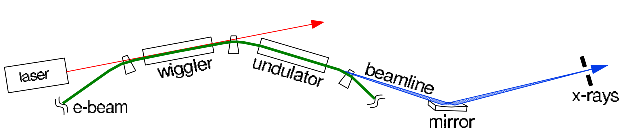


Figure 1: Sketch of slicing arrangement at ALS.

Initial scientific experiments have been carried out until 2005 using an ALS bending magnet beamline. Based on the performance limitations of that beamline, particularly the very low flux, an upgrade was successfully implemented in 2002-2007, which enables more experiments that make use of time resolved spectroscopic techniques (like time resolved x-ray diffraction or time resolved x-ray absorption spectroscopy) and require higher average photon flux (compare Fig. 2).

* This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

† CSteier@lbl.gov

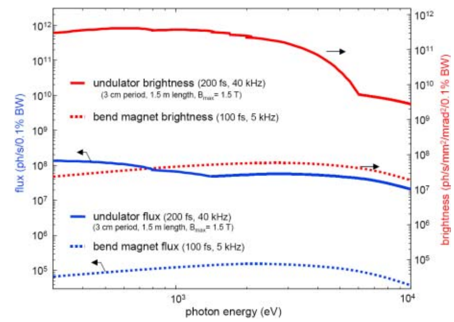


Figure 2: Flux and brightness of the original and upgraded fs slicing sources at the ALS.

Based on the slicing concept pioneered at the ALS, other light sources like BESSY and SLS have implement undulator slicing beamlines as well, however all three facilities use different methods to generate the spatial separation of the elctron slices and also are targeted for different wavelength regimes and science applications.

### *Components of the undulator slicing upgrade*

The upgrade consists of many new components, some of which were technically challenging. In addition, a large set of accelerator physics challenges needed to be overcome. The new hardware consists of two new insertion devices (modulator and radiator), two new undulator beamlines, a new laser system with significantly higher repetition rate and modifications to the storage ring to create the vertical dispersion bump used for spatial separation. One of the new insertion devices is a wiggler which is simultaneously used for protein crystallography and as modulator for the slicing. The second insertion device is an in-vacuum undulator. Since the photon energy range required by the science case is large (about 200 eV to 10 keV) and the beam energy of the ALS is only 1.9 GeV, the in-vacuum undulator is used as an undulator up to about 4 keV and as a wiggler up to 10 keV. At a later time it is planned to add an eliptically polarizing undulator to enable studies of ultrafast magnetism.

### *Challenges*

The accelerator physics challenges created by the new facility were centered in 3 main areas: generating the vertical dispersion bump to provide the spatial separation to isolate the fs x-rays pulses, minimizing the vertical emittance and spurious dispersion, and studying insertion device related issues [3, 4]. The issues studied in connection with the insertion devices include - to just name some examples

 

- their effect on the nonlinear dynamics, resistive wall heating effects, impedance issues and the effects caused by the field imperfections of the devices (coupling, focusing and orbit errors).

## PROJECT STATUS

Starting in 2002 the design, construction and commissioning of the upgrade started. First the new modulator was installed and commissioned in 2004 verifying the nonliear transverse dynamics studies carried out beforehand. A significant technical challenge that was solved was a completely new carbon filter assembly for the protein crystallography beamlines fed by this wiggler, which was necessary because of the higher power density. The lattice modifications to provide the vertical spatial separation were implemented and tested over a long period, optimizing the properties of the closed vertical dispersion bump along the way. The initial demonstration happened in 2002. The final, optimized solution that is compatible with the new higher brightness user lattice and provides very small global as well as local coupling was implemented in 2005. A technical challenge of the dispersion bump was that it required some skew quadrupoles of up to 4 times the strength of the original ALS skew quadrupoles (k values of more than $0.4 m^{-2}$). In order to provide this whithout giving up the ability to use the horizontal correctors in the combined functions sextupoles/correctors/skew quadrupoles, significant changes were made to the magnets and verified in magnetic measurements and later with beam. The new in-vacuum insertion device together with new vacuum chambers, beam diagnostics, chicane magnets, interlock systems, and beam aperture defining collimators were installed in 2005. The soft x-ray beamline started commissioning in late 2005 and the hard x-ray beamline in early 2007. The main challenge in the beamlines were the chopper systems which reduce the heat load, background and radiation damage due to light from unsliced bunches. The 20 kHz laser system is in use since summer 2005. First science experiments on the soft x-ray beamline were carried out in 2006.

## NEW INSERTION DEVICES

As the first insertion device for the upgrade, the new wiggler (1.9 T, 114 mm period) was installed in 2004. The potential impact of the new insertion devices on the beam dynamics [5] was studied very carefully in advance. The geometry of the magnetic assembly was chosen such that the nonlinear effects are negligible. Once the wiggler was installed this was verified experimentally. The protein crystallography beamline using the wiggler employs carbon filters in the beamline frontend, to reduce the heat load on the downstream beamline optics and the beryllium window. Since the new shorter period wiggler delivers a higher power density, a complete redesign of those carbon filters was carried out using two layers of highly oriented carbon, clamped between watercooled metal frames. The new design works extremely well, requiring no maintenance or exchange of parts.

The in vacuum undulator (see Fig. 3) was installed in the upstream half of one ALS straight in April 2005. It is the first such device installed in the ALS and has a minimum physical aperture of about 5.2 mm, compared to the more than 8 mm of the smallest physical aperture before than. Extensive dynamics studies were carried out beforehand, to demonstrate that this reduction in physical aperture will not have a significant impact on the momentum aperture [3].


Figure 3: Picture of the first ALS in-vacuum undulator with 3 cm period and 1.52 T maximum field.

The undulator has been in routine user since 2005 and measurements of the Touschek lifetime (which generally is the dominating lifetime contribution at the ALS) as a function of gap confirmed that with the improvements in coupling control and the improved dispersion bump with small local coupling at the location of the undulator, there is no measurable impact of the gap reduction on the dynamic momentum aperture (see Fig. 4).

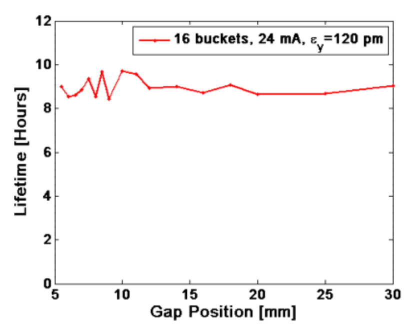


Figure 4: Touschek lifetime as a function of magnetic gap of the in vacuum insertion device. The physical aperture is about 0.3 mm smaller than the magnetic gap.

### *Radiation Damage*

One major issue with permanent magnet insertion devices, especially when operating with relatively short lifetimes in top-off mode is radiation damage. The in-vacuum undulator installed at the ALS uses a heat treated, high $H_{ci}$ NdFeB material (Neomax-38VH), which minimizes the sensitivity to radiation damage. In addition, as part of the top-off upgrade, beam loss patterns for injection, stored beam losses, as well as beam trips were studied in detail. Realtime radiation monitors are installed around the undulator and adjustable vertical collimators were designed and installed at 4 locations of the ring. Measurements after their installation confirmed that they are very effective at localizing stored beam losses away from people and sensitive equipment as well as preventing injection mishaps when the undulator is closed. Before top-off operation starts we will add more local shielding to those collimators.

## VERTICAL DISPERSION BUMP

The vertical dispersion bump used to provide the spatial separation now uses 12 skew quadrupoles, spanning 3 arcs. It is optimized in terms of the single particle beam dynamics. The coupling is zero everywhere outside of the bump, and in addition the local coupling in the straight with the in vacuum undulator is nearly zero. It is also optimized to minimize the increase in beamsize for the beamlines next to the fs-slicing facility and to minimize emittance increase. The settings of the skew quadrupoles are corrected regularly (about once a month) and measurements of dispersion and other lattice functions agree extremely well with the design.

Measurement of the x-ray flux through the slits in the user beamline confirmed that the spatial seperation scheme works well and the signal to noise ratio is consistent with what is expected. It is mostly dominated by the surface roughness of the focusing beamline mirror. The measured amplitude of separation (amplitude of energy modulation) is slightly smaller than one would expect based on the laser pulse energy, an effect that is also observed at all other slicing facilities. However, the separation is sufficient to carry out good user experiments (see Figure 5).

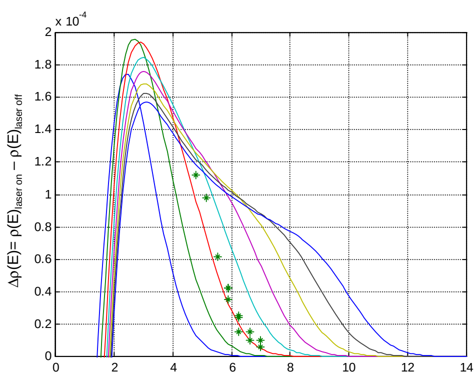


Figure 5: Measured femtosecond x-ray flux (crosses) compared with model calculations (solid) of the differential electron density distribution for laser modulation of the electron beam energy ranging from $3\sigma_E$ to $10\sigma_E$ with $\frac{\tau_{\text{laser}}}{\tau_e} = 10^{-3}$ and collecting the integrated flux over a slit width of $1\,\sigma_E$. The measured energy modulation is between $5\sigma_E$ and $6\sigma_E$. Note: $1\sigma_E$ corresponds to $\Delta y = 27.2\mu m$.

### *Emittance Control*

The operation of the ALS with the femtoslicing source requires continous and excellent control of global+local coupling as well as the vertical dispersion. To achieve this, orbit response matrix analysis (with LOCO) is applied at least once a month, correcting the gradient symmetry as well as all 27 skew quadrupoles. This ensures optimum and reproducible injection efficiency, momentum aperture (Touschek lifetime), spatial separation of the sliced electron bunch, emittance and beamsize stability.

Applying the loco results, all (coupled) lattice errors are corrected. Simultaneously the local dispersion bump for the slicing experiment is corrected and a global dispersion wave is added increasing the vertical emittance to the nominal 120 pm (without intoducing betatron coupling). The in-vacuum insertion device with its 1.52 T peak field contributes significantly to the vertical emittance (up to 60 pm) because of the vertical dispersion used to generate the spatial separation. Since users are allowed to scan the undulator field to change the photon energy, one has to compensate to avoid that the overall emittance changes. This is done by adjusting the global dispersion wave in a feed-forward scheme whenever the undulator field is changing. The dispersion wave does not use any skew quadrupoles between the fs modulator and radiator, therefore this feed-forward does not affect the separation of the fs slice.

## SUMMARY

All accelerator modifications for the undulator based femtosecond slicing facility at the ALS have been fully operational during user time for over a year and a half. Despite the large number of challenges which had to be resolved as part of the project, the migration into routine user operation went very smoothly and without any negative side effects on other users. The overall complexity of the project in terms of beam dynamics, coupling/dispersion control, impedances, radiation damage/safety, injection efficiency and lifetime was very substantial and some of the solutions implemented (particularly lattice/coupling/dispersion control) as part of this project are establishing a new state-of-the-art.

## REFERENCES

[1] Zholents and Zolotorev, Phys. Rev. Lett., 76, 916,1996.

[2] J. Safranek et al., Phys. Rev. STAB 5, 010701 (2002).

[3] C. Steier, et al., Accelerator Physics Challenges of the fs-Slicing Upgrade at the ALS, Proceedings of PAC 2003, Portland.

[4] C. Steier, et al., The New Undulator Based fs-Slicing Beamline at the ALS, Proceedings of PAC 2005, Knoxville.

[5] C. Steier et al., Phys. Rev. E 65, 056506 (2002).


1-4244-0917-9/07/$25.00 