# ACCELERATOR PHYSICS CHALLENGES OF THE FS-SLICING UPGRADE AT THE ALS*

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## *Abstract*

The goal of the Femtoslicing project at the ALS is to provide 100-200 fs long pulses of soft and hard x-rays with moderate flux and with a repetion rate of 10-40 kHz for experiments concerning ultrafast dynamics in solid state physics, chemistry and biology. The femtoslicing principle employs a femtosecond laser beam to interact resonantly (inverse FEL interaction) with the electron beam in the ALS. The induced energy spread over the femtosecond duration is converted to a transverse displacement by exploiting the dispersion of the storage ring. The displaced femtosecond electron pulse then radiates and produces femtosecond synchrotron radiation. To achieve the necessary spatial separation of the energy modulated slice from the rest of the bunch, a sizeable local vertical dispersion bump in the undulator used as radiator is required. This presents challenges in terms of the nonlinear dynamics and control of the vertical emittance.

## INTRODUCTION

The ALS is a third generation synchrotron light source located at Lawrence Berkeley National Laboratory. It was originally designed to provide very bright VUV and soft x-ray beams and has been in operation since 1993. To generate short pulses of x-rays with durations of a few hundred femtoseconds, an innovative technique has been developed at the ALS [1]. This technique uses the interaction of an electron bunch with a femtosecond laser beam within a wiggler to energy-modulate (slice) a short section of that bunch. Using spatial or angular [2] dispersion downstream of the interaction with the laser one can then isolate fs x-ray pulses. Over the past years a science case has been developed to make use of this new source of x-rays. The proposed experiments make use of time resolved spectroscopic techniques (time resolved x-ray diffraction or time resolved x-ray absorption spectroscopy) and require higher average photon flux than can be delivered by the ALS bending magnet beamlines which were used for the demonstration experiments of the slicing technique. To increase the average flux of fs x-rays a plan for a new ultrafast x-ray undulator beamline has been developed. The beamline complex is now in its design and initial construction phase. A sketch of the main accelerator components of the new beamline is shown in Fig. 1.

The upgrade consists of several key components, including two new insertion devices (modulator and radiator), a new undulator beamline complex, a new laser system with significantly higher repetition rate and modifications to the storage ring to create the vertical dispersion bump used to spatially separate the sliced electrons/photons. One of the new insertion devices is a new wiggler which is simultaneously used for protein crystallography and as modulator for the slicing. It will have a shorter period (11.4 cm compared to 16 cm of the existing wiggler) to allow for optimized use both by the protein crystallographers and the slicing experiments by allowing slicing on its first instead of third harmonic at 1.9 GeV. The second insertion device will be an in-vacuum, permanent magnet undulator, similar to the ones used at Spring-8, ESRF and SLS. Since the photon energy range of the science covered by the new facility is very wide (about 200 eV to 10 keV), the new undulator will be used both as an undulator up to about 3-4 keV and as a wiggler up to 10 keV.

## CHALLENGES

The accelerator physics efforts to support the new fs x-ray undulator beamline have been centered on three 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 [3], and studying insertion device related issues [4, 5]. Additional details about those studies can be found in the given references. This article summarizes all results.

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). Working together with the magnet group of the ALS, a set of specifications and a magnetic design for the new wiggler have been developed minimizing all detrimental impacts on the electron beam. For the in-vacuum undulator, the studies are in their final phase.

### *Beam Dynamics in Insertion Devices*

One of the most dangerous effects insertion devices can have on the transverse single particle beam dynamics is the effect of the transverse field roll-off [6]. Since the particles follow undulating trajectories the nonlinear kick due to the transverse field roll-off can accumulate resulting in a potentially large reduction in dynamic aperture and dynamic

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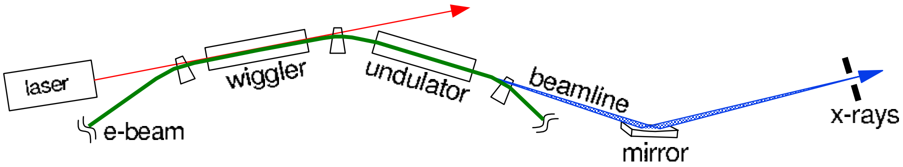

Figure 1: Sketch of fs-slicing layout for the new undulator beamline at the ALS.

momentum aperture. Since the (Touschek) lifetime at the ALS is already dominated by the transverse single particle dynamics (i.e. the dynamic momentum aperture [7]) this is a potentially very serious effect. Therefore it has been studied in extensive detail using 3 dimensional magnetic field models (TOSCA) of the chosen wiggler design, the fit of an analytical field model to this numerical field data and a new symplectic integrator [8]. Fig. 2 shows the results of one of the simulation runs. Shown are on-energy fequency maps in configuration space calculated by tracking particles with different initial conditions for 1000 turns. The color code indicates the diffusion rate on a logarithmic scale.

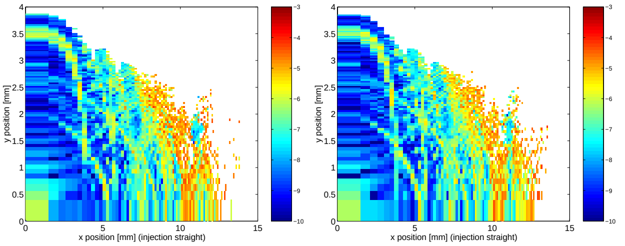

Figure 2: Comparison of two frequency maps in configuration space. W11 wiggler without any horizontal field roll-off (left) and with 125% of the nominal horizontal field roll-of (right).

The left plot shows the frequency map for a wiggler (11.4 cm period, 1.91 T field) without any horizontal field roll-off (i.e. the main effect in the tracking is the vertical tune shift from the wiggler). The right plot shows the case of a wiggler with mostly the same parameters but now a horizontal field roll-off is included (125% of the nominal field roll-off). As one can see, there is virtually no difference between the two frequency maps. The same was true in off-energy simulations. Therefore we are very confident that the field roll-off of the chosen design will not be an issue and the effects of the new wiggler on the beam dynamics will be completely dominated by its linear vertical tune shift (which is virtually identical to the one from the existing wiggler it replaces).

## *Separation*

To separate the sliced beam from the main bunch, different techniques can be used. We decided to use vertical spatial separation with a closed vertical dispersion bump, since it allows the use of the radiator in wiggler mode and the use of dispersive spectroscopy in the beamline. Fig. 3 shows the vertical dispersion bump, which is generated as a closed bump with negligible coupling using four or eight skew quadrupole magnets. The main issue that has been studied in connection with the dispersion bump is the impact on the nonlinear dynamics of the ALS, particularly injection efficiency and lifetime.

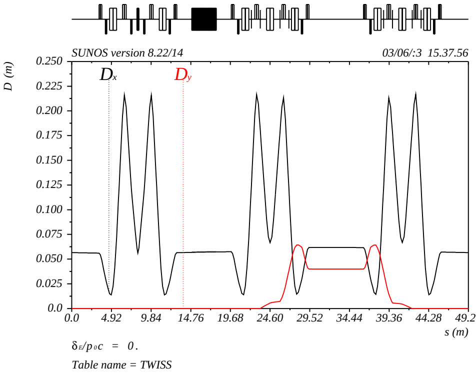

Figure 3: Layout of the closed vertical dispersion bump used to generate the necessary separation of the sliced bunch at the radiator. A total of four or eight skew quadrupoles is used.

A dispersion bump of sufficient amplitude has been demonstrated experimentally (see Fig. 4) and its impact on the momentum aperture was negligible. To generate the necessary skew quadrupole gradients, some magnets had to be modified and the effects of differential pole saturation was studied. No problems were found related to the about 1% reduction of the sextupole field of the combined sextupole/skew quadrupole magnets, caused by the strong skew quadrupole fields. The increase in vertical emittance caused by the dispersion bump was relatively modest (quantum excitation in the two bending magnets inside the bump) and agreed with calculations. However, in simulations we found one potential problem: the dispersion bump as we currently implement it generates a large local coupling inside the bump, which causes the (planned) small vertical aperture of the insertion device to be transformed into a moderate horizontal aperture, limiting the momentum aperture. This effect is currently under study and a solution using more (eight) skew quadrupoles to generate the dispersion bump while minimizing the local coupling angle looks very promising.

## *Coupling Correction*

Minimizing the vertical emittance and spurious dispersion allows one to maximize the brightness of a synchrotron radiation source. Because the Touschek lifetime of a low emittance, low energy light source like the ALS is very short, reducing the vertical emittance below the op-

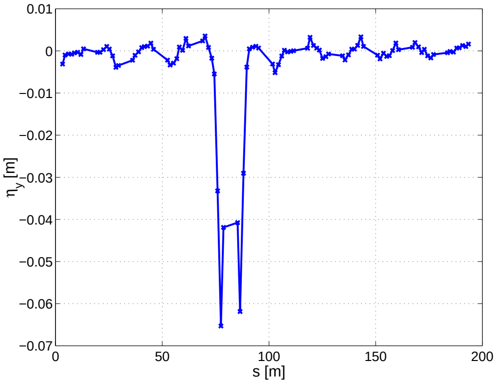

Figure 4: Measured vertical dispersion bump. The leakage of the bump was caused by a difference in saturation between the individual skew quadrupoles due to the additional orbit correction windings. Nevertheless, the leakage is already acceptable.

erational value of about 150 pm, which is used at the moment, would have reduced the lifetime to unacceptable values (below 8 hours at 400 mA). For the future, this situation will change with the use of top-up injection. The new fs beamline on the other hand will directly create vertical emittance because of the fairly strong insertion device inside the vertical dispersion bump. Therefore it will be important to minimize the baseline vertical emittance without the dispersion bump. Using 18 individual skew quadrupole magnets, whose power supplies have been installed last year, vertical emittances of about 5 pm have been demonstrated (an improvement of a factor of 30 compared to the current operating condition) [3]. This will allow the new beamline to operate with an optimized size of the vertical dispersion bump maximizing the femtosecond x-ray signal to noise ratio for a given brightness (vertical emittance) for all other beamlines.

### *Impact of Vertical Aperture on Lifetime*

For permanent magnet as well as for superconducting insertion devices the possible performance depends strongly on the possible minimum gap of the magnetic structure. Therefore it is important to determine the minimum physical vertical aperture which can be tolerated with respect to beam lifetime and injection efficiency. At the ALS the limit used to be a full vertical aperture of about 8 mm. With an improved lattice, better correction of the lattice symmetry and especially better control of coupling it was possible to reduce this limit to a full aperture of about 5 mm [5]. This was verified by measurements using a scraper at the ALS. Fig. 5 shows a scraper measurement in the ALS with corrected coupling and the vertical emittance increased to its current nominal value of 150 pm by using a vertical dispersion wave. The lifetime reduction in those conditions is fairly small down to a full vertical aperture of about 5 mm.

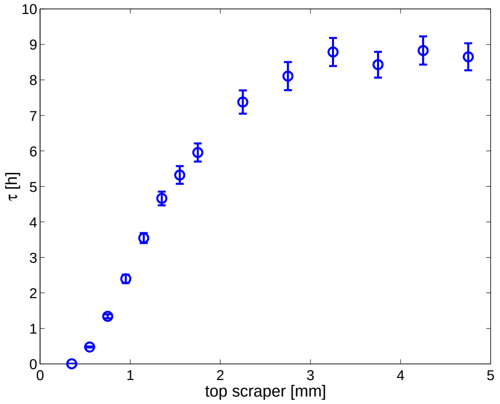

Figure 5: Lifetime of the ALS versus half aperture in one straight, measured using a scraper: The lifetime reduction for a lattice with corrected coupling and vertical dispersion wave to increase the vertical emittance is small down to a full vertical aperture of about 5 mm.

## SUMMARY

A new undulator beamline for femtosecond x-rays is under design and consruction at the ALS. It will start with beamline commissioning at the end of 2004 or early in 2005. The accelerator physics issues associated with the new facility have been successfully studied. The dynamics in the insertion devices (especially the effects of the transverse field roll-off of the wiggler) has been studied extensively and no problems were found. A vertical dispersion bump for spatial separation of the fs x-rays has been demonstrated with more than sufficient amplitude (4 cm) and minimal negative impact. Methods for vertical emittance and dispersion control have been established, achieving much better results than necessary. The impact of small gaps (5 mm full gap) on lifetime and injection efficiency have been studied with positive results. The main remaining issue is the interaction between the narrow vertical aperture in the radiator and the vertical dispersion bump. A solution using 8 instead of 4 skew quadrupoles to minimize the local coupling for a fixed vertical dispersion works in simulations. A measurement program to test this in detail will start in June.

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