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Toward operation of series IDs at BL43LXU of SPring-8

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Abstract. This paper discusses two issues relating to using 3 small gap insertion devices in series at BL43LXU of SPring-8 to make a uniquely powerful source in the 15-26 keV region of the x-ray spectrum. The issues discussed are (1) damage to the covers of the downstream IDs by radiation from the upstream IDs and (2) proper steering of the electron beam to get the best photon beam properties. After tests in several configurations, including one where an ID was run without an impedance-reducing cover, the damage issue was solved by installing a distributed absorber in the most downstream ID. The steering issues were mostly resolved by the introduction of appropriate corrector magnets and feedback. The paper is written from the viewpoint of an interested beamline scientist impressed with the cooperation of different groups to make a source for new science possible.

INTRODUCTION

BL43LXU of SPring-8 is designed to provide world-leading x-ray flux between 14.4 and 26 keV for high-resolution inelastic scattering [1]. This is a special opportunity made possible by the combination of advanced insertion device, accelerator and beamline technology, at the SPring-8 storage ring. The increased flux, in a highly flux limited field, offers the opportunity make notable strides in the investigation of meV dynamics, phonons, to understand the behavior of complex materials (correlated materials, multi-ferroics, *etc.*) at the forefront of materials research, geoscience (to probe the structure of the earth's core) and to investigate also electronic excitations. The starting point is a highly optimized source for this energy range based on 3 x 5m permanent magnet in-vacuum undulators [2], all with 19 mm periods and < 6 mm minimum magnetic gap, in a long, 30 m, straight section of the 8 GeV storage ring. This allows, in principle, the desired energy range to be spanned in the fundamental of the IDs with K varying from K=0.68 (26 keV, flux ~$2x10^{15}$ photons/s/0.1% BW in the central cone) to K=1.56 (14.4 keV, ~$4x10^{15}$) [3]. While the 15m ID length is less than the 25m of 32mm period ID installed at BL19LXU, the flux at BL43LXU is similar, or larger, between 15 and 26 keV than what BL19LXU could provide in principle, and, in, practice, fills the "hole" in the spectrum at BL19LXU between ~16 and ~24 keV. However, to avoid severe reduction of the storage ring beam lifetime, small gap operation of the IDs at BL43LXU requires focusing (and steering) the electron beam between each ID segment (see [4] and references therein), which means that about half of the available straight section is used for magnets, and the center-to-center spacing between the 5m IDs is 10.7 m (see figure 1).

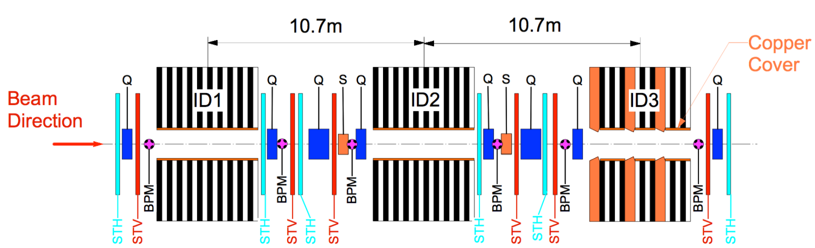

FIGURE 1. Component layout, including IDs for BL43LXU. Positions of steering correctors, focusing magnets, and BPMs are as indicated. The beam travels from left to right. The last ID has a distributed absorber. Figure not to scale.

Here we discuss two issues that arise from having 3 small-gap IDs in series, with large distances between the IDs: (1) the power from the upstream IDs damaging the covers of the downstream IDs and (2) the steering of the beam through the multiple IDs to properly align the photon beam axis. The beamline is now, June 2015, running well, with use of 3 IDs possible beginning in April of 2015, and steering significantly improved in May of 2015. The discussion here is from the point of view of a beamline scientist looking at, participating in, and, being impressed with the cooperation needed to optimize the new source for experiments.

IN-VACUUM ID COVERINGS

The magnets for the insertion devices, as initially installed, were covered with copper foils, one each on the lower and upper magnet array. The foils were 50 μm of Cu, onto which a 25 μm layer of Ni was electroplated. The purpose of the cover is to reduce the impedance of the ID as seen by the electron beam, and therefore avoid exciting instabilities. It also reduces power dissipation into the magnetic array. The foils were clamped on either side (left and right) of the magnet array and also held by the magnetic force on the nickel layer. When the gap of ID3 is closed, its covering is then illuminated by radiation from ID1: one side of ID3 subtends an angle, as seen from the center of ID1 of between 112 and 143 μrad in the vertical plane. This corresponds to a normalized angle, $\gamma\psi$, of 1.75 to 2.23, which is only slightly outside the central power cone (HWHM~ $\gamma\psi$ =0.5) from ID1. This leads to ~120 W impinging on one cover of ID3 when both ID3 and ID1 are at minimum gap. The power from the nearer IDs is smaller, ~20W onto a single cover (angles of 204 to 329 μrad).

During the first tests of multi-ID operation it was found that closing both ID3 and ID1 to small gaps caused beam loss. Upon investigation, melted sections (typically 1 to 3 cm long) were found in the Cu ID of ID3. The speculation was that non-flat sections, possibly as created during the ID bake-out (with the Cu foil over-constrained due to being fixed on both sides) caused run-away heating and eventually melting. The thin cover was then replaced with thicker (0.3 mm) Cu segmented covers, fixed only on one side, in the expectation that they would retain their shape better. However, this still did not allow closure of all three IDs in most operating configurations. Finite element calculations then suggested that the crucial parameter was probably the heat transfer from the cover into the magnets, as most of the cooling came through the magnets, and, even for the thicker, 0.3 mm, covers, heat transport in the copper only was insufficient.

OPERATION WITH BARE MAGNETS

Removing the covers entirely was also tested. This is dangerous because of the increased impedance due to the electron beam seeing the low-conductivity material of magnets and the (~500 x 0.05 mm) gaps between magnets, leads both to excitation of single-bunch instabilities and to power dissipation. Both of these effects scale with the peak electron beam current, so depend sensitively on the bunch structure: few-bunch fill modes have much higher peak currents than near uniform fill modes. The power dissipation into ID3, at minimum, 5.8 mm, magnet gap was estimated (via simulations by MAFIA and wave guide analysis) to be between 0.03 and 1.5 kW depending on the bunch mode, and <410 W at maximum, 40 mm, gap. This, with careful temperature monitoring, was considered acceptable, so tests were made to determine the effect on beam stability. The peak current allowed, after tuning of the transverse bunch-by-bunch feedback system [5], was found to correspond to ~1.5 mA/bunch in single bunch mode (as compared with 5 mA/bunch with Cu covers on all IDs), with the 1.5 mA in good agreement with a PIC simulation using a calculated wake-field. However, approximately half of the beam time at SPring-8 is in few bunch modes with >= 1 mA/bunch, so removal of the cover was finally deemed a non-optimal solution.

DISTRIBUTED (INTRA-ID) ABSORBER

The final solution adopted was to remove 2 magnet periods each at distances of L=0, 0.8, 2.5 m from the front of ID3 and replace these with Cu blocks that extend d=0.5, 0.8, 1.0 mm, respectively, beyond the surface of the magnets (see fig 1). The Cu blocks act as absorbers, shadowing the downstream magnets and their (now replaced) Cu cover. The positions, L, were chosen to match vacuum access ports, and distances d based on the expected beam size (beta function). The cover was also changed to 60 μm Cu / 40 μm Ni to improve adhesion to the magnets, and was not baked. The absorbers extending closer to the beam than the magnets has the negative consequence that the minimum magnet gap for ID3 is increased by ~0.85 mm and the removal of the magnetic periods slightly damages the phasing of the ID, leading to some flux loss (~6%) at smaller gaps. The beamline now can operate 3 IDs at energies $\geq$ 15.8 keV in most conditions (excepting a mode with 5 mA bunch current) and with 2 IDs at 14.4 keV.

STEERING THROUGH MULTIPLE IDS

It is desirable that the photon beam trajectory from, and therefore the electron beam trajectory through, all three insertion devices be coincident. This minimizes the source size contributions to the final x-ray focal spot on the sample, and allows optimization of the main beam-/power-load- defining aperture, the front-end slit, simultaneously for all IDs. (Another issue important for experiments, but not discussed here, is that the power, and the power density, impinging on optical elements should be stable over ~few day time scales). The relevant angular scale is set by the divergence of the photon beam, about 8.5 μrad, FWHM (K=1) in the vertical and 33 μrad, FWHM, in the horizontal. The length scale is set by the source size in the horizontal, ~620 μm FWHM, and by appropriate back-magnification of the smallest desired x-ray beam size in the vertical, ~200 μm FWHM in the present case. In principle, then, one would like the deviation in angle of the electron beam through each ID to be small (say, <10%) compared to these angular limits, and the overlap of the trajectories, as projected to the center of ID2, to be also within these distances (to ~20%). Given that the electron orbit in the storage ring is monitored by BPMs with sub-micron resolution and few micron stability spaced over several m length scales, it was expected that the relevant angular limits, 0.5 to 1 μrad in the vertical and 3 μrad in the horizontal, would be possible with care, and the position tolerances (roughly <50 μm in the vertical and <100 μm in the horizontal) should be relatively straightforward. The reality turned out to be slightly more complicated than expected, but mostly successful, with essentially all desired tolerances achieved, excepting the most stringent, the vertical angle, which still drifts at about the ~1 μrad level.

Investigation of the beam trajectory was carried out using different systems. The primary system for electron orbit control in the storage ring uses electron BPMs, based on 4 button pickups on a ellipse. Meanwhile x-ray beam position monitors (XBPMs) are usually placed in the front-end of each beamline [6], in the case of BL43, about 35m from the center of ID2. The XBPMs are current monitors that see the tails of the photon beam and usually are carefully calibrated to operate at a particular ID gap size [7]. Typically, after longer shutdowns and just before user operation, the angle of the beam orbit through each ID is corrected based on XBPM measurements. Finally, slit scans were implemented to determine the photon beam position at the front-end slit (about 44 m from the center of ID2) and also a slit, "S1", located in monochromatic (eV) beam, 83 m from the center of ID2. The front-end slits, massive devices, with encoders, inside the storage ring tunnel, provide an absolute reference (to within 10 to 20 um), while the S1 scans provide a relative reference for all 3 IDs (ie: the position of optics - monochromator & mirror- upstream of S1 were stable over one setup, but are adjusted over longer time scales). Slit scans are usually done by closing one ID gap at a time and therefore are usually a major perturbation on the heat load of the optical elements, so can not be done easily.

The initial lattice had some steering correction magnets installed, but as it became clear that more precise control was needed, more magnets were added, and the power supplies were upgraded, with the final complement of correctors as shown in figure 1. The BPM locations are also shown there. They are not exactly on either side of the IDs (there is a preference to place them near sextupole magnets) but allow approximate estimation of the beam path through the IDs. For the BPMs, two of them (one for ID1 and one for ID3) having new electronics were found to be noisy, and these were excluded from the global orbit feedback loop, so that, initially, there was only extremely indirect feedback on the electron beam path through ID1 and ID3. However, beginning at the end of May 2015, the output from the noisy BPMs was averaged and they were included in the feedback loop.

Figure 2 shows the beam angle measured by the storage ring BPMs and scans of the font-end slit. For quick adjustments of beam angle using the steering magnets, the two measurements give consistent results (e.g. if the steering magnets are used to introduce a 5 μrad shift in the beam angle, as confirmed with the BPMs, the slit scan typically indicates a shift of similar size, say ~5 $\pm$ 1 μrad), but over longer time scales they do not always agree, with, occasionally (e.g. 25 Jan 2015, 4 April 2015) deviations by large amounts. As the shifts in the FE slit position in those cases are ~0.3 or 0.4 mm, and the stability of the FE slit and encoders is < 0.02 mm, this is a serious discrepancy. It is believed to be due to the fact that BPMs are not at optimal positions for measurement of the x-ray source, with steering and lattice magnets located between the BPMs and the IDs for all but two of the BPMs (fig. 1). This means the calculation of the x-ray source position and angle from the BPM positions is approximate. In particular, as the orbit drifts, the calculation of the source angle from the BPM data may be increasingly unreliable. This should now be improved by the inclusion of all BPMs in the feedback, reducing local orbit drift, and possibly by future modification of the orbit feedback system.

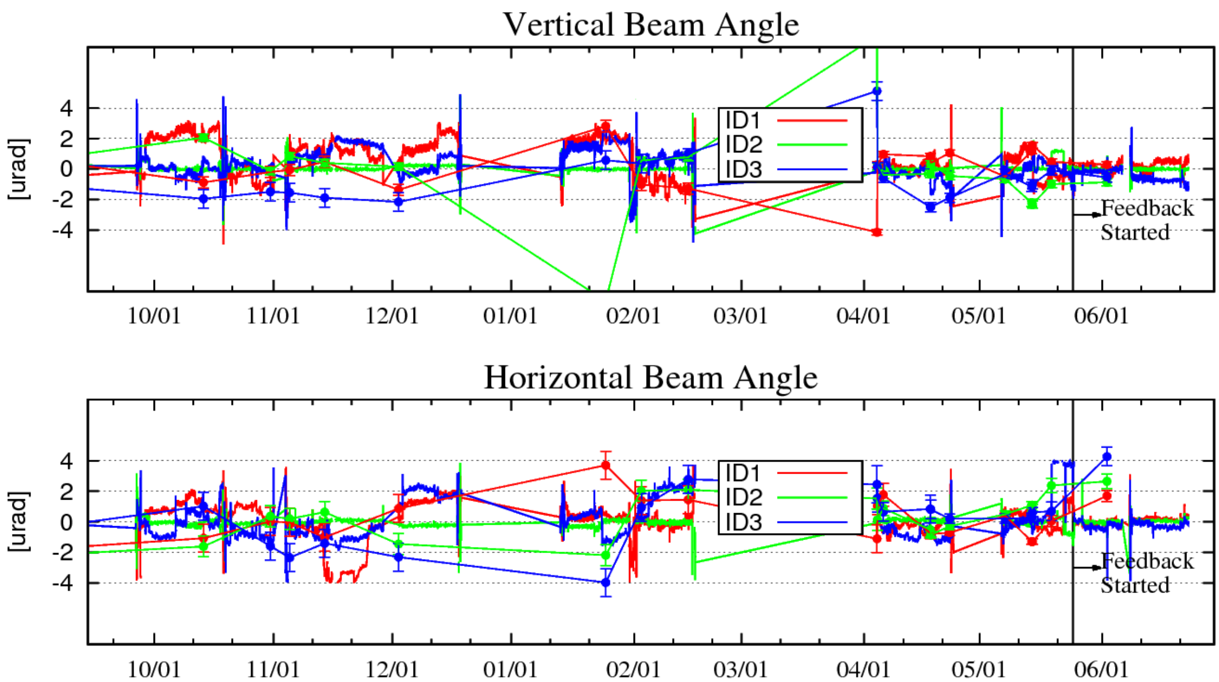

FIGURE 2. Source angle as measure by the storage ring BPMs (lines with dense points) and scans of the front-end slit (sparse lines) for 3 IDs at BL43. The plot covers the period from October of 2014 through June of 2015. Strong differences between the two measurements (e.g. 1/25/2015, 4/4/2015) were carefully confirmed. See text for discussion.

CONCLUDING COMMENTS

After the work discussed above, the beamline has begun to operate well. The insertion devices perform nicely between 15.8 and 26 keV in all bunch modes (except one mode 5 mA/bunch), and the orbit stability has greatly improved after all BPMs were added to the feedback loop. This has enabled, as of June, 2015 very high flux on the sample for both the phonon spectrometer (>30 GHz with 1.3 meV resolution at 21.7 keV and >90 GHz with 2.8 meV resolution at 17.8 keV) and that for electronic excitations (>1THz with 25 meV resolution at 15.8 keV) and holds promise for excellent experiments.

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