Phase-locked MHz pulse selector for x-ray sources

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Picosecond x-ray pulses are extracted with a phase-locked x-ray pulse selector at 1.25 MHz repetition rate from the pulse trains of the accelerator-driven multiuser x-ray source BESSY II preserving the peak brilliance at high pulse purity. The system consists of a specially designed in-vacuum chopper wheel rotating with ≈1 kHz angular frequency. The wheel is driven in an ultrahigh vacuum and is levitated on magnetic bearings being capable of withstanding high centrifugal forces. Pulses are picked by 1252 high-precision slits of 70 μm width on the outer rim of the wheel corresponding to a temporal opening window of the chopper of 70 ns. We demonstrate how the electronic phase stabilization of ±2 ns together with an arrival time jitter of the individual slits of the same order of magnitude allows us to pick short single bunch x-ray pulses out of a 200 ns ion clearing gap in a multibunch pulse train as emitted from a synchrotron facility at 1.25 MHz repetition rate with a pulse purity below the shot noise detection limit. The approach is applicable to any high-repetition pulsed radiation source, in particular in the x-ray spectral range up to 10 keV. The opening window in a real x-ray beamline, its stability, as well as the limits of mechanical pulse picking techniques in the MHz range are discussed.

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Science with pulsed radiation not only requires short and well-defined individual pulses, but also tailored repetition rates optimized to the sample under investigation and the detection scheme employed. Here a range from single-shot pulses at Hz repetition rate, to kHz, MHz, and even GHz for highest average brilliance are required. For multiuser radiation sources—in particular accelerator driven synchrotron and potential x-ray free electron laser sources—it has been so far difficult to accommodate the counteracting requirements–high peak power AND high repetition rate, simultaneously. Thus, dedicated operating modes, i.e., single-bunch or reduced-bunch fill-pattern operation for individual experiments had to be employed limiting the versatility of multiuser operation.

The reason is that for the x-ray spectral regime there are no efficient ways of down-sampling and pulse-picking from the typically 0.5 GHz repetition rate given by RF-cavity systems of accelerator-based sources. While there are other simple optical pulse separation techniques like Pockels cells in the IR/VIS/VUV range, direct optical pulse separation in the x-ray range remains a challenge owing to the strong absorption of x-rays in optical materials. A few approaches to a mechanical pulse separation in the kHz range for x-ray applications in synchrotron beamlines have been reported [1,2]. In electron storage ring sources, pulse picking techniques based on special beam deflection techniques are possible [3,4] but not applicable to all x-ray sources. However, many experiments, e.g., time-of- flight or coincidence electron detection [5] or time resolved x-ray pump-probe techniques—being performed not only at accelerators—require highest pulse purity AND a temporal separation.

In this work, we report on the development and continuous operation of a phase-locked MHz x-ray pulse selector from the 0.5 GHz synchrotron radiation source BESSY II as achieved by the interplay between mechanical precision, a fast-phase-locked electronic feedback control, and a high-performance x-ray beamline, creating 1.25 MHz repetition rate at preserved peak brilliance and high single-bunch purity. This approach is generally applicable to select MHz pulse rates from all high-repetition-rate x-ray sources.

The system ("MHz light chopper") as depicted in Fig. 1 consists of a high-strength aluminum alloy chopper wheel rotating with 998 Hz angular frequency. The wheel has a diameter of 339 mm at full speed and a contour that reduces the thickness from 30 mm at the center to 0.5 mm on the outermost rim and is optimized to yield equal "von Mises"- stresses in operation. It is driven in vacuum and levitated by magnetic bearings to minimize friction and thus to enable a steady angular velocity. Pulses are picked by 1252 high-precision slits of 70 μm width on the flat outermost rim of the wheel. These slits were made by electric discharge machining, have a length of 1 mm, and end in a notch shape optimized for stress minimization. The wheel has been proven to withstand (i) the high radial forces during operation that lead to a radial expansion of 0.5 mm and (ii) a total beam power of ca. 80 mW absorbed by the aluminum bars between the slits (see the photo in Fig. 1).

For a 70-μm-wide chopper slit with a resulting orbital velocity of 1063 m/s, the time required to pass a given point in space is 66 ns. The resulting transmission time window of the x-ray beam, which is limited by an entrance slit, is longer than this and given by a convolution of the fixed entrance slit and the moving chopper slit. This situation is sufficiently described by a one-dimensional movement in x-direction using transmission

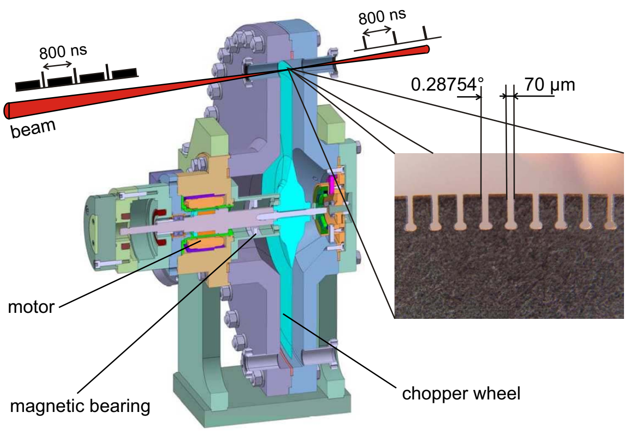

Fig. 1. Optical layout and mechanical assembly drawing of the MHz light chopper system. A specially designed wheel (cyan) with radially decreasing thickness (minimum 0.5 mm) has 1252 slits (of 70 μm width) at its outer edge and rotates with 998 Hz. After passing a variable entrance slit (here 70 μm), the incident focused light beam (red) has to pass these chopper slits. The patterns close to the beam (red) depict a temporal pattern as emitted by the source and after the chopper, respectively, indicating that only a single x-ray pulse at 1.25 MHz (800 ns) may transmit through the slits.

functions $s(x)$ for the entrance slit and $c(x,t)$ for the chopper slit. Ideally, these would be step functions $s(x) = \Theta(x + 0.5 \cdot w_s) \cdot \Theta(0.5 \cdot w_s - x)$ and $c(x,t) = \Theta(x - vt + 0.5 \cdot w_c) \cdot \Theta(vt - x + 0.5 \cdot w_c)$ with the Heaviside step function Θ, the entrance slit width w_s, the chopper slit width w_c, and the chopper slit velocity v. In fact, the slit widths vary over the slit lengths due to angular misalignment and manufacturing tolerances. Assuming normal distributions of the effective width variation over the slit lengths, the functions change to

$$s(x) = \frac{1}{4}\left(1 + \operatorname{erf}\left(\frac{x + 0.5 \cdot w_s}{\sqrt{2}\sigma_s}\right)\right) \cdot \left(1 + \operatorname{erf}\left(\frac{-x + 0.5 \cdot w_s}{\sqrt{2}\sigma_s}\right)\right) \quad (1)$$

and

$$c(x,t) = \frac{1}{4}\left(1 + \operatorname{erf}\left(\frac{x - vt + 0.5 \cdot w_c}{\sqrt{2}\sigma_c}\right)\right) \cdot \left(1 + \operatorname{erf}\left(\frac{-x + vt + 0.5 \cdot w_c}{\sqrt{2}\sigma_c}\right)\right). \quad (2)$$

σ_s and σ_c are the standard deviations of the entrance slit widths and the chopper slit widths, respectively, and erf is the error function.

For a single slit traversing the beam, the transmission time window function $w(t)$ is given by:

$$w(t) = \frac{1}{w_0}\int_{-\infty}^{\infty} s(x)c(x,t)\mathrm{d}x, \quad (3)$$

with the normalizing constant

$$w_0 = \int_{-\infty}^{\infty} s(x)c(x,0)\mathrm{d}x.$$

To operate the MHz-chopper, a special fast electronic chopper control system for the drive and the magnetic bearing has been developed. A digital-signal-processor (DSP) and a field programmable gate array (FPGA) are forming the core of the controller, which synchronizes the chopper frequency to the bunch clock of the storage ring and stabilizes the phase velocity of the rotating wheel with respect to the arrival time of the x-ray pulse. The latter is highly defined by an optical bunch clock signal that is directly derived from the accelerator's master clock and transported by an optical fiber link (of ca. 50 m length) to the control cabinet. The extreme high demands relating to phase locking required many development efforts. For the mandatory high-precision time measurement, a time-to-digital-converter (TDC) is used. The orbital speed and the phase of the wheel are measured by detecting a pickup signal from a small magnet being attached to the wheel and employing the TDC at a resolution of 75 ps. The resulting internal turn-by-turn process variable derived from that measurement allows for a phase control loop as accurate as ± 2 ns time deviation between the synchrotron clock (1.25 MHz, x-ray pulse arrival) and the chopper's velocity pickup signal (998 Hz).

The chopper was tested in a dedicated test setup on a dipole magnet beamline at BESSY II [6]. The device was placed in the intermediate focus after the first mirror (toroidal mirror at 6° grazing incidence, 12° total horizontal deflection, Gold coating) that produces a 1:1 image of the source 24 m behind the electron beam at a beam height of 1.4 m. After that mirror, the beam is a "white beam" as limited at high photon energies by the mirror's reflectivity cut-off and at low energies by a 2-μm-thick Aluminum filter in front of the detector (APD-Avalanche Photodiode, Hamamatsu-2381) as used 1 m behind the chopper.

The APD signal as measured under the condition that the beam passes the outer rim of the wheel is depicted in Fig. 2(a), what naturally happens if the chopper is at rest. If the chopper is ramped to it's maximum speed, the disc diameter increases, and the slits move into the beam. When the chopper is phase locked to the bunch clock such that the transmission window $w(t)$ is centered to the single bunch, only the single-bunch pulse is picked out as confirmed by the waveform in Fig. 2(b). These measurements have proven that by a combination of two 70 μm slits that match the intermediate focus in the beamline, a single-bunch x-ray pulse can be picked out of the regular multibunch pulse train of BESSY II with almost no intensity losses.

To analyze the system's capability of lossless picking of a camshaft pulse in an dark gap shorter than 200 ns, we have measured open time window functions $w(t)$ by setting the chopper phase to a value, where the window $w(t)$ was set to the homogeneous pulse train within the multibunch train (of 2 ns distance each). The measured $w(t)$ were then obtained by using the envelope of the average peak APD signals (100 sweeps at 1.25 MHz).

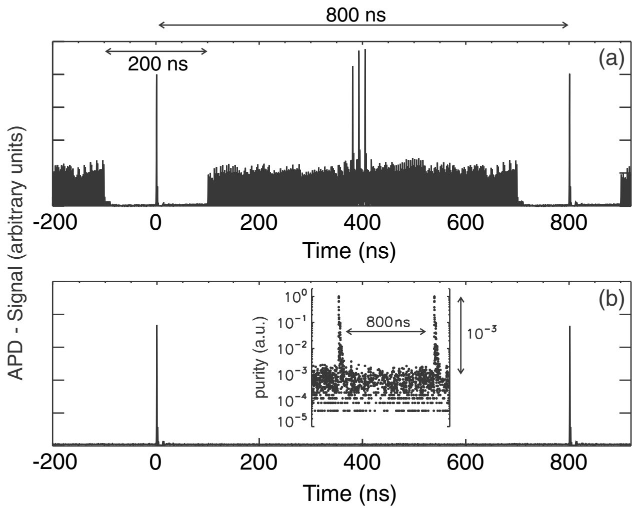

Fig. 2. (a) X-ray signal with chopper at rest and free passage of the beam. (b) X-ray signal behind the chopper with the chopper slit phase locked to the bunch clock and at a phase value that keeps the transmission time window symmetrical to the camshaft bunch. The same waveform is plotted again but at logarithmic y-scale in the inset.

Figure 3 shows two such envelopes as dashed line and as black line. The latter one was obtained by using a trigger of 1.25 MHz (i.e., 1 turn in the storage ring) for recording the average APD signal, meaning that it was averaged over all 1252 chopper slits. This black line includes all broadening contributions of the transmission time window and thus represents $w(t)$ of the chopper system as currently installed. The envelope shown as dashed line was taken by triggering a 2 GHz oscilloscope with 998 Hz (i.e., the chopper frequency), meaning that the signal was averaged using only one and always the same slit out of the 1252 possible ones. Thus, this dashed line should correspond to the simple model for $w(t)$ represented by Eqs. (1)–(3). Indeed, it is quite similar to a calculated curve using $w_s = 70$ μm, $w_c = 70$ μm, $v = 1063$ m/s, and $\sigma_s = \sigma_c = 10$ μm (dotted line). To show the contribution of manufacturing tolerances and drive jitter to $w(t)$, the ideal (triangular) case resulting from the Heaviside step functions for the slits is plotted as red line in Fig. 3. While the ideal $w(t)$ coincides with that for $\sigma_s = \sigma_c = 10$ μm over a large range, there are considerable differences at the center and at the tails. At the center, only the maximum transmitted intensity is decreased by 16% by using the realistic slit model. Much more relevant is the blurring of the outermost tails of $w(t)$, which considerably increases the length of the transmission time window compared to the idealized slits. The length of the transmission time window thereby depends of the demanded suppression factor $s(t)$, which is defined by $s(t) = w(t)/w(0)$. If, for example, a suppression of $s = 1000$ is desired, the transmission time window enlarges to $\Delta t_s \approx 193$ ns compared to the $\Delta t_s = 132$ ns for the ideal function. However, even though the model described by Eqs. (1)–(3) leads to results that are quite close to the measured $w(t)$ for a single slit, the assumption of normally distributed width variations along the length of the slits is considerably oversimplified. As the 70-μm-wide slits have a height of 1 mm and a length of 0.5 mm, a three dimensional view is required for a more detailed explanation. Furthermore, one has to consider the energy-dependent absorption lengths of the x-rays in aluminum for a complete 3-dimensional treatment. As this leads to very complex dependencies, just a short qualitative description is given below.

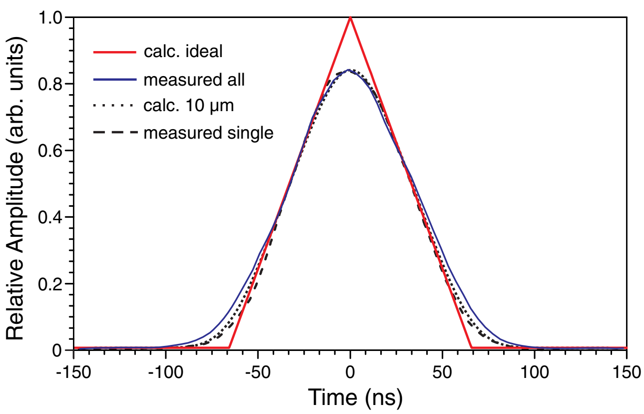

Fig. 3. Comparison of transmission time windows. Red line: ideal window for perfect slits and without drive jitter. Dotted line: calculated window using Eqs. (1)–(3) with $\sigma_s = \sigma_c = 10$ μm. Blue line: measured window of the chopper/slit system including all broadening contributions. Dashed line: measured window (envelope function measured on a homogeneous multibunch train) for a single slit.

Figure 4 depicts an oblique 3D projection of the entrance slit(a) and a chopper slit (b). For the open time windows, the two side facets of the slits are relevant, one of each (the visible one) is indicated in red color in Figs. 4(a) and 4(b). Several possible deviations from the ideal facet contribute to deviations from the ideal transmission time window, which are: (I) absolute position, (II) waviness, (III) roughness, (IV) angular tolerance of the facet normal within the slit plane, and (V) angular tolerance of the facet normal out of the slit plane. In addition to these mechanical tolerances, another contribution to the broadening of the transmission window is given by the temporal jitter of the drive of $\approx \pm 2$ ns. At photon energies above 10 keV, the chopper wheel is not opaque anymore [see Fig. 4(c)] and a purity of

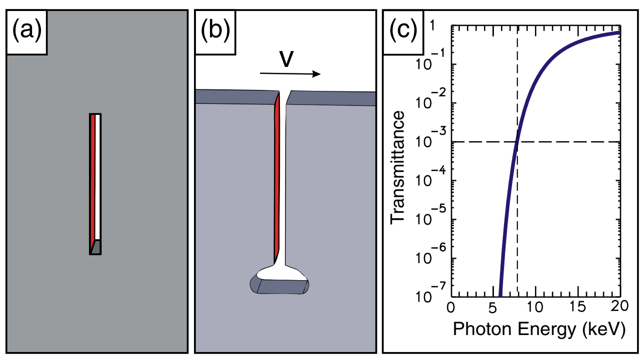

Fig. 4. Oblique 3D projections of (a) the entrance slit and (b) one of the chopper slits. For both slits, one of the two relevant facets is indicated by red color. The calculated spectral x-ray transmittance of the wheel is plotted in (c); the horizontal dotted line marks a transmittance of 10^{-3}.

$s = 1000$ only holds up to 8 keV. Our measurements do not permit to fully disentangle all individual contributions to the broadening of $w(t)$. However, the influence of the tolerances of the absolute slit positions, combined with the differences between the 1252 slits, is given by the difference between the dashed and the black line in Fig. 3. At the tails, Δt_s at $s = 1000$ for the single slit is in total about 20 ns smaller than that given by using all slits. As a result, we estimate that the installed chopper system could losslessly pick a camshaft pulse centered in a dark gap of ≈ 140 ns if the size of the intermediate focus (and the chopper entrance slit) is reduced to about 10 μm. In order to address lossless picking of a camshaft pulse in an even shorter dark gap of ≈ 100 ns, the manufacturing precision of the chopper slit array has to be further improved.

We have devised a phase-locked MHz mechanical chopper system and used it to select single x-ray pulses of ≈ 50 ps pulse length [FWHM] out of the regular multibunch pulse train in the BESSY II storage ring. The temporal opening window is given by the convolution of two 70 μm slits—an entrance slit and the actual chopper slits. At the current beamline, it is sufficiently wide to pick pulses out of a 200 ns clearing gap in BESSY II's pulse pattern at extraordinary purity. However, at beamlines with smaller intermediate focus, the ultimate limit as given by the 70-μm-wide chopper slits, and their orbital velocity of $v = 1063$ m/s is $\Delta t_s = 100$ ns at photon energies up to 10 keV. We finally achieved that only pulses of 1.25 MHz repetition rate may pass the chopper mimicking a single bunch-mode x-ray emission at preserved peak brilliance and excellent purity $>10^3$. The device is currently being commissioned as a permanent installation in a bending magnet beamline at BESSY II but applies to undulators as well. We foresee wide applicability at x-ray facilities worldwide.

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