Preliminary report on alternate bunch schemes for the MAX IV storage rings

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Background

The primary design goal of the MAX IV storage rings from the outset has been to achieve ultralow emittance in the storage ring for a diffraction-limited source. The MAX IV laboratory will provide a 3 GeV storage ring with an emittance down to 0.2 nmrad for hard x rays and a 1.5 GeV storage ring for soft x rays. The laboratory has promised to deliver this source during the spring of 2016. The MAX IV design has thus far only focused on multibunch operation in the storage rings implementing the present solution with a 100 MHz RF system and passive higher harmonic cavities. The FEMTOMAX short-pulse beam line will deliver a 100 fs x-ray pulse of spontaneous radiation from an undulator on the linear accelerator. However, the repetition rate of the FEMTOMAX is limited to about 100Hz.

A number of design considerations have been taken into account in order to achieve good beam stability, to maintain a very low equilibrium emittance and to preserve a relatively simple and compact overall design for the magnet lattice. An early decision was made to implement 100 MHz RF system for the MAX IV storage rings, a standard implemented in the present MAX-Lab storage rings. The ring will implement active 100 MHz RF cavities and passive higher harmonic cavities operating at 300 MHz in order to increase the bunch length from 40 ps to about 200 ps in order to damp longitudinal instabilities in the beam and preserve the ultralow emittance in the 3 GeV ring. The harmonic cavities reduce the energy spread increase due to intrabeam scattering, and ensure achieving the specified Touschek life time but the fields in these cavities have time constants which are relatively long. Storage ring currents will be maintained at 500 mA in multibunch operation by top-up injection with a charge per bunch of 5 nC in both rings.

A workshop was held in March in order to investigate the needs for different timing pulses, different filling modes in the ring, or the need for synchronization of choppers or laser pulses. This report summarizes the main directions that the user community has outlined, and analyzes some possible solutions to meet these needs from the point of view of different accelerator schemes.

Three basic directions for timing experiments were specified by the user community at the meeting:

1. Coincidence and time-of-flight experiments require a 10-100 kHz x-ray pulse at the experiment. This microsecond interval can only be achieved if the storage ring bunch period of 320 ns is reduced further by a mechanical chopper.
2. Short electron pulses for electron time-of-flight measurements using the ARTOF electron spectrometer. Relatively high repetition rate but low current/bunch.
3. Pump-probe schemes requiring synchronization and longer time intervals, and adjustable pulse lengths. Gating schemes for detectors with similar requirements as option 1 above are requested.

In multibunch operation (176 bunches in the 3 GeV ring) the interval between electron bunches is 10 ns. The single-bunch period in the 1.5 GeV ring is 320 ns, and in the 3.0 GeV ring the period for a single bunch is 1.8 microseconds. The bunch length (5 nC) in both rings when harmonic cavities are implemented will be at maximum 200 ps (rms).

1. **User timing requirements for time-of-flight and coincidence experiments:**

RMS bunch length (ps)	Up to 500
Nr of photons/s (within 1% ΔE/E)	10^7
Rep rate at experiment	3 MHz
Interval between neighboring pulses (ns)	±150 or more for synchronization

As the 1.5 GeV ring circumference is 96 m, the single-bunch period is around 320 ns. The flight times in a magnetic bottle electron TOF are much longer, and ion flight times can be on the order of 30 microseconds. In order to avoid electron signals originating from two different light "flashes", the effective ring period needs to be reduced using a chopper. This will be discussed later.

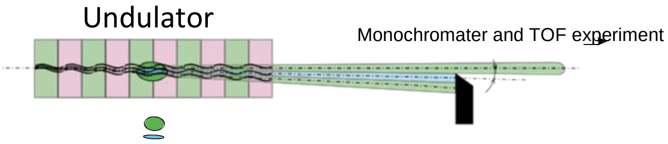
The longer interval between pulses demands an alternate pulse structure or a scheme such as cam-shaft modes or single pulse picking schemes. With a 320 ns single-bunch period if a filling scheme is envisioned that includes a ±100 ns interval to a single (hybrid) pulse then the current is reduced by 67% from the multibunch current. The question of bunch stability within the present design where harmonic cavities are implemented is unclear at present but is currently under investigation at MAX II.

A. Resonant pulse picking

This option maintains multi-bunch operation by implementing a feedback kicker to incoherently excite one electron bunch that remains on the same orbit as the rest of the electron bunches, but has a larger bunch size horizontally. This 'resonant pulse-picking' solution has been demonstrated at BESSY and can deliver a short photon pulse to any beam line. A solution to shadow the multibunch pulse at the beam line where the excited pulse will be used must be mounted at relevant beam lines. However, such a knife edge could be implemented in future monochromators or relatively simple reconstructions of existing monochromators. See the reference to Holldack *et al.* below.

Resonant pulse picking creates a separable single bunch soft X-ray source in addition to multibunch operation. At BESSY a photon flux of up to 10^7–10^9 ph s^{-1}/0.1%BW at purity values of 10^4–10^2 and a repetition rate of 1.25 MHz (800 ns revolution period) was demonstrated at beam line UE56/1. The quasi-resonant excitation of incoherent betatron oscillations of electrons allows horizontal pulse separation at variable polarization accessible for both regular 30 ps pulses and ultrashort pulses of 2–3 ps duration. The ring was operated in a cam-shaft mode (four cam-shaft bunches) in an ion clearing gap of 200 ns. The remainder of the ring is filled with a multibunch train. Resonant pulse picking in a low-alpha mode for 100 micro A bunches with lengths of 2-3 ps was also demonstrated. The lower emittance and the longer pulse length at MAX IV will be advantageous and it seems likely that it will be possible to run in full multibunch mode. The expected performance at MAX IV should be better than the result reported from BESSY.

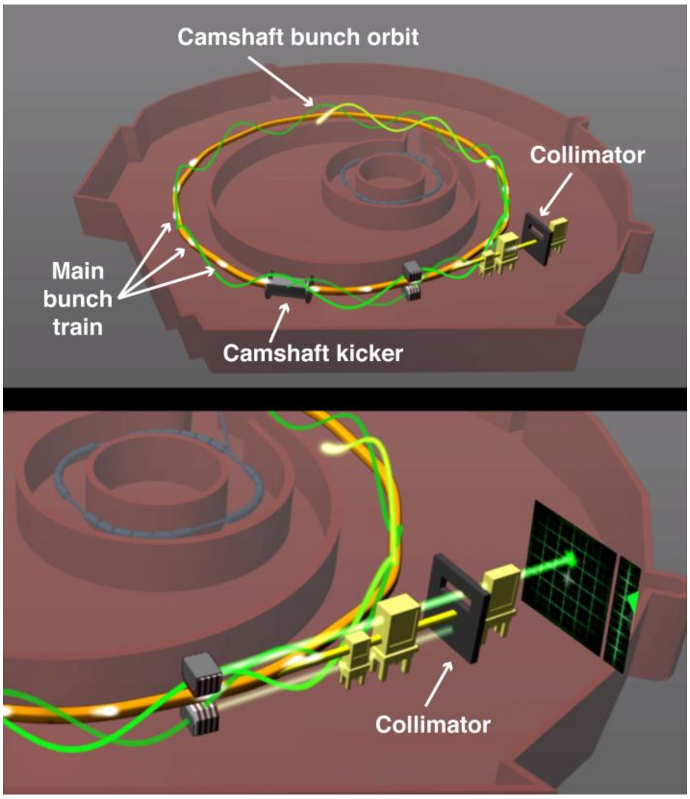
K. Holldack et al, Nat. Comm. 4, 4010 (2014), DOI: 10.1038/ncomms5010



B. Fast beam kicker solutions (Pseudo single bunch)

An active harmonic cavity can be used in a dedicated operations mode to produce a long 'camshaft' bunch with a long gap on either side of this bunch. This implies a reduction in ring current for other users. Another option is to use a very fast kicker to coherently excite an individual bunch that is then used in an individual beam line.

The idea behind pseudo single bunch operation is to use a high-repetition-rate (MHz), short-pulse (<100 ns) magnet to vertically kick the cam-shaft bunch relative to the bunch train. A single electron bunch is displaced transversely from other electron bunches using a short pulse, high repetition rate kicker magnet. Putting this bunch in the middle of the ion-clearing gap reduces the required bandwidth of the kicker magnets. A collimator or aperture at the beam line where the electron bunch is displaced (bumped) stops light from the normal bunches. The time spacing can (theoretically) be tuned from milliseconds to microseconds. The system has been developed and tested at the ALS and at SOLEIL (reference C. Sun, et al., PRL 109, 264801 (2012)



http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.109.264801 (see figure from this paper above).

2. User timing specifications for short-pulse needs (ARTOF)

RMS bunch length (ps)	10
Nr of photons/s (within 1% ΔE/E)	10^7
Rep rate MHz	3 MHz
Empty neighbours (ns)	100

With the presently planned MAX IV lattice, RF system and other hardware a bunch length of 100 ps FWHM will be possible if the charge per bunch is lowered. A 50 ns interval between bunches is probably feasible without any new hardware. A 3 MHz repetition rate, corresponding to single-bunch operation in the 1.5 GeV ring, would be possible.

A. Separate RF mode operation

A rather simple way of meeting the assumed specs above is to introduce a higher RF system in one of the rings. This is the most powerful and economical way to achieve short bunches in the rings but suffers from the disadvantage of separate hardware for operation in single bunch and multi-bunch modes.

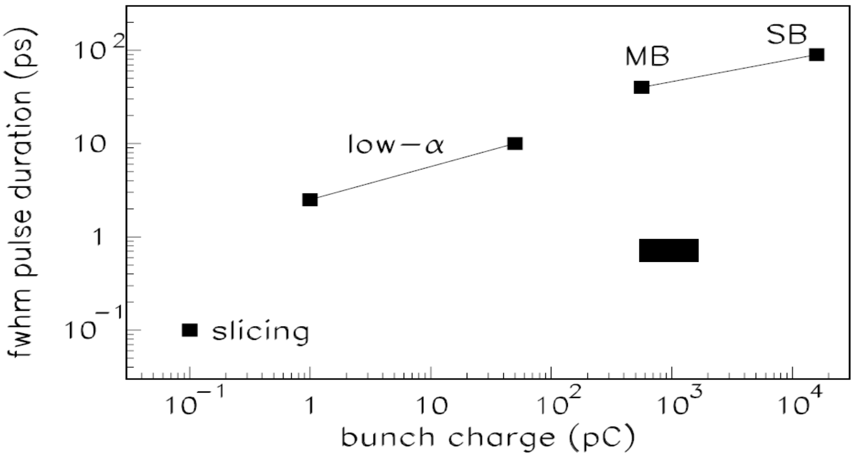
As an example, we choose an L-band RF system in the 1.5 GeV ring operating at 1.25 GHz. This frequency allows for almost any bunch population: one bunch, 2 opposite bunches, 4 90 degrees separated bunches etc. One reason to look at this frequency is the commercial availability of high power RF generators and the simplicity of the cavity structures. The Higher Order Mode (HOM) spectrum of these cavities might prohibit multi-bunch operation, so it’s likely that the 1.25 GHz cavities should be removed when the ring is operated in the multi-bunch mode.

RF (GHz)	1.25
RMS bunch length (ps)	10
Photons/s per pulse	10^5
Lowest rep rate (MHz)	3
Bucket height (%)	2
Charge/bunch	1.25 nC
Touschek lifetime (min)	46
Coupling (%)	1
RF power (kW)	20
Cavity length (m)	3

The parameter values in the table above are interlinked. The separate mode operation allows adjustment the momentum compaction factor and/or changing the coupling factor to vary the Touschek life-time.

B. Low-alpha mode operation

A further reduction in the pulse length can be obtained if the storage ring is operated with a single cam-shaft pulse in the low-alpha mode with bunch currents on the order of 100 microamps. This mode may not be applicable for most users. A comparison of different modes discussed here is given in the figure below.



3. User specifications for gating and chopper systems requiring synchronization

RMS bunch length (ps)	100
Nr of photons/s (within 1% $\Delta E/E$)	10^{14}
Rep rate MHz	6 MHz
Interval between neighboring pulses (ns)	±100 or more

A. Optical beam chopper systems for x rays

Optical beam choppers using the reflective properties of mirrors, the diffractive properties of rotating crystals, or surface acoustic waves have been proposed in many configurations at synchrotron light sources. The APS has implemented an optical beam chopper that takes advantage of the narrow acceptance angle for diffraction of a rotating crystal (Si) to produce a fast opening window for the transmission of an x-ray pulse. This phase-locking capability and the fast transmission window time, about 10 ns for a perfect crystal cube, means that this beam chopper can be used with any storage-ring loading pattern to produce short x-ray pulses in the 8-10 keV range for time-resolved experiments.

Phase locking to the 271.548 kHz APS storage-ring orbital frequency is done by referencing the APD signal to an external master clock reference signal that the APS is referenced to.

Reference: A. McPherson, W.-K. Lee, and D. M. Mills, “A synchronized rotating crystal x-ray beam chopper,” *Rev. Sci. Instrum.*, vol. 73, no. 8, p. 2852, 2002.

B. Mechanical chopper systems

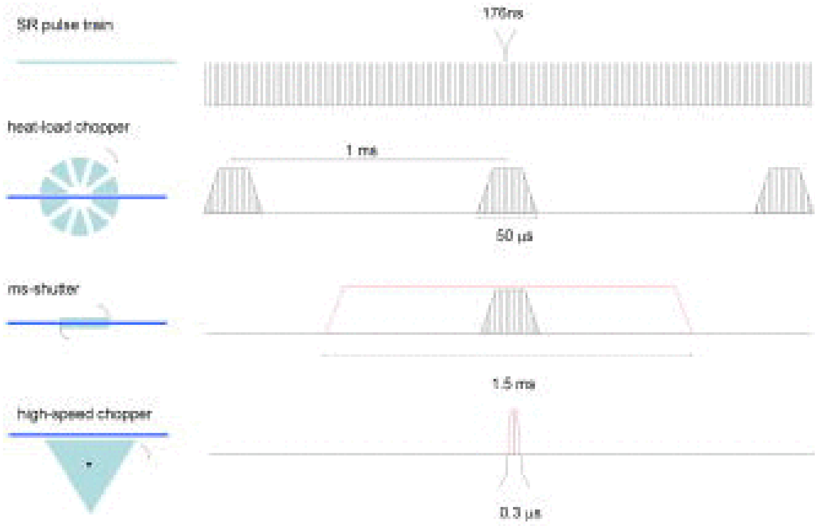
The basic principle of mechanical chopper systems is to devise an aperture system that blocks a large fraction of incoming photon bunches on a particular beam line. Mechanical chopper systems based upon rotation must also be phase-locked to the storage ring, and the chopper must be located at a point in the beam line where the beam is highly focused. Chopper systems are applicable for use on a specific beam line and require a particular electron bunch structure in order to enable the synchronization scheme.

Phase locking requires an interval of 150 ns in present chopper designs.

1. A mechanical chopper system was implemented at BESSY for soft x-ray time-of flight measurements with the BESSY-II ring operated in single-bunch mode (800 ns pulse intervals) and the chopper reduced the repetition rate from 1.25 MHz to less than 100 kHz. The opening time of the chopper was 750 ns and the rotational frequency of the disc was 650 Hz.
Reference: (S. Plogmaker, P. Linusson, J. H. D. Eland, N. Baker, E. M. J. Johansson, H. Rensmo, R. Feifel, and H. Siegbahn, Review of Scientific Instruments 83, 013115 (2012).)

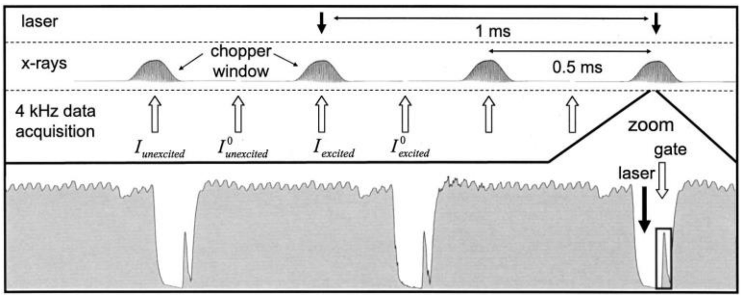
2. A MHz chopper system with 150 ns windows was developed at Julich operating at 1.25 MHz. This is being implemented at BESSY and can be an interesting option. This chopper synchronizes to the RF pulse.

At the ESRF a mechanical chopper with a time window down to 200 ns is implemented for time-resolved x-ray experiments. The ESRF operated in 16-bunch mode with 100 ps long pulse trains separated by 176 ns in the ring. The chopper system consists of three different mechanical devices to first select 50 microsecond bunches (5% of the initial photon beam is transmitted), and then a shutter further reduces the number of bunches, and a high-speed chopper isolates a single pulse from the remaining bunch.



The chopper system above is installed at beamline ID09B at the ESRF. The chopper system can produce x-ray pulses as short as 200 ns in a continuous beam and repeat at frequencies from 0 to 3 kHz. The jitter is 2.8 ns (RMS). For bunch-filling patterns with pulse separations greater than 100 ns, the high-speed chopper can isolate single 100 ps x-ray pulses that are used for the highest time resolution. [Ref. Cammaratta, Rev. Sci. Instrum. **80**, 015101 (2009); http://dx.doi.org/10.1063/1.3036983]

At the ALS implementation of an x-ray chopper provides a source for time-resolved XAS. The setup is on beam line 5.3.1 and utilizes the ALS cam-shaft mode of operation where 276 bunches (out of 328 buckets) are filled (1.4 mA/bunch) and in the remaining empty section an isolated camshaft pulse is placed (bucket 318). The chopper operates at 1.52 MHz revolution rate for the cam-shaft pulse. Synchronization is made to an APD signal with a rise time of 700 ps, and a pulsed laser (150 fs pulse duration) is synchronized to the x-ray pulse.



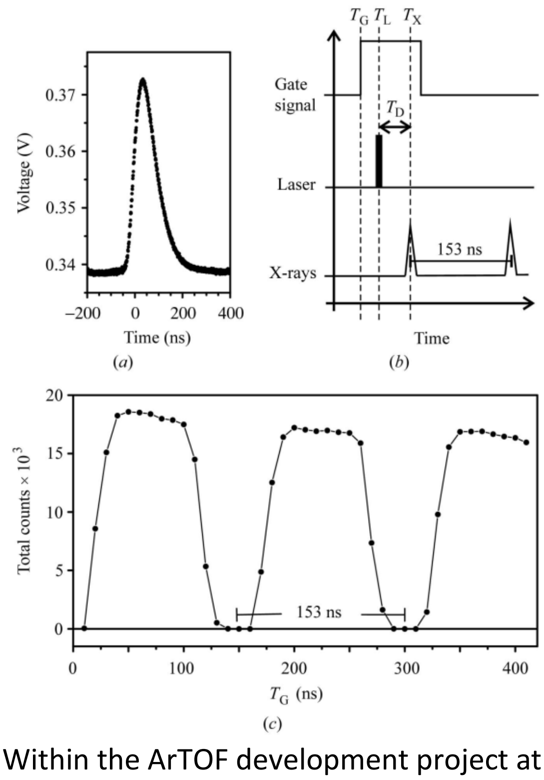
In the diagram to the left the total x-ray signal without chopper is shown on the bottom, and the laser and x-ray signal is in the upper part. The chopper window is clea

Reference: M. Saes, et al., “A setup for ultrafast time-resolved x-ray absorption spectroscopy,” *Rev. Sci. Instrum.*, vol. 75, no. 1, p. 24, 2004.

C. Gated x-ray detector systems

A gating scheme for an x-ray detector enables time-resolved experiments at synchrotron beam lines without the need for optical or mechanical chopper systems. The gating pulse can enable the detector during the gating window, and a laser can be synchronized to the x-ray pulse within the window. The gating pulse duration is chosen to encompass both the laser pulse and the x-ray pulse both of which are measured by an avalanche photodiode.

The APS ring is operated in a 24 bunch filling mode with 4.25 mA per bunch and 153 ns between bunches. The bunch length is 40 ps (rms) and the x-ray pulse duration is measured to be about 60 ps. The timing scheme is shown below in panel (b). The PILATUS area detector is enabled during the external gating pulse, and the measured signal is shown above in panel (a) for a single pixel and the total number of counts on the detector is shown in (c) as a function of the gating pulse delay. Ejdrup (J. Synchrotron Rad. (2009). 16, 387–390) reports that bunch separation of at least 130 ns is needed to ensure detection of a given X-ray pulse.



Within the ArTOF development project at BESSY a gating module for the delay line detector was implemented. Electrons were deflected by a pulsed electric potential introduced on a gold mesh close to the detector. The pulse was synchronized to the camshaft bunch in BESSY hybrid mode, allowing only photoelectrons originating from the camshaft light pulse interaction to be detected. By blocking temporally unresolvable electrons originating from the multi-bunch train (with pulses that overlap in the TOF instrument), the detection efficiency was increased more than 20 times. ArTOF detector gating demands a 150 ns hybrid window.

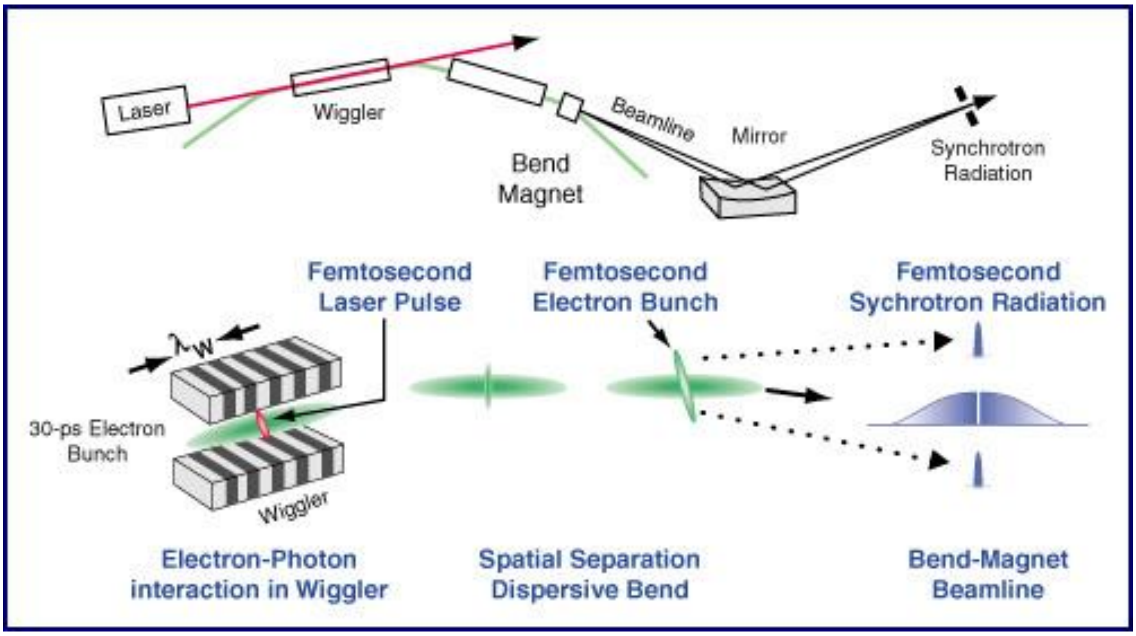
D. Femtosecond laser slicing

Zholents and Zolotorev at Berkeley proposed the laser time-slicing technique as a way to achieve effective electron bunch lengths in the femtosecond range. At the heart of the proposal was the use of a high-power, femtosecond laser synchronized with the electron bunches so that a pulse of laser light passed collinearly with an electron bunch through an undulator or wiggler. The high electric field of the shorter laser pulse modulated a portion of the longer electron bunch, with some electrons gaining energy and some losing energy. Subsequently, when the energy-modulated electron bunch reached a bend magnet (or other section of the storage ring with a nonzero dispersion), a transverse separation occurred making it possible to spatially isolate the sliced part of the pulse. An adjustable knife edge selected the synchrotron radiation from the displaced bunch slices.

A sliced pulse with a duration of 300 fs with a repetition rate of up to 100 kHz for 300 bunch operation in the storage ring was measured in a wiggler, and pulse durations down to 100 fs are possible.

On the basis of the known parameters of an ALS bend magnet and undulator at a beam energy of 1.9 GeV with $\eta_1\eta_2\eta_3 \approx 10^{-8}$ (for example, laser pulses of 25 fs, 100 µJ at 20 kHz), an average femtosecond flux from a bend magnet of $\sim 10^5$ photons s^{-1} per 0.1% bandwidth (BW) (for a collection angle of 1 mrad) at 2 keV is found. For an ALS small-gap undulator, the calculated average femtosecond flux is $\sim 10^7$ photons s^{-1} per 0.1% BW for the same energy.

Femtosecond slicing methods are presently in use at the ALS, BESSY and the SLS. The scheme is shown schematically below. The modulation takes place in the wiggler or undulator and the separation takes place in the bending magnet before the beam line.



4. Timing experiments at MAX IV—Summary

The user needs can be briefly summarized as primarily two different directions that are of interest to the user community. One direction requires a short pulse for time-of-flight experiments. Implementing a higher frequency RF system is a straightforward scheme for multibunch filling modes. Pulse lengths of down to 10 ps could be obtained with such a scheme. In addition to the cost of new hardware a disadvantage of this method is that all users on the storage ring are affected and the ring current will be severely reduced.

Femtosecond laser slicing could be an alternative to implementation of a second RF cavity for short pulses. Based upon experience at the SLS and at the ALS the best result obtained so far is radiation from 1% of the sliced bunch, which results in a much reduced photon flux. The pulse length obtained is short, but the number of photons is low. This points to the use of either absorption techniques in the end stations, or to high transmission experiments in the case of observation of photoelectrons.

Experiments that demand inter-pulse intervals on the order of microseconds most likely require a pseudo single-bunch mode such as a cam-shaft mode, and a mechanical or optical chopper to reduce the repetition rate at the sample. The most promising pseudo single-bunch scheme appears to be the resonant pulse picking method. This method may be possible to implement in the standard multibunch filling mode. Although the resonantly-excited bunch can be ‘bumped’ at any location in the ring, the beam line requires a knife edge to block the normal synchrotron radiation.

Pulse picking can be achieved either using the vertical fast pulse kicking tested at ALS or using the resonant pulse-picking scheme currently used at BESSY II. The first scheme is more costly and more technically challenging than the second but could potentially provide a single bunch with a lower repetition rate during multi-bunch mode. The excitation in the vertical plane will degrade the diffraction limited performance. The accelerator physics group at MAX lab has initiated tests at MAX II that indicate that at a resonant pulse picking scheme similar to that implemented at BESSY II could be potentially exploited in the 1,5 GeV ring during operation in multi-bunch mode. The cost for such a solution would be rather small and several undulator beam lines can be operated simultaneously. Both of these solutions should be investigated and the pros and cons from the MAX IV accelerator and user point of view should be examined.

Choppers can be used with a variety of experiments, but for efficient operation choppers require synchronization to the storage ring. Many of these require a signal pulse (i.e. cam-shaft bunch mode). Time intervals of at least 150 ns are needed for synchronizing the chopper to the pulse structure.

Gated detectors can be an option for photon-in, photon-out experiments such as x-ray absorption or in the ARTOF experiment the electron detector can be gated with a pulsed signal. Pump-probe experiments utilizing pulsed lasers also require a synchronization signal for timing the two pulses accurately. The criteria are quite similar to the criteria for chopper synchronization.

This report, in a more complete form, should be presented to the MAX IV directors. The user community requests a policy decision on MAX IV taking timing modes and experiments into account for storage ring operation. While the FEMTOMAX beam line will deliver 100 fs x-ray pulses with a millisecond period it offers a very low duty cycle source that will be inefficient for spectroscopy experiments or coincidence measurements. The crystal monochromator will not provide low-bandwidth light for experiments and the polarization of the light. This beam line will offer limited possibilities for some of the planned experiments. Since the timing experiments suggested at the workshop extend over a relatively broad scientific range (AMO, cluster physics, biomolecules, surface science, condensed matter, photochemistry, liquid samples, magnetic samples) alternative operating modes for the 1.5 GeV ring may well be motivated.

An informative discussion should be held in conjunction with the MAX IV user's meeting in September. Hopefully the summary above can be expanded. A speculative presentation of possible timing modes and estimated parameters should be done in order to inform users of possible future developments.

If the MAX IV directors see this proposal favorably then a scientific case should be put together during 2015. A continuing dialog with accelerator physics on short pulses and timing modes will provide a clearer picture of what can be achieved with MAX IV and which solutions are most feasible.

Brief and incomplete survey of timing modes at existing synchrotron radiation sources

ESRF (2009)

The ESRF runs 20% in uniform bunch-filling mode and 80% in various bunch filling modes for single-pulse experiments. There are currently four modes for single pulse experiments: the 4-bunch (40 mA) and 16-bunch (90 mA) modes with equidistant bunch fillings, the hybrid mode (24x8 +1) , and the 7/8 multibunch mode (both 200 mA).

The circumference of the ESRF 6 GeV ring is 844.39 m. The period for an electron to circulate around the ring is 2.816 57 μs (orbit frequency of 355.042 kHz). The 350 MHz RF cavities can support up to 992 bunches in a (quasi) uniform fill with pulse separations of 2.839 ns. The time gaps in the 4-bunch and 16-bunch modes are 704 and 176 ns, respectively. In the hybrid mode, the time gaps are slightly asymmetric, 429 and 344 ns. Finally the 7/8 mode has a 352 ns gap with a single bunch in the middle. The low bunch charge in the 7/8 mode, 2.5–5.0 nC, shortens the x-ray pulse to 60–80 ps [full width at half maximum (FWHM)].

BESSY

BESSY operates in single-bunch mode twice per year, and in low-alpha mode four three-day periods per year.

The standard operating mode is **Multi Bunch Hybrid Mode** where 350 RF buckets out of 400 available buckets are filled with electrons (up to 0.9 mA per electron bunch, 30 ps bunch length). In the gap a single bunch (10 mA) is injected for pump-probe experiments using the fs-slicing facility.

Multi Bunch 3+1 Hybrid Mode for femtosecond slicing operation is based upon the multibunch hybrid mode but three additional pulses, separated by 12 ns are included in the multibunch train. A total of 280 mA is stored in the multi bunch train, the single bunches carry a maximum of 5 mA each.
Single-bunch operation at BESSY provides a single bunch with 20 mA total current every 800 ns.

In the **Low-alpha Multi Bunch Hybrid Mode** the momentum compaction factor is modified , resulting in reduced electron bunch lengths (1-2 ps) but the current is 100 nA per bunch.

ALS

The ALS storage ring typically operates in two distinct modes: "multi-bunch" and "two-bunch" modes.
The ALS normally operates with a multi-bunch mode, with train of 276 bunches out of a possible 328 for a total current of 400 mA. There is a single 5 mA "camshaft" bunch in the middle of a 100-nanosecond gap (bucket 318) for timing or slicing experiments. In two-bunch mode, only two bunches of electrons are filled, usually at 35 mA total ring current. The lifetime in two-bunch mode is considerably shorter and the beam is typically refilled

every two hours (compare 8 hours for multi-bunch mode). The spacing between bunches in two-bunch mode is 328 ns, compared to 2 ns in multi-bunch mode.
The ALS has been successful in serving multiple users with a diverse set of requirements such as high-photon flux and brightness, a large range of wavelengths, variable polarization, and relatively short pulses. However, a major limitation of the ALS and other synchrotron light sources is the inability to serve two other classes of experiments simultaneously—brightness or flux-limited experiments and timing experiments .

The concept of using a camshaft bunch in multibunch operations originated out of the desire for timing experiments to operate during multibunch mode. Most timing users cannot use the camshaft due to the short 100-ns gap. The ones that do must use gated detectors or expensive mechanical choppers to reduce the background from unwanted bunches. These choppers are challenging to fabricate and operate, and for beamlines that operate without a monochromator, they have to absorb about a kW of power while rotating at high speeds.

SOLEIL

In the standard SOLEIL Storage Ring 400 mA operation, the electron bunch length is 18 ps RMS for bunches in the multibunch train, and 25 ps RMS for the 5 mA single bunch of the hybrid filling pattern. A new mode of operation which provides electron bunch lengths in the range of a few picoseconds has been optimized. The beam was delivered to users in December 2011 and April 2012. The low-alpha mode is intended to satisfy studies in the ps range using THz spectroscopy which highly benefit from the coherent emission, and time-resolved science with X-rays.

ELETTRA

The typical Elettra filling mode is multi-bunch, i.e. 432 bunches with 60 ps full-width-half-maximum (FWHM) bunches rotating in the storage ring with a 2 ns interbunch period. The RF frequency is 500 MHz and the ring is usually operated with a 30-bunch dark gap.

SLS

The SLS works in top-up mode together with a filling pattern feedback system which makes it possible to have tailored current profiles around the ring. In normal operation mode a filling pattern in which a bunch train of 390 filled buckets (with 1 mA) plus 1 camshaft (i.e., a single bunch with 4 mA) in the gap (with 90 ns intervals before and after) is used. Synchronization can be done to the cam-shaft bunch

https://accelconf.web.cern.ch/accelconf/e04/PAPERS/MOPKF006.PDF