

# INSERTION DEVICES: NEW CONCEPTS AND PERFORMANCE

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## Abstract

Three major areas for the most recent insertion device developments for user facilities can be identified: (1) Short period devices operated at gaps below 10 mm to enhance the brightness and to reduce the wavelength. (2) Variable polarization devices including quasi-periodicity and (fast) polarization switching. (3) Long segmented undulators with strong focussing for single pass, high gain FELs.

## 1 INTRODUCTION

Optimum radiation from ID based SR sources is achieved by the optimization of following quantities: (a) pulsed time structure (shortly mentioned in section 8), (b) linear and circular polarization (section 6), (c) high flux (intensity) (sections 3, 5), (d) high brightness (sections 4, 2), (e) small angular divergence, (f) small source size, (g) spatial coherence and (h) temporal coherence. ID developments related to (a)-(d) are primarily discussed in this paper ((d)-(g) are interrelated and temporal coherence is usually given by the monochromator bandwidth). Emphasis is given to IDs developed for 3rd generation SR user facilities, which are the basis for the IDs needed for future 4th generation facilities, as discussed and proposed so far, namely high gain FEL facilities[1] and diffraction limited light sources[2]. The status of IDs at high energy SR facilities (APS, ESRF, SPring-8) is found in [3,4]. For the most recent ID developments we also refer to the detailed review[5] as a reference. High harmonic operation of small gap undulators and polarization switching schemes are discussed in more detail in this review.

It has been mainly the progress in ID technology that has led to the concept of a 3rd generation Intermediate Energy Light Source (ILS)[6]. At such a facility ( $E=2.5-4.0$  GeV,  $\epsilon_x=4-10$  nm-rad) high and low beta straights of various lengths (typically 4-11 m) are needed to serve many of the demands for (polarized) radiation at 10 eV - 50 keV. That undulator based high brightness research at 5 - 20 keV (so far mainly the domain of high energy SR facilities) can be considered from the outset of an ILS project (such as SOLEIL or SLS[7]) is due to three major developments: (I) Undulators can be built with low phase errors ( $\leq 2.5^\circ$  rms) that near theoretical brightness is obtained at higher harmonics[8] (by field shimming[8,9], magnet bloc sorting[10] or precision machining[11]). (II) Work at SPring-8 (KEK) demonstrates that pure permanent magnet (PPM) undulators can be operated in ultra-high vacuum[4]. (III) A small gap ( $g=3.3$  mm) in-vacuum undulator has successfully been operated in the NLS X-ray ring (2.58 GeV) with usable flux up to 13.8 keV (3rd harmonic) and 10% lifetime reduction[12]. Based on this experience, SLS will

be the first ILS facility that explicitly relies on the high harmonic (9th/11th) output of a small gap in-vacuum undulator[13].

The preference given to planar helical undulators (APPLE-II type) at several laboratories (ALS, BESSYII, ELETTRA, ESRF, PLS, SLS, Spring-8 and TLS) relies on the following characteristics: (I) Both vertical and horizontal fields can be generated in a planar PPM design with performance limited only by the vertical gap. The fields can be changed by a relative shift of upper and lower magnet arrays[14,15,5]. (II) The APPLE-II structure[16] can generate linear, elliptical and circular polarization with high fields in the helical mode. (III) Two undulators can be used in a "chicane" arrangement to produce two beams with opposite helicity[14]. A single set of optical elements is used to steer and monochromatise the two beams from a twin-undulator[17].

## 2 LOW FIELD IDS (< 1.5 T)

PPM and hybrid technology dominate for IDs with a peak field below 1.5 T. The main reason is that high remanent ( $B_r=1.15-1.22$  T) magnet blocs with a high coercivity ( $H_{cJ}=17-22$  kOe) allow by superposition the realization of

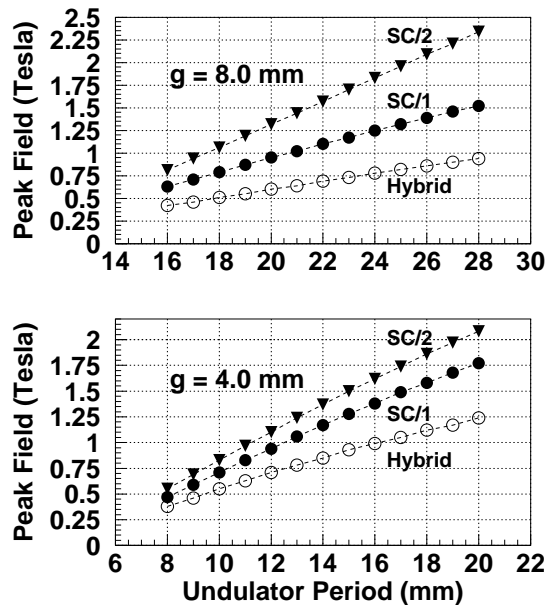


Figure 1: Planar superferric vs. hybrid undulator.

complicated 3D fields in a compact geometry ('3D PPM Lego'), which can further be optimized by multipole and spectrum shimming to reach tight magnetic tolerances on phase errors and on integrated first and second field integrals (below  $3 \cdot 10^1$  Gcm and  $2 \cdot 10^3$  Gcm<sup>2</sup> after compen-

sation). The planar helical devices[5], the Figure-8 undulator[4], non-steering passive end-pole designs, multiple trim magnet multipole correctors, phasing of undulator segments[3], the superposition of a strong focussing FODO lattice to a regular (hybrid) undulator[18] and the PM in-vacuum technology illustrate the dominance of PM ID technology today.

For long period (low field) undulators, pulsed devices and high field IDs, PM technology is replaced by either room temperature or superconducting (SC) electromagnets. Compared to PM undulators, the development of SC undulators has been modest so far. As current densities close to  $j=120 \text{ kA/cm}^2$  can be reached at small periods ( $\leq 18 \text{ mm}$ ) and gaps ( $\leq 8 \text{ mm}$ ), superferric undulators (i.e. field properties depend mainly on the iron pole profile) can provide higher fields on axis compared to PM hybrid IDs in a range relevant for small gap, short period ID operation at ILS and FEL facilities (Fig.1). Based on demonstrated performance[11], an operating current of 20% below the critical current has been assumed for undulators labelled 'SC/1', and similarly for undulators labelled 'SC/2', which have recently been analyzed for SASE FEL applications[19]. To retrieve the higher fields, SC undulators would have to be operated as (cold bore) in-vacuum devices. Such a (preliminary) test has successfully been performed by FZK, where now a new 14 mm period SC device with 1.5 T at 5 mm gap is under construction[20].

### 3 HIGH FIELD IDS ( $> 1.5 \text{ T}$ )

SC undulators in Fig.1 operate typically at current densities of  $80\text{-}120 \text{ kA/cm}^2$  and a maximum field in the coil of about 3 T, whereas SC wavelength shifters and SC multipole wigglers, the dominant devices in the high field regime, operate at  $30\text{-}60 \text{ kA/cm}^2$ . At lower energy storage rings, 7 T wavelength shifters are used to extend operation into the

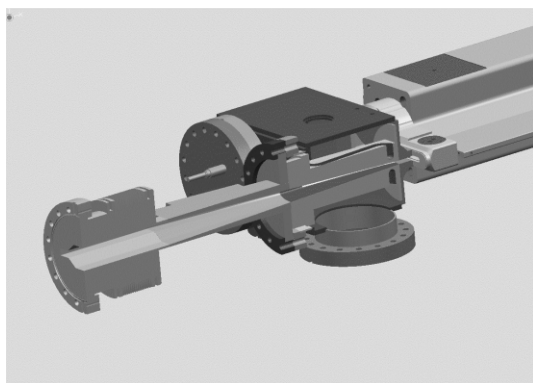


Figure 2: Small gap, low impedance ID chamber with entrance taper, instrumentation port and beam position monitor.

harder X-ray region (Aurora-2D, CAMD, BESSY II)[5]. For the same reason, 5 T superbends will be installed at ALS to enhance the flux and brightness by a factor 10-100 at 10-20 keV. For SPring-8, a 10 T SC wavelength shifter

has been built by BINP. At NSLS and DELTA, flexible multipole wigglers have been installed with different peak fields (2.7-5.5 T), depending on the configuration of poles that are powered in the symmetric or asymmetric mode[5].

Recently, the limit of reaching high fields with PM technology has been explored at ESRF and SRRC. Peak fields of 3.13-3.57 T have been reached for periods of 218-378 mm and gaps of 6-12 mm. A 60.5 mm period hybrid wiggler with 1.95 T at 7.5 mm gap is under construction at SLS (to be compared with a 3.5 T, 60 mm period SC wiggler under study at MAX-lab[5]). For small gap ID operation, high precision chambers with a low impedance are needed as alternative to the in-vacuum operation. Such chambers, with a minimum beam stay clear (BSC) aperture of 5 mm, have been developed at APS[21]. Because of the short bunch length at SLS (4.4 mm), the taper transition has been extended (see Fig.2) to keep its impedance below  $1 \text{ m}\Omega$ .

### 4 HIGH HARMONIC OPERATION

Short period undulators extend the high brightness radiation into a region otherwise only accessible using lower brightness wigglers. Small gap in-vacuum undulators are under construction at ESRF (g,  $\lambda_w$  (mm): 6,17; 6,17; 6,18 and 6,21) and at SPring-8/SLS (8,24) or planned in the near future at SLS (4,17), NSLS (2,12.5) and ALS (5,20). For photons up to 18 keV the 9th/11th harmonic output of an hybrid in-vacuum undulator (period 17 mm, gap 4 mm, phase error  $2^0 \text{ rms}$ ,  $K_{eff}=1.46$  ( $\text{Sm}_2\text{Co}_{17}$ )) will be used at a later stage at SLS (2.4 GeV). In Fig.3 the brightness is compared to an alternative 21.5 mm device ( $K_{eff}=1.48$ )

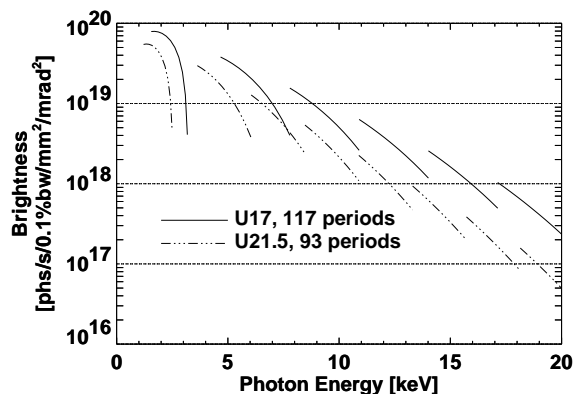


Figure 3: Hybrid U17 in-vacuum (gap: 4 mm) vs. hybrid U21.5 out-of-vacuum undulator (gap: 6.5 mm, BSC aperture: 4 mm).

operated out-of-vacuum with the fixed BSC aperture chamber shown in Fig.2. The gap taper has to be controlled within  $5 \mu\text{m}$ . If a 14 mm period in-vacuum SC undulator (1.5 T) indeed becomes available in the future, the brightness at 5-20 keV could further be increased significantly (Fig.4).

Undulators with low phase (multipole) errors cause a minor reduction in brightness. It is rather the emittance

( $\epsilon = \sigma' \sigma$ ) and the energy spread of the electron beam which cause a significant reduction in intensity which increases with harmonic number. The brightness reduction factors for the proposed SLS U17 undulator due to various

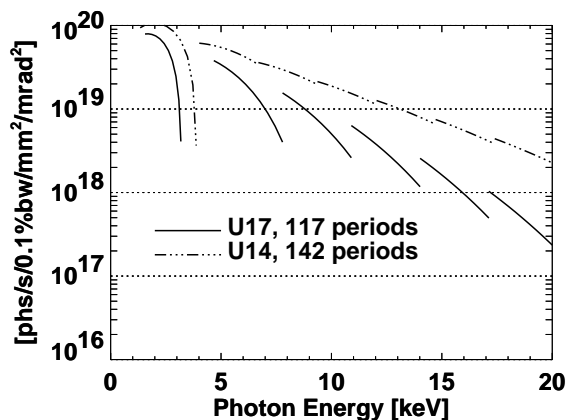


Figure 4: Hybrid U17 in-vacuum (gap: 4 mm) vs. U14 SC in-vacuum undulator (gap: 4 mm).

effects are compared in table 1. The on axis flux density  $F_{00} := d^3N/dt(d\omega/\omega) d\Omega |_{\theta=0}$  [photons/sec/mrad<sup>2</sup>/0.1% bw] has been calculated numerically[22] including (i) phase errors in a realistic undulator field, (ii) electron beam emittance ( $\epsilon=4.8$  nm-rad,  $\beta_x=1.2$  m,  $\beta_y=2.6$  m, coupling 1%) and (iii) energy spread ( $\Delta E/E=0.09\%$ ). The natural brightness is defined as  $B_n = F_{00}/2\pi\sigma_\gamma^2$  and  $\sigma_\gamma = \sqrt{2\lambda L}/2\pi$  ( $\sigma_\gamma' = \sqrt{\lambda/2L}$ ). An independent analysis with similar results has been published earlier[5].

Table 1: SLS U17 Undulator: Brightness Reduction

N	$h\nu$ [keV]	$F_{00}$	$B_n$	$\sigma_\gamma'; \Delta E/E$ 1) ; 2)
1	1.5	2.1 E+18	<b>4.2 E+21</b>	2.7 E-1 ; 8.7 E-1
3	4.6	2.1 E+18	<b>1.3 E+22</b>	1.5 E-1 ; 5.0 E-1
5	7.7	1.4 E+18	<b>1.4 E+22</b>	1.1 E-1 ; 3.3 E-1
7	10.8	8.1 E+17	<b>1.1 E+22</b>	8.7 E-2 ; 2.5 E-1
9	13.9	4.3 E+17	<b>7.7 E+21</b>	7.4 E-2 ; 2.0 E-1
11	17.0	2.2 E+17	<b>4.8 E+21</b>	6.3 E-2 ; 1.6 E-1
13	20.0	1.1 E+17	<b>2.8 E+21</b>	5.4 E-2 ; 1.4 E-1

## 5 HIGH HARMONIC SUPPRESSION

Contamination of higher harmonics transmitted by the monochromator can be a major problem in certain experiments. Since Sasaki and coworkers, in analogy to a 1-D quasi-crystal, proposed the quasi-periodic undulator scheme to solve this problem, field amplitude modulation instead of periodicity modulation has been proposed by ELETTRA and successfully tested at ESRF (see [5]). Quasi-periodic amplitude modulation is more practical and can be accomplished by vertical magnet block dis-

Table 2: U17 brightness reduction: continued

	Phase Error	Phase Error	Beam Size $\Sigma$	All Factors
1)⊕2)	3) 2 <sup>0</sup> rms	4) 4 <sup>0</sup> rms	5)	1)-3), 5)
2.4 E-1	1.00	0.99	7.3 E-2	<b>1.7 E-2</b>
1.0 E-1	0.99	0.95	2.8 E-2	<b>2.8 E-3</b>
5.8 E-2	0.97	0.87	1.8 E-2	<b>1.0 E-3</b>
3.7 E-2	0.95	0.76	1.3 E-2	<b>4.6 E-4</b>
2.6 E-2	0.93	0.64	1.0 E-2	<b>2.4 E-4</b>
1.9 E-2	0.90	0.51	8.3 E-3	<b>1.4 E-4</b>
1.4 E-2	0.88	0.31	7.1 E-3	<b>8.7 E-5</b>

placement, both for PPM (ELETTRA, ESRF) and hybrid (BESSY II) devices, or by current modulation of selected pairs of poles, in the case of EM IDs (SLS). The result is a spectrum consisting of a number of discrete lines, but not at harmonics of the fundamental. Quasi-periodicity can be integrated into elliptical structures. The device presently under construction at ELETTRA has the added feature of being an APPLE-II structure. According to calculations, rejection is achieved in the linear, elliptical and circular modes, even when the flux is integrated over a finite acceptance angle[5]. The EM elliptical polarized twin-undulator under construction at SLS is capable of producing periodic circular fields as well as quasi-periodic linear polarized fields. A factor of 10 reduction in the ratio of the 3rd and 5th harmonic intensities to the fundamental has been calculated, close to what has been measured at ESRF. After the monochromator the harmonic contamination is reduced to 0.3%.

## 6 VARIABLE POLARIZED LIGHT

Experiments which aim at measuring dichroic signals from magnetic surfaces or chiral molecules need oppositely polarized, rapidly switched photon beams under otherwise identical conditions. IDs for polarized radiation have been developed (1) as pure electromagnets, (2) as PM devices or (3) a combination of both. For polarization switching two general concepts exist: (I) Pulsed operation of IDs of type (1) and (3) in the range 10-100 Hz, or mechanical 'shift operation' of type (2) in the range 0.1-1 Hz. (II) Static operation of twin-undulators in conjunction with static (or pulsed) chicane magnets with switching rates of 1-100 Hz.

Type (1) devices have been built at ELETTRA (EM elliptical wiggler, 100 Hz), at LURE (Onuki-type undulator capable of producing any polarization state, 0.5 Hz) and recently in an APS/BINP collaboration (undulator, 10 Hz). A elliptically polarized EM twin-undulator will be installed at SLS (not pulsed, magnetic design identical to the ELETTRA device). Type (3) devices are operated at NSLS and APS (elliptical multipole wigglers, 100 Hz, developed in an APS/BINP/NSLS collaboration) and at ESRF (undulator, 10-100 Hz). A disadvantage of pulsed EM devices is

that close to 100 Hz the transient regime is reached which causes energy shifts in an undulator spectrum. In addition, to keep the residual electron beam displacement below  $5 \mu\text{m}$ , elaborate DSP-controlled ID compensation and dynamic orbit correction are needed to minimize field errors caused during switching or influenced by eddy current effects.

Type (2) planar helical devices are now planned at several laboratories. In a few cases, twin-undulators are used in combination with either a static (ESRF, BESSY II, SLS) or pulsed (Spring-8) chicane to tilt or displace the electron beam. Such a scheme has advantages over a pulsed ID operation. Today the APPLE-II structure has almost become the standard for planar helical undulators (as recently proposed [16] linear polarization with any orientation is also possible). Although field measurement and optimization is more difficult compared to a non-helical planar device, recent results at ALS, BESSY II, ELETTRA and TLS show that the field quality is sufficient to allow use of the 3rd and 5th harmonic in the linear and elliptical modes. The end-field compensation for a combined gap and shift parameter change is not always sufficient. At ALS both local orbit correctors and 2-dimensional feed-forward correction tables are used to reduce orbit distortions of  $\pm 200 \mu\text{m}$  vertical and  $\pm 100 \mu\text{m}$  horizontal to the  $\pm 3 \mu\text{m}$  level during row shift for a polarization change. At BESSY II, two twin-undulators with a chicane are now in operation. At SPring-8, a helical twin-undulator is operated with a pulsed chicane (10 Hz), where the helicity is reversed without a nominal change in the lateral position.

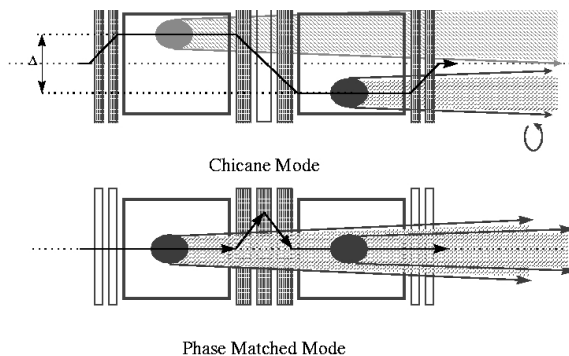


Figure 5: Twin-undulator operation modes.

For dichroism experiments, the flipping ratio error is a minimum at maximum polarized flux  $P_c^2 \cdot I$ . For a polarized flux ratio of  $10^{-3}$ - $10^{-4}$  the source should be inherently stable to avoid polarization changes and energy shifts. For this reason, statically operated twin-undulators are used. The electron beam can be tilted (BESSY II) or displaced (SLS, Fig.5) using static chicane magnets to separate the two radiation beams with opposite polarization. A mechanical chopper is used for the polarization switching. In the parallel displaced mode, not only are the same optical components used in the beamline, but the same 'footprint' on the optics. Whereas in the tilted mode both foci overlap at the

sample, in the parallel displaced mode the overlap of both beams at the sample is shifted by  $150 \mu\text{m}$  with respect to the focal plane, leading to a vertical and horizontal beam size of  $75 \mu\text{m}$  and  $150 \mu\text{m}$  (FWHM) respectively (Fig.6). If both undulators are combined in the 'phase matched mode', the sample is again in focus and sees a size of  $50 \mu\text{m} \times 60 \mu\text{m}$ . A fast mechanical chopper (1-10 kHz) will be used at the intermediate, closely separated ( $400 \mu\text{m}$ ) foci. In case of normal incidence optics, an optical delay (5 ns) could be installed in one branch to reach very high switching rates (200 MHz).

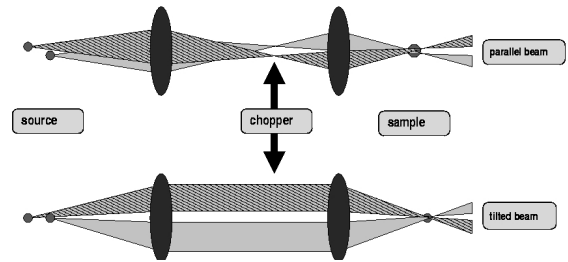


Figure 6: Helicity switching: tilted vs. parallel beams.

## 7 LONG IDS

To increase the brightness beyond its present level, the first of three 25 m long in-vacuum undulators will be installed at SPring-8 during the summer 2000. The undulator consists of 5 standard PPM in-vacuum devices joined in a continuous structure, operating with a variable gap.

For single pass, high gain SASE FELs, which reach saturation after exponential growth at wavelengths as short as  $1 \text{ \AA}$ , the undulator length is 10-15 times the gain length (typically 4-11 m). The SASE undulators studied so far[1,19] would have a period of 25-50 mm with a deflection parameter  $K=3-4$  at gaps of 6-12 mm. The shortest (longest) gain length is reached by the most (least) efficient technology, namely the SC (room temperature EM) technology. Both for the PM and SC technologies, helical undulators always yield a shorter gain length than planar devices. The reduction of saturation length to be expected from a smaller gap undulator scales proportionally to the corresponding reduction of the undulator period[19]. Strong focussing is required, and optimum gain is obtained with beta functions of 10-20 m. A segmentation of the undulator is therefore possible, with segment lengths of 2-5 m and a 0.2-0.5 m space in between to allow for the installation of diagnostic stations and quadrupoles (50 T/m) in a periodic, strong focussing FODO lattice. As an option, a distributed FODO lattice (alternating gradients of about  $\pm 20 \text{ T/m}$ ) can be superimposed on the undulator field[18]. Because the superimposed quadrupole magnets contribute dipole errors which significantly complicate the engineering of the undulator, a regular, lumped FODO lattice is preferentially considered with the additional advantage that beam based alignment methods can be applied. To generate tunable

SASE radiation by varying the field in a segmented undulator, additional magnets for phase correction between the segments are needed (similar to the phase matched operation in Fig.5).

Compared to IDs for storage rings, phase errors and integrated multipole errors are less critical. The greatest difficulty is to keep the electron beam straight within 5-10  $\mu\text{m}$  over the gain length to guarantee adequate overlap between the electron and photon beams. The field on axis therefore has to be corrected to a level of 3  $\text{kGcm}^2$ , and the (tapered) gap must be controlled to within 5  $\mu\text{m}$  (as for the high harmonic operation discussed in section 4.). The crucial problem of aligning a 100 m long undulator is beyond the scope of this paper and will not be discussed further.

## 8 NON-STANDARD IDS AND IDEAS

Femtosecond bunch slicing demonstrated at ALS with a bending magnet as the radiator, can be used to generate 0.2 ps x-ray pulses with higher brightness from an undulator installed in a straight section with modest (vertical) dispersion. The average brightness at 2 keV, with a 10 W laser (Ti:Sapphire, 800 nm, 50 fs, 10 kHz) and a small gap invacuum undulator (20 mm period,  $L=1$  m), would be  $2 \cdot 10^{11}$  photons/s/mrad<sup>2</sup>/mm<sup>2</sup>/0.1% [23]. At SLS (2.4 GeV) the 3rd harmonic (250 nm, 200 fs, 10 W, 10 (100) kHz) would have to be used to achieve resonance with a modulator wiggler (75 mm period, 25 periods,  $L=2$  m,  $K=17$ ) - a device close to the wiggler currently under construction for the SLS Material Science beamline. If such a modulator would be installed, together with a (polarized) twin-undulator as the radiator, in a single long (10 m) straight section in order to minimize bunch lengthening effects, two (opposite) circular polarized X-ray pulses with the time structure shown in Fig.7 could be generated.

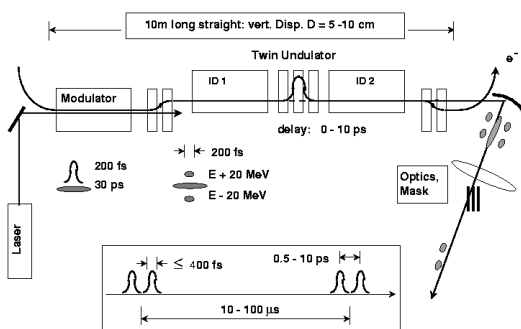


Figure 7: Twin-undulator with sub-picosecond pulses

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