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Insertion devices for Alba beamlines: some ideas

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Introduction

As in all 3rd generation synchrotron sources, the most frequently used photon sources which will feed the future beamlines of Alba will be the insertion devices. Their properties will strongly influence the characteristics of the beamline downstream. Therefore they have to be carefully chosen, taking into account the needs of the experiments whilst having in mind the technological possibilities.

In order to help future users to better know the available sources, we present here a preliminary study to illustrate the possibilities of ALBA with insertion devices within the hard x-ray regime. Results for helical undulators (i.e. APPLE II type) or large period undulators, used at the soft X-ray region, as well as superconducting wigglers used for hard X-rays, will be presented in due course.

The tables and graphs shown below, have been conceived to show the performances of different insertion devices. The numerical values of brilliance and flux have to be used only as a guide. They may be useful to get order of magnitude estimates but to obtain more precise numerical values, detailed calculations including important aspects not treated in this report are needed.

Parameters in the optimisation of insertion devices

In the process of optimising an insertion device there are parameters that depend on the machine and, therefore, they are constant for all the devices. One of them is which straight section is used to install the insertion device. The Alba lattice has several possible lengths of straight sections which have different values of the beta function and beam sizes. We have taken the 4.6m-long straight sections which have the smallest horizontal dimension of the beam since many applications benefit from small sources. Table 1 shows the electron beam dimensions at these locations.

Horizontal electron beam size	σ_x	μm	137.6
Vertical electron beam size	σ_y	μm	6.1
Horizontal electron beam divergence	σ'_x	μrad	41.0
Horizontal electron beam divergence	σ'_y	μrad	6.0
Current	I	mA	250

Table 1. Electron beam parameters of Alba machine at the straight sections used in this report.

Other questions to consider are:

- *Type of undulator*: *PPM (Pure Permanent Magnets)* or *Hybrid (they include Fe blocks in addition to the magnets)*. The elements of the PPM devices have a permanent magnetization and the maximum field is given by the remanent field. On the other hand, hybrid insertion devices use ferromagnetic materials with high permeability to concentrate the magnetic field. Hybrid insertion devices create a stronger field (thus preferred in wigglers), whilst PPM devices are easier to manufacture.

- *Magnetic material*: Typically *SmCo* or *NdFeB*. The latter gives a higher field, so it is the first choice in in-air undulators or wigglers. However, NdFeB loses magnetization when baking above ~120°C. Therefore, SmCo (hybrid) undulators are generally preferred in in-vacuum undulators.

- *Insertion device period* (λ_{ID}): Technologically can be varied from ca. 15 mm onwards. It is designed as λ_W or λ_U for a wiggler or an undulator, respectively.

- *Insertion device length*: It is mostly limited the geometrical and optical constraints of the storage ring. In this study we have chosen a length 2 meters. The number of poles is then defined by $N_p = L_{ID}$ / period.

- *Minimum gap*: In this report we consider the minimum gaps to be *11mm* and *5.5mm* in in-air and in-vacuum insertion devices respectively. These values could slightly change depending on practical details.
  From the point of view of the optics, the smaller the gap the better is the radiation in terms of flux and tunability. However, there are limits as these imposed by the ultra-high vacuum (UHV) requirements in the ring and the dynamic aperture of the electron orbit.

Optimisation of the undulators

The period of the undulator (λ_u) is chosen to optimise the optical characteristics (brilliance, flux density and flux) at one or some pre-determined photon energies. Many undulators (i.e. when λ_u > 20mm in in-vacuum undulators and λ_u > 26mm in out-vacuum undulators approximately), allow the selection of a given photon energy using different harmonics, although only one of them is optimal.

The optimization has been done as follows. For a given photon energy (for example 12.4 keV) we looked for the period of an undulator which at minimum gap produces the maximum flux and brilliance at that energy. In general, for a given undulator length, the lower is the undulator period the higher is the brilliance, the flux density and the flux.

However, the decrease of the undulator period makes the undulator less tuneable, i.e., the adjustment of the undulator gap makes a given harmonic to cover a smaller energy range. Eventually, this would lead to a situation where the undulator harmonics do not overlap, so there would be forbidden energies for the undulator. To avoid this situation, the plots of the optical characteristics versus the energy have to be carefully inspected.

Optimisation of the wigglers

As the spectrum of a wiggler is structureless (i.e. does not show harmonics in the hard X-ray range), its optimization is simpler than in the case of undulators. The parameters listed above are optimised so that the optical characteristics are maximal at the required energy.

When using wigglers one has to remember that they disrupt more the electron orbit in the storage ring and produce much more power than undulators (a factor ~3 compared to in-vacuum undulators), although delivered over a wider angle. This large power load on the optics is an important design issue for the beamlines and it needs to be carefully studied if one has to use a wiggler instead of an undulator.

Some examples of IDs for Alba

Taking into account the considerations described above, here we present some examples of undulators. We consider different types of insertion devices (PPM/Hybrid) and magnetic materials (NdFeB/SmCo) that are optimized at 2 different energies: 12.4 keV and 20 keV. We have considered as well 2 different minimum gaps, 5.5 and 11mm, corresponding to the in-vacuum and in-air devices.

Results are shown in table 2. Inspection of the table shows that in-air undulators (minimum gap 11 mm) result in periods of ~28 mm both for PMM and Hybrid technologies if they are optimized at 12.4 keV and periods of ~ 27 mm if they are optimized at 20 keV. Both periods are so close that their difference may be disregarded in practice. Also, in-vacuum undulators (minimum gap = 5.5 mm) if optimized at 12.4 keV result in periods of ~20 mm and of ~19 mm if they are optimized at 20 keV. Again both values are very close each other.

In conclusion one may state that the insertion devices in the hard x-ray regimes will have periods of 28 mm and 20 mm for in-air and in-vacuum undulators respectively.

Figures 1 and 2 show the plots of the spectral distribution of photons delivered by typical undulators in air and in vacuum, respectively. For comparison the distributions for a wiggler and bending magnet sources are also shown. The black curves (which show a decrease upon increasing the photon energy) represent the behaviour of a given harmonic when opening the magnetic gap. Only the odd harmonics are shown (1, 3…, 15), since these are the only ones that deliver photons in the optical axis. The lowest energy reached by a curve, that is, by a given harmonic, corresponds to the minimum gap of the undulator and, generally, to the highest brilliance, flux and flux density. For example, in the undulator shown in figure 1, the energy of 7 keV can be achieved either by the harmonic #5 (with a brilliance of about 10^{19} and gap of 11 mm) or by the harmonic #3 (with a brilliance of about 3×10^{18} and a gap value of 17.5 mm).

Premises					Optimized parameters					
optimized at energy [keV]	ID type	Magnetic material	Min. gap	ID period [mm]	Used harm.	Brill. at optimal energy	Flux density at opt. E	Flux at optimal energy	Total power [kW]	K max
12.4	PPM	NdFeB	11	28.4	#9	$1.5\ 10^{18}$	$1.2\ 10^{16}$	$6.2\ 10^{13}$	0.97	1.553
12.4	Hybrid	NdFeB	11	28.1	#9	$1.6\ 10^{18}$	$1.3\ 10^{16}$	$6.6\ 10^{13}$	1.01	1.565
12.4	Hybrid	SmCo	5.5	20.4	#7	$5.8\ 10^{18}$	$5.0\ 10^{16}$	$2.6\ 10^{14}$	2.15	1.655
12.4	Hybrid	NdFeB	5.5	19.7	#7	$6.6\ 10^{18}$	$5.9\ 10^{16}$	$3.1\ 10^{14}$	2.50	1.728
20	PPM	NdFeB	11	27.5	#13 #11	$1.2\ 10^{17}$ $5.5\ 10^{16}$	$1.2\ 10^{15}$ $4.9\ 10^{14}$	$6.4\ 10^{13}$ $2.5\ 10^{13}$	0.89	1.445
20	Hybrid	NdFeB	11	27.3	#13 #11	$1.3\ 10^{17}$ $6.2\ 10^{16}$	$1.3\ 10^{15}$ $5.3\ 10^{14}$	$7.1\ 10^{12}$ $2.8\ 10^{12}$	0.92	1.455
20	Hybrid	SmCo	5.5	19.1	#9 #7	$9.9\ 10^{17}$ $4.5\ 10^{17}$	$9.9\ 10^{15}$ $3.6\ 10^{15}$	$5.4\ 10^{13}$ $1.9\ 10^{13}$	1.81	1.427
20	Hybrid	NdFeB	5.5	18.4	#9 #7	$1.3\ 10^{18}$ $6.7\ 10^{17}$	$1.4\ 10^{16}$ $5.6\ 10^{15}$	$7.3\ 10^{13}$ $2.9\ 10^{13}$	2.12	1.486
20	wiggler Hybrid	NdFeB	11	60	---	$2.6\ 10^{17}$	$7.7\ 10^{16}$	$2.7\ 10^{14}$	5.75	8.000

Table 2. Parameters of the undulators calculated using the short sections of Alba machine (see table 1 for properties). Brilliance is given in [ph/s/0.1%BW/mm^2/mrad^2], flux density in [ph/s/0.1%BW/mm^2] and flux in [ph/s/0.1%BW]. The optical characteristics of the undulators optimized at 20 keV are shown for the 2 strongest contributing harmonics at this energy (the weaker shown in grey). The optical characteristics of a wiggler optimized at 20keV are also given. In the case of the wiggler, the flux density and the flux are calculated for a horizontal aperture of 1 mrad. The length of all the insertion devices is 2m.

It is worth noticing the undulators in figures 1 and 2 can be used optimally as well at lower energies. In particular, the optimisation at 7 keV produces practically the same results than the optimization at 12.4 keV. Effectively, as it can be seen from figure 1, the optimisation of the 9th harmonic at 12.4 keV gives automatically the optimisation of the 5th harmonic at 7 keV. In the case of in-vacuum undulators (Fig. 2), the optimisation of the 9th harmonic at 20 keV sets the 3rd harmonic at 7 keV.

In summary, inspection of Figs. 1 and 2 shows that the brilliance achieved by the standard in-air undulators in Alba will be of the order of 10^{18} ph/s/0.1%BW/ mm^2/mrad^2 at 12.4 keV. The figures of the flux density and the flux are 10^{16} ph/s/0.1%BW/mm^2 and 5×10^{13} ph/s/0.1%BW, respectively. These values are all about 10 times lower at 20 keV.

For in-vacuum undulators, the brilliance, flux density and flux increase (relative to the air undulators) all by a factor of 4 and 10, at 12.4 and 20 keV respectively.

Regarding the total power, there are obvious differences between insertion devices. The devices delivering less power (so less demanding in terms of cooling of the optical elements) are in-air undulators, with a typical generated power around 1 kW. Still, this power is very high compared to a bending magnet (37.7 W per horizontal mrad). In-vacuum undulators deliver around 2 kW, whilst wigglers produce a power of about 6 kW.

In what concerns photon flux density and flux, standard wigglers are better sources that undulators for all the hard X-ray energy range. However, undulators are brighter sources (i.e. more photons per unit of phase space) for energies below 15 keV (in-air undulators) or 30 keV (in-vacuum undulators).

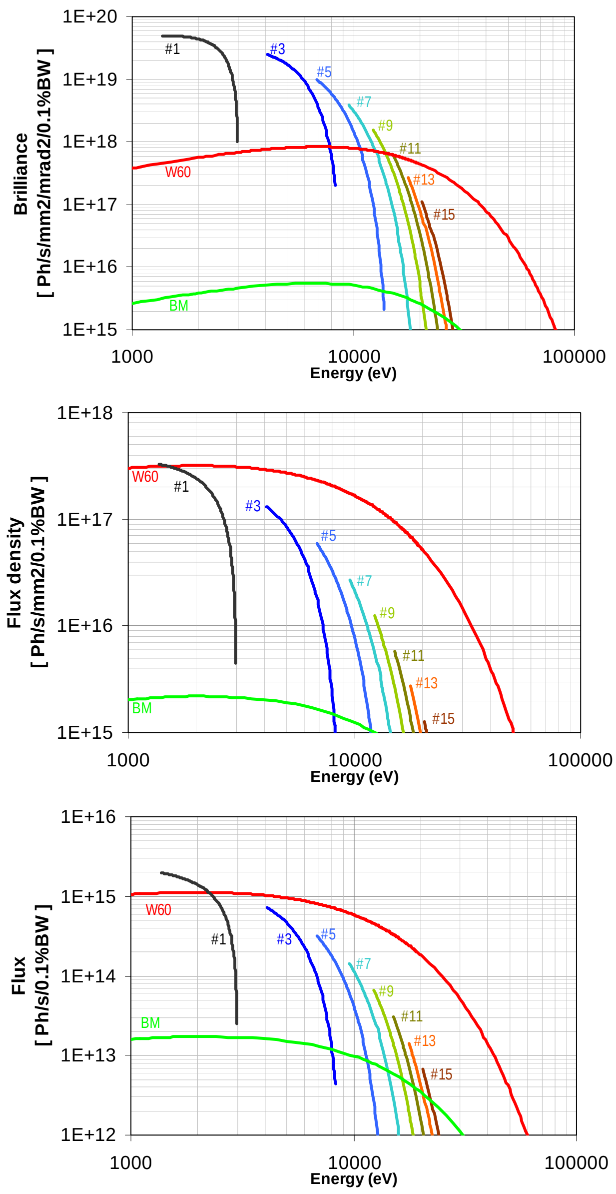


Fig. 1. Beam characteristics of a **NdFeB PPM undulator**, minimum gap **11mm** with a period of λ_u= 28.4 mm optimized at 12.4 keV. Red curve shows the W60 wiggler, optimized at 20keV (Hybrid NdFeB, λ_W = 60mm, gap=11mm). See table 2 for complete numbers and comparisons. Radiation from the bending magnet is also shown (green). The bottom plot compares the flux included in the central cone of the undulator, and the flux delivered by the wiggler and bending magnet in a horizontal fan of 1 mrad.

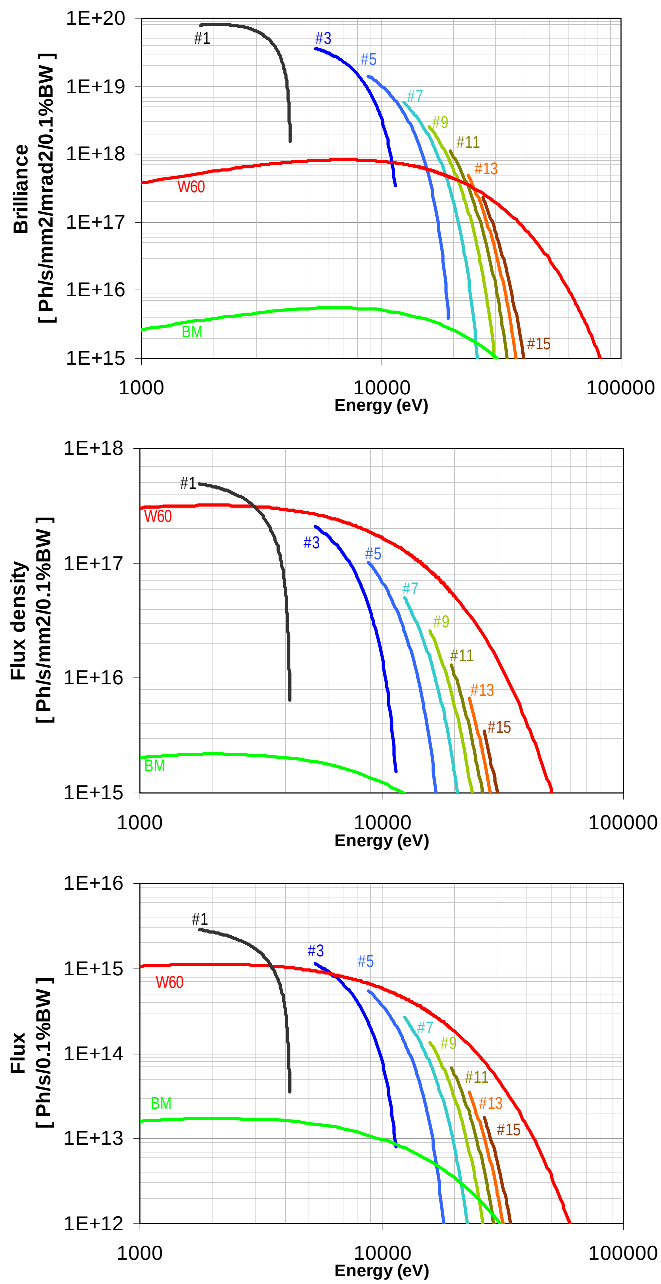


Fig. 2. Beam characteristics of a **SmCo Hybrid undulator**, minimum gap **5.5mm** with a period of λ_u= 20.4 mm optimized at 12.4keV (harm #7), Red curve shows the W60 wiggler, optimized at 20keV (Hybrid NdFeB, λ_W = 60mm, gap=11mm). See table 2 for complete numbers and comparisons. Radiation from the bending magnet is also shown (green). The bottom plot compares the flux included in the central cone of the undulator, and the flux delivered by the wiggler and bending magnet in a horizontal fan of 1 mrad.

Spectra through a pinhole

From the optical point of view, there are different ways to define a representative figure of merit. A commonly used one is to rely on the brilliance, the flux or the flux density, already defined above. However, these figures of merit characterise optically the source, but not the flux that the beamline can actually receive. In fact, there is *not* any single absolute value or figure able to evaluate the best source that can feed any beamline, since the properties to optimise strongly depend on the application.

For example, a different way to define which source is best for a given application is to calculate the flux through a characteristic defining aperture. This number, together with the divergence and the source size, can also give a representative figure of the effective performance of the source.

Here we consider 2 particular examples of this evaluation: The flux through an aperture covering the central cone, and the flux through 1 mrad horizontal and 23.2 μrad vertical apertures and covering a limited spectral bandwidth.

Flux from an undulator through a pinhole

Let us evaluate the effective flux of the undulator through a pinhole covering the FWHM of the central cone. We will consider 2 different cases: a NdFeB undulator with a period of λ_u= 28.1 mm and an in-vacuum SmCo undulator with λ_u= 20.4 mm. These undulators are described in table 2.

The pinhole covering the FWHM of the central cone at 12.4 keV has to have an angular aperture of (HxV) 67×20 μrad^2 approximately for ALBA, for both undulators. This solid angle corresponds, at 15m from the source, to a pinhole of only 1×0.3 mm^2. The resulting flux up to 30 keV through this aperture is shown in figures 3 and 4.

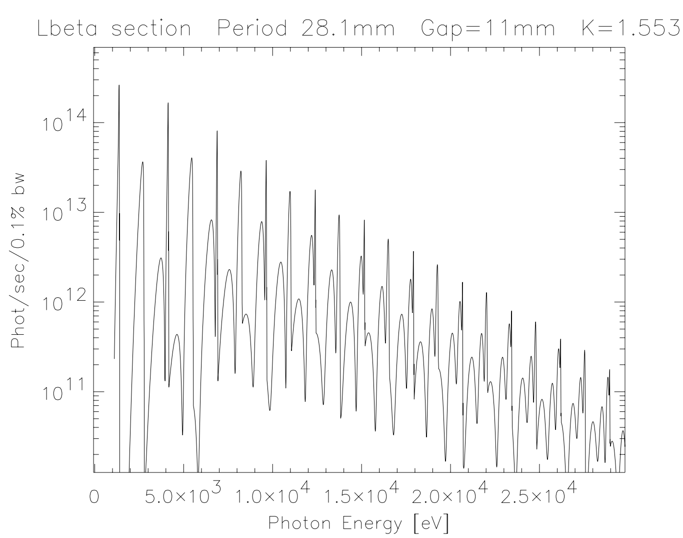


Fig. 3. Spectral flux through a pinhole of $1{\times}0.3mm^2$ at 15 m (covering the FWHM of the central cone) given by a **NdFeB hybrid undulator** at a minimum gap of **11mm** , with a period of λ_u= 28.1 mm.

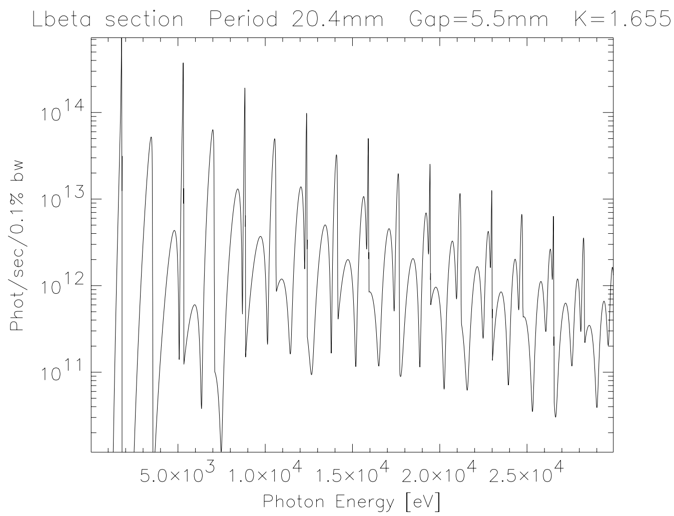


Fig. 4. Spectral flux through a pinhole of $1.04{\times}0.29mm^2$ at 15 m (covering the FWHM of the central cone) given by a **SmCo hybrid undulator** at a minimum gap of **5.5mm**, with a period of λ_u= 20.4 mm.

At 12.4 keV the flux through the pinhole is 2 10^{13} and 9 10^{13} ph/s/0.1%BW, for the U28.4 and the U20.4 undulators, respectively. It is interesting to compare these values with those obtained by integrating all the delivered flux. The total delivered flux is respectively 6.2 10^{13} and 2.6 10^{14} ph/s/0.1%BW (see table 2), that is, 3 times higher than the flux passing through the pinhole.

The main conclusion here is that the optics design of the beamline is a crucial factor that limits the effective flux that can be used in experiments.

Case of high energy resolution and "photon-hungry" beamline

We consider here the case of a hard X-ray beamline requiring a high energy resolution and a good flux, but not needing very high collimation. The question here is: which kind of device will fit the best in these requirements? To answer this, let us assume that the beamline uses a symmetric Si(111) monochromator, that has an energy resolution of $\Delta E/E = 1.33\ 10^{-4}$. In order to not degrade this energy resolution, only the flux whose vertical divergence is less than the natural angular acceptance of the monochromator (the so-called *Darwin width*) will be accepted. At 12.4 keV, the Darwin width is as small as 23.2 μrad.
In the horizontal direction we will accept 1 mrad, which is a typical acceptance for wiggler beamlines. At 20m distance this acceptance yields to a 20mm wide spot, which is still manageable for the beamline optics if any focusing is required. Therefore, in this example we will consider the flux through a pinhole accepting a divergence of $1{\times}0.0232\ mrad^2$.

Let us then consider a wide range of the insertion devices: the U28.4 and U20.4 undulators (see table 2 for details) and 2 wigglers (the conventional W51 and the superconducting SCW30). The characteristics of these sources are listed in table 3. They represent a large variety of ID periods and magnetic fields, and therefore the corresponding power output.

We take into consideration here a conventional wiggler with a period of 51 mm, instead of the one of 60 mm chosen before (table 2). This is because of the limited horizontal acceptance. As a smaller period produces a horizontal narrowing of the cone of emission, the W51 yields more accepted flux than the W60, which would not be the case if we considered the total flux emitted. Again, the parameters we choose to optimise the source have strongly influenced the final decision.

Figure 5 shows the transmitted flux between 5 and 30 keV taking into account all the considerations above. As we could expect, in-vacuum undulator (U20.4) produces a higher flux than in-air undulator (U28.4), and so does the superconducting wiggler (SCW30) with respect to the conventional one (W51). The differences increase with energy. Letting aside the superconducting wiggler, the choice between wigglers and undulators is not completely obvious and will finally depend, among other factors, on the useful energy range for a given application, the need for tunability and the efficiency of the cooling system to absorb the heat load (compare the emitted power in table 3).

ID	Type	Material	Period [mm]	B [T]	K	Power [kW]	Optimization
U28.4	Undulator out vacuum	PPM NdFeB	28.4	0.585	1.553	0.97	Harm #9 at 12.4 keV at min. gap 11mm
IVU20.4	Undulator in vacuum	Hybrid SmCo	20.4	0.868	1.655	2.148	Harm #7 at 12.4 keV at min. gap 5.5mm
W51	Wiggler	Hybrid NdFeB	51	1.235	5.885	4.324	Optimises flux at 12.4 keV within 1 mradH
SCW30	Supercond. Wiggler	Super conductor	30	2.0	5.622	11.28	

Table 3. Characteristics of the considered insertion devices. The length of all devices is 2 m.

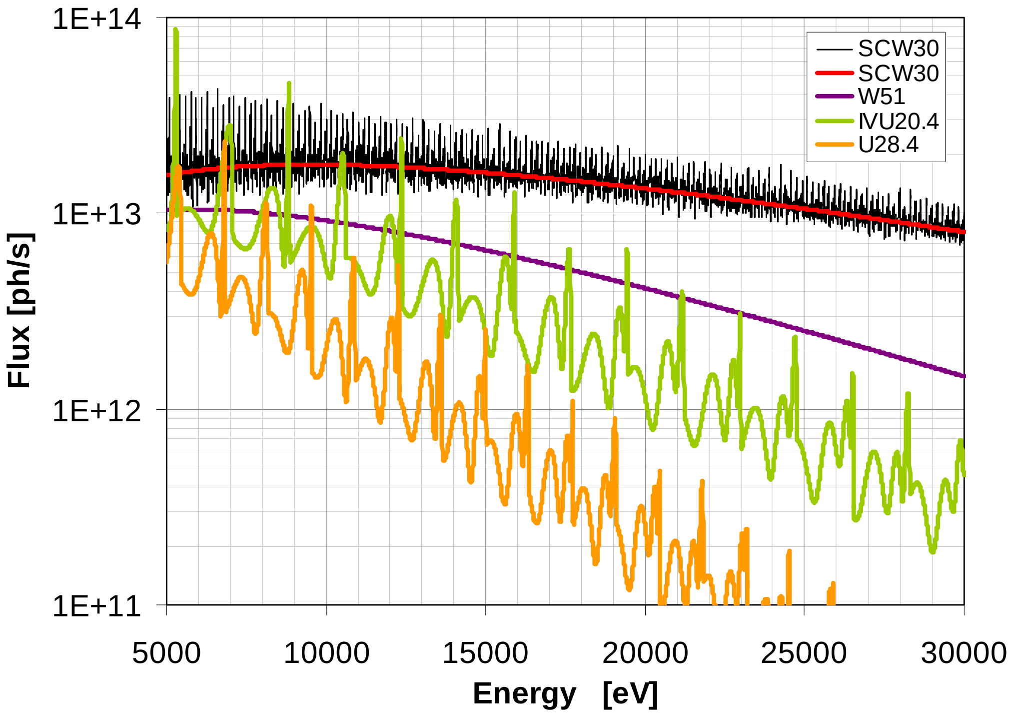


Figure 5. Flux though a pinhole with an acceptance of 1×0.0232 mrad^2 and a spectral band pass of 1.33 10^{-4}. Description of these devices is shown in table 3. The flux of the superconducting wiggler SCW30 has been calculated through both the undulator character (black line) and wiggler character (red line).

Wiggler vs. in-vacuum undulator at 20-30 keV

The choice between undulator and wiggler is clear at energies lower that 25 keV. If the experimental technique requires high brilliance, the choice is the undulator. In case of a need of photons, the beamline should be fed by a wiggler.

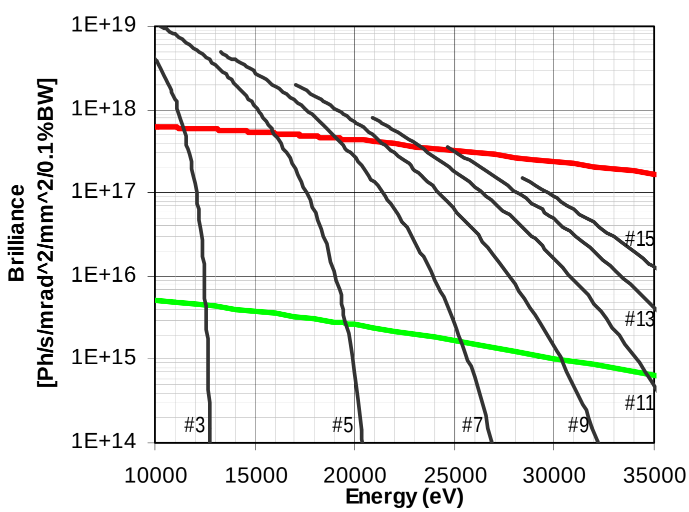
However, the choice is more difficult in the energy range 25-30 keV. We have studied 2 insertion devices: an in-vacuum undulator and a wiggler optimized at 25-30 keV energy range. (The optimization is practically the same for 25 keV than for 30 keV). The results are shown in table 4, and the optical characteristics in the hard X-ray range are shown in figure 6.

Both devices present pros and cons. At this energy range both wiggler and in-vacuum undulators can deliver a suitable beam. Their brilliance is similar, although the wiggler delivers a higher flux and flux density. In the other hand, the power delivered by the wiggler is 8.8 kW, four times the power delivered by the in-vacuum undulator. This puts a serious drawback on the wiggler in what concerns beamline optical design.

There is still another important point to be considered. The imperfections in the periodicity of the magnetic field in an undulator have negative effects on their spectral characteristics since these devices are based on interference effects. Field errors cause a broadening in the energy spread of the undulator peaks which is most pronounced at high harmonic numbers. Quantitatively, the effect of the field errors can be described by a Debye-Waller type of factor: $I/I_0 = \exp(-n^2\sigma_\phi^2)$, where I is the peak intensity of the actual device, I_0 is the ideal intensity for a perfect undulator, n is the harmonic number and σ_ϕ is the so-called phase error, which is a parameter that quantifies the imperfections in the magnetic lattice.

Premises					Optimized parameters (at 25 keV)					
optimized at energy [keV]	ID type	Magnetic material	Min. gap	ID period [mm]	Used harm.	Brill. at optimal energy	Flux density at opt. E	Flux at optimal energy	Total power [kW]	K max
25-30	Hybrid	SmCo	5.5	20	#13 #11	$3.1\ 10^{17}$ $1.8\ 10^{17}$	$4.1\ 10^{15}$ $2.1\ 10^{15}$	$1.1\ 10^{13}$ $2.1\ 10^{13}$	2.047	1.584
25-30	wiggler Hybrid	NdFeB	11	80	---	$3.2\ 10^{17}$	$5.2\ 10^{16}$	$2.4\ 10^{14}$	8.837	13.16

Table 4. Comparison of a wiggler and in-vacuum undulator optimized in the range 25-30 keV. Brilliance is given in [ph/s/0.1%BW/mm^2/mrad^2], flux density in [ph/s/0.1%BW/mm^2] and flux in [ph/s/0.1%BW]. In the case of the wiggler, flux and flux densities are calculated for a horizontal aperture of 1 mrad, which is the typical horizontal acceptance of a beamline. The optical characteristics of the undulator are shown for the 2 strongest contributing harmonics at 25 keV (the weaker shown in grey). The length of both insertion devices is 2m.



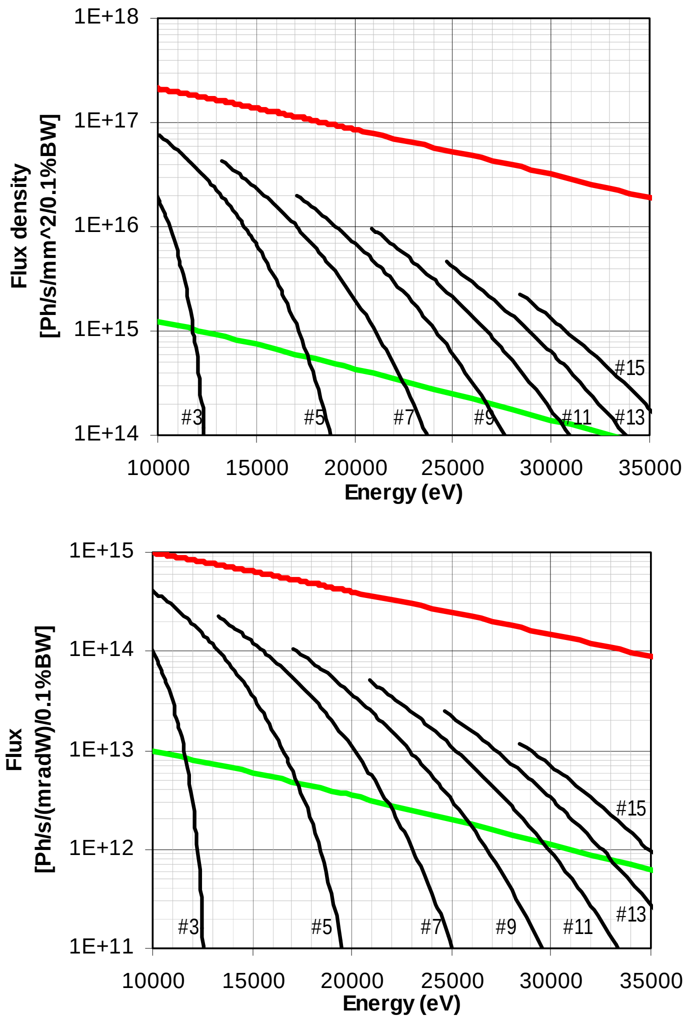


Fig. 6. Beam characteristics of a **SmCo Hybrid in-vacuum undulator**, with a minimum gap of **5.5mm** and a period of λ_u= 20mm (*black*), and a **NdFeB Hybrid wiggler** with a gap of 11mm λ_W= 80 mm (*red*). Both insertion devices are optimized at 20-30keV. Radiation from bending magnets is also shown (green). The bottom plot compares the flux included in the central cone of the undulator, and the flux delivered by the wiggler and bending magnet in a horizontal fan of 1 mrad.

The magnitude of the phase error depends on the quality of the magnetic blocks and on their accurate mounting. By sorting and shimming techniques it can be reduced to low values, typically 2-3 degrees. If we take $\sigma_\phi = 2.5$ degrees, then for harmonics n=11 and 13 one finds I/I_0 = 0.79 and 0.72 respectively. If $\sigma_\phi = 5$ degrees, the above values raise to the 4^{th} power, resulting in 0.38 and 0.27 respectively. This clearly illustrates how important the effects of the imperfections are at high orders. In practice this means that the values of the brilliance in the theoretical curves shown above should be decreased by a significant amount at high harmonic orders.

Comparison of Alba / Soleil undulators

It is illustrative to compare the throughput of insertion devices in similar sources. As an example, we show in figure 7 a comparison between two in-vacuum undulators:

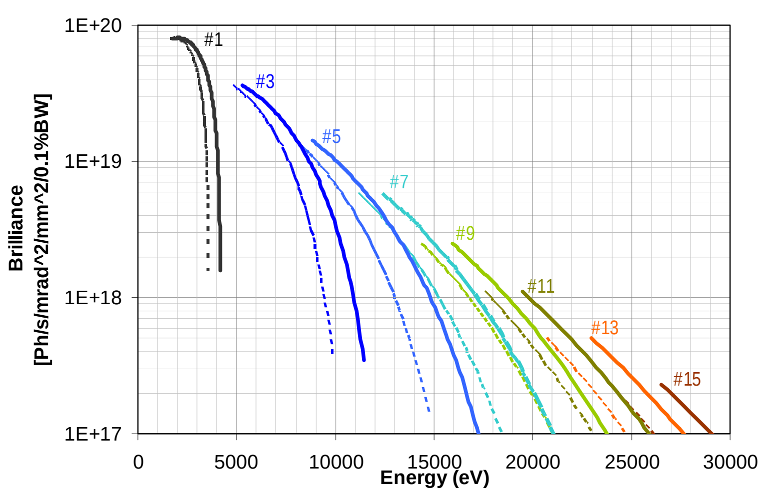
the U20 to be installed in Soleil, and the hypothetical U20.4 undulator of Alba. The results are listed in table 5. For both undulators we have considered a length of 2m and a minimum gap of 5.5 mm.

The in-vacuum undulator U20 will feed several beamlines in Soleil (PROXIMA, CRISTAL, SWING). It is a hybrid type undulator, the magnetic material being SmCo, and optimized for the energy range of 5-15 keV. Although its actual number of periods will be Np=90, for the sake of comparison we have assumed N_p=100, so that the length of both undulators is the same. With respect to the Alba undulator, we have chosen an in-vacuum undulator of the type (i.e. hybrid, made of SmCo as a magnetic material) optimized at 12.4 keV, with a period of 20.4 mm.

The optical characteristics for both undulators are comparable with slight differences. The brilliance is very similar at relatively low energies (less than ~ 6 keV), but at higher energies the brilliance of U20 (Soleil) decreases more than the U20.4 (Alba). For instance, at 25 keV U20.4 is 3 times brighter than U20 for the same harmonic. This is due to the slightly higher electron energy of the Alba machine compared to Soleil (3 and 2.75 GeV, respectively). We should note that both undulators were optimized for lower energies.

Premises					Optimized parameters (at 12.4 keV)						
optimized at energy [keV]	ID type	Magnetic material	Min. gap	ID period [mm]	Used harm.	Brill. at optimal energy	Flux density at opt. E	Flux at optimal energy	Total power [kW]	K max	shown in fig.
12.4	Hybrid	SmCo	5.5	20.4	#7 #5	$5.7\ 10^{18}$ $4.1\ 10^{18}$	$5.0\ 10^{16}$ $2.6\ 10^{16}$	$2.6\ 10^{14}$ $1.4\ 10^{14}$	2.148	1.655	9
5-15	Hybrid	SmCo	5.5	20	#7	$4.3\ 10^{18}$	$1.4\ 10^{16}$	$2.6\ 10^{14}$	3.439	1.584	9

Table 5. Comparison between the U20 at Soleil and the U20.4 in Alba in-vacuum undulators. They are calculated using the short sections of Alba and Soleil machines. Both undulators are supposed to be 2 m long and have a minimum gap of 5.5 mm. Brilliance is given in [ph/s/0.1%BW/mm^2/mrad^2], flux density in [ph/s/0.1%BW/mm^2] and flux in [ph/s/0.1%BW]. The optical characteristics of the U20.4 undulator are shown for the 2 strongest contributing harmonics at 12.4 keV (the weaker shown in grey).



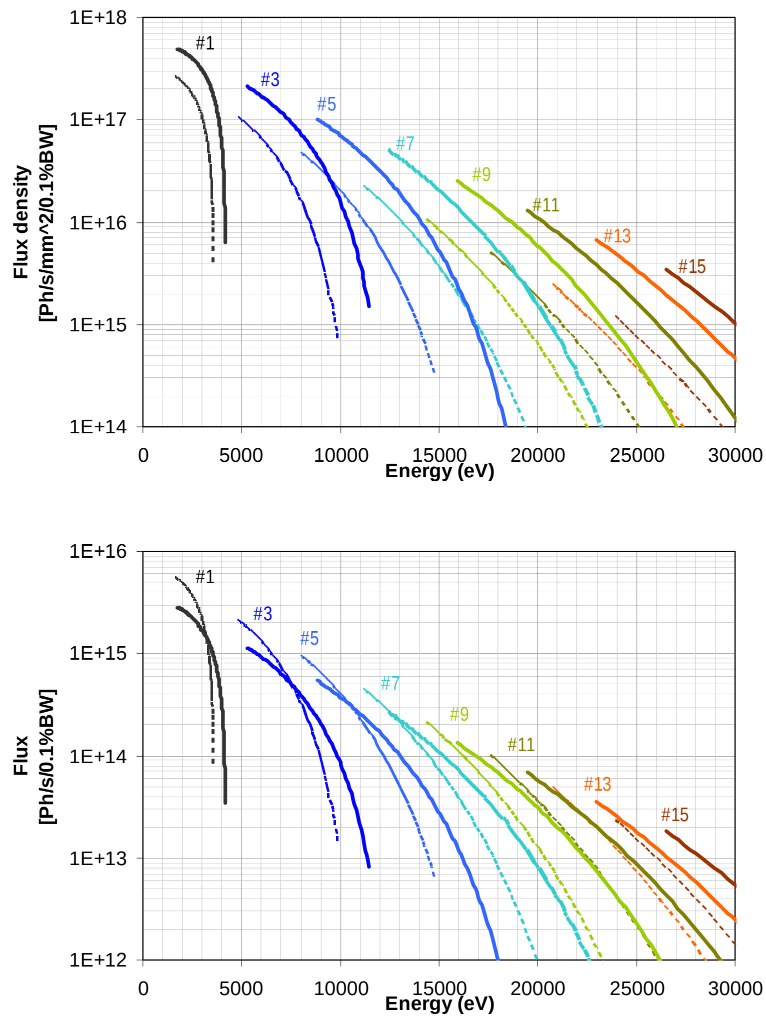


Fig. 7. Comparison of the optical characteristics between the U20 at Soleil (dotted line) and the U20.4 in Alba (continuous line) in-vacuum undulators. Both undulators have a minimum gap of 5.5mm and a length of 2 m.

With regards to the flux density, the advantage is clear for the U20.4 undulator (Alba) by a factor of 5, due to the smaller beam size. However, the situation is the opposite in the case of the flux: the U20 undulator (Soleil) delivers more photons for hν < 10 keV than U20.4 (Alba), due mainly to the higher current stored in the ring.

It is worth noting that at 12.4 keV the brilliance of the #7 harmonic of the U20 undulator (Soleil) is identical to that of the harmonic #5 of U20.4, whilst the brilliance of the harmonic #7 of U20.4 is about the double. Thus Alba will deliver higher brilliance beams at this particular energy since it will work at lower order harmonics than Soleil.

Finally, we note that the power delivered by the U20 undulator (Soleil) is 1.6 times higher than that of the U20.4 (Alba), mostly due to the higher current stored in Soleil (500 mA) with respect to Alba (250 mA). This is not compensated by the slightly higher energy of Alba storage ring compared to Soleil (3 and 2.75, respectively), which accounts only for a 20% more delivered power.