Accelerator Division

Insertion Devices Section

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Title

Tolerances of the HU71 Apple II device for Alba

Abstract

This document contains an extensive description of the different error sources that can affect the light output or the machine physics performance of an HU71 Apple II undulator. First we parameterize the source of errors, after selecting a criterion a tolerance level is defined for each parameter.

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Distribution List

Everybody who asked

History of Changes

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0.1	*20-07-2006*	*19*	*Provisional values in last table introduced (marked in red)*

References

[1]: *Period of Apple II undulator for CELLS (third approach), Zeus Martí.*

[2]: *AAD-SR-ID-AN-0036, "Some theoretical discussions at Elettra", Zeus Martí.*

[3]: *Briane.M.Kincaid, "Random errors in undulators and their effect on the radiation spectrum", J.Opt. Soc. Am. B/Vol. 2,No. 8/August 1985..*

[4]: *Richard P. Walker, "Insertion Devices: Undulators and Wigglers", CERN Accelerator School: Synchrotron radiation and free electron lasers, CERN 98-04, 3 August 1998.*

[5]: *P. Elleaume, "A New Approach to the Electron Beam Dynamics in Undulators and Wigglers", Proc. of the EPAC92, Berlin, March 22-28, 1992.*

[6]: *C. Mullin," Out of Vacuum Insertion Device Modular Support Structures", CLS report num. 5.8.25.1.*

[7]: **"***Request for tender for Design, Supply, Installation Supervision, Commissioning and Performance Demonstration of an APPLE II Insertion Device for a Soft X-Ray Beamline Australian synchrotron project", MPV-SYN-082*

1 Introduction

In the internal report [1] we defined the period, the length and the block size for an Apple II device. This defines all the ideal performances of the undulator. In this internal note, we will study the effect of different sources of errors. Some errors will affect mainly the radiation output, some others the impact on the machine physics. We will define first a parameter describing each type of error, the influence of this parameter will be described through a cost function, and then after once we set a limit value for the cost function we will get a limit value for the parameter defining the source of error.

2 Cost functions

2.1 RMS optical phase error

Hereafter called OPE, this function is very sensible to the non periodicities of the field [2]. It will contribute to the decay of the intensity peak of the radiation. In few words, the non periodicities destroy the interference effect. A global change of the magnetic field all along the ID would not affect the OPE, but a random distribution can cause dramatic decreases of it.

For this Apple II device we will use up to the third harmonic of the radiation. The effect of the phase error at a given harmonic *n* is described by:

$$\frac{\Delta I}{I_0} = e^{-n^2\sigma^2} \qquad (1)$$

Here σ is the RMS of the phase error at each pole point, this distribution is assumed to be Gaussian. It is known [3] that the average value of the magnetic error of the blocks is not directly related with the decay of the peak intensity. We will generate a set of magnetic errors in the blocks to simulate their real characteristics. Typically to characterize these error distributions in a given set of magnets, the maximum error is reported. We will assume square distributions of errors inside our set of magnets. This does not imply a square distribution of phase errors all along the undulator. As said above there is not a direct relation between magnetic errors and phase errors. Next graphs show some calculated optical phase errors histograms along the central part of simulated undulators with a square distribution of magnetization errors.

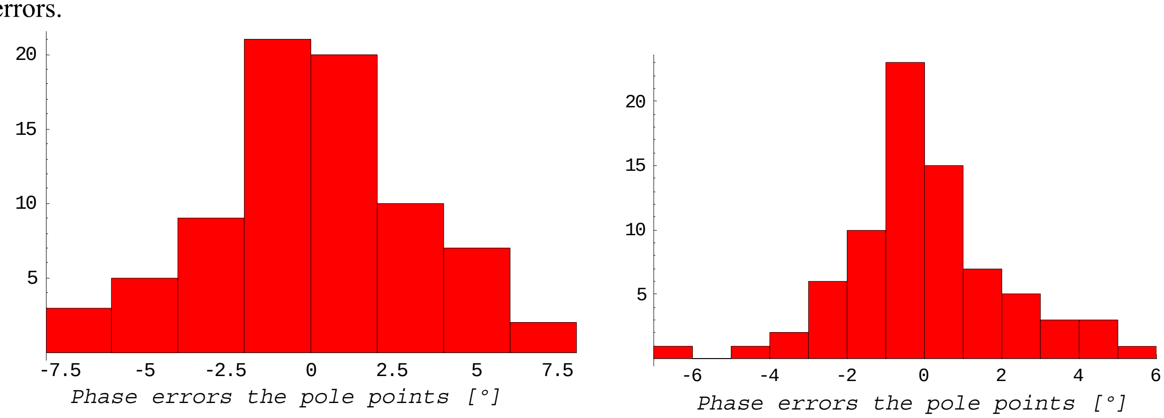

Figure 1: *Two histograms of the phase error distribution in the undulator for two different square distributions of the block magnetization errors.*

We have observed that the phase errors distribution can be assumed to be Gaussian for a square distribution of the field errors. Then equation (1) holds for square field error distributions.

We will accept up to a 1% decay in the photon flux intensity, hence using formula (1) for *n=3,* we conclude that we could accept a OPE up to 2º.

2.2 Stokes parameters

For a given gap and undulator phase a peak of photon flux is expected at a given photon energy and polarization. This flux is distributed in a certain angular cone; polarization is not uniform in this cone. This peak does not entirely act on the sample; a *beam line* is designed to deliver a much better conditioned beam to the sample. In particular, this beam line contains a monochromator. The energy resolution of this monochromator is several orders of magnitude below the width of the radiation peak; a shift in the energy of the peak implies a decay of the intensity that passes through the monochromator.

We will mostly be worried by the global errors. A global error affects in the same way to all the periods of the undulator, it produces a change in the K_x and K_y values of the whole undulator. A Global error in the undulator can move the peak, change the height of the peak and change the degree of polarization of the peak.

Most global errors affect differently K_x and K_y. For example the gap error, undulator phase error, horizontal facing, etc, etc.

For those errors affecting equally K_x and K_y, the linear polarization state in the third harmonic of the radiation will be more sensible. Hence, in this case stokes parameter *s1* [4] will be used as cost function. We will not allow errors above the 1% in *s1*.

In the case of errors affecting unequally the field components, the change of polarization is the main responsible of the loss of useful radiation in the peak. After some comparisons we concluded that the most sensible cost function is the circular Stokes parameter *s3* at circular polarization phase (first harmonic). We will not allow errors above the 1% in *s3*.

2.3 Effects on the electron beam

However in each period we have one positive pole and one negative pole, thus we have a big cancellation of this effect. To evaluate the effect of the bad alignment, we have to consider second order kicks. At second order, the exit angles and positions do not depend only in the first and second field integrals but can be expressed through the function [3]:

$$U(x,z,1\,period)=\int_{-\frac{\lambda}{2}}^{\frac{\lambda}{2}}\left(\left(\int_{-\infty}^{s'}B_x ds\right)^2+\left(\int_{-\infty}^{s'}B_z ds\right)^2\right)ds'$$

Here, *x* is the horizontal direction, *z* the vertical and *s* is the integration variable along the electron motion. This function can be evaluated in just one period if, as in the case of the roll, all periods are identical. In this case however, not all periods can be considerer identical, and the function to calculate is:

$$U(x,z)=\int_{-\infty}^{\infty}\left(\left(\int_{-\infty}^{s'}B_x ds\right)^2+\left(\int_{-\infty}^{s'}B_z ds\right)^2\right)ds' \qquad (1)$$

Then we have to study both phase error and the effect on the electron beam.

3 Sources of error

3.1 Beam parallelism

The parallelism between the two beams can be defined with six degrees of freedom. There are three planes of rotation, and for each plane one angle per beam. How ever, it is preferable to refer the plane position to real surfaces, for example referring the angular position of one beam to the other. Then the two degrees of freedom per plane are distributed into two angles, the angle between beams θ, and the angle φ between the mid plane of the beams and the electron beam. Each one of the planes of rotations takes usually one particular name: roll, yaw and pitch.

3.1.1 Pitch (tapering error)

Figure 1 shows schematically the definition of the pitch, the rotation plane is perpendicular to the horizontal axis (*x* axis in our reference system).

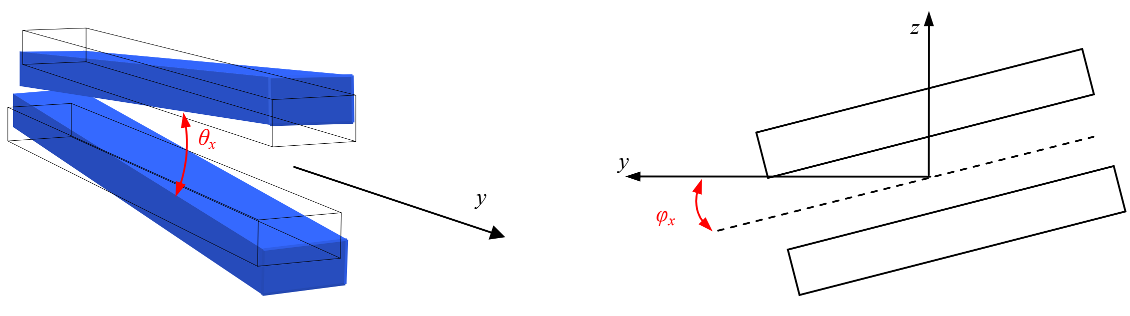

Figure 2: *Pitch angles θ_x and φ_x definition.*

Our Apple II undulator will have four motors to control the gap motion and the tapering, and each motor will have an absolute linear encoder associated. Both θ_x and φ_x can have an origin in the error in the encoder reading or in the mechanical non elastic behaviour.

3.1.1.1 θ_x

The effect of the tapering is the broadening of the interference peak, and hence produces a decay in the photon flux. OPE is the cost function considered.

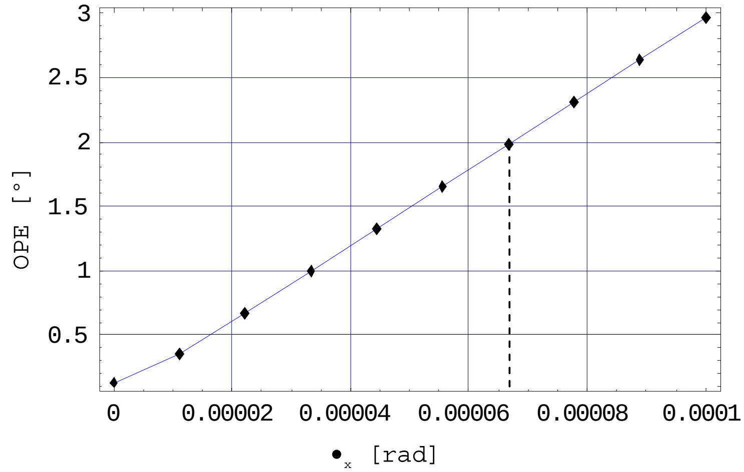

Figure 3: *Optical Phase error vs. tapering angle.*

With this criterion the maximum allowed unwanted tapering is *65 μrad*.

3.1.1.2 φ_x

In this case, not only phase error is affected, in the extremities of the undulator, a quadrupolar component arises. Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature.

3.1.2 Yaw

Figure 3 shows schematically the definition of the yaw, the rotation plane is perpendicular to the vertical axis (*z* axis in our reference system).

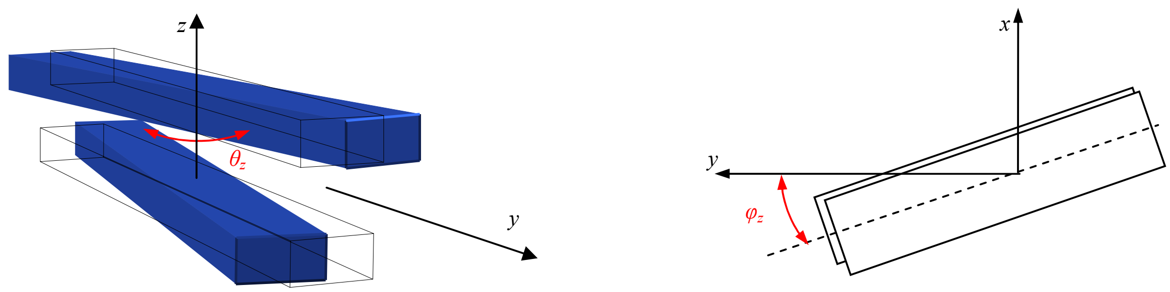

Figure 4: *Yaw angles* θ_x *and* φ_x *definition.*

In the case of the Apple II there exist some torsion momentums that can cause this type of deformations; also a bad mounting could produce this type of error.

3.1.2.1 θ_z

As in the previous case, this effect has an impact in the periodicity of the undulator; the periods at the sides will have a different magnetic field. Phase error will be used again to set the tolerances to this type of error. In this case, the undulator phase has an impact on the result. In linear polarization the device is much less sensible to this error, the phase error is calculated at circular polarization mode. We will allow only a 1% decay of the ideal flux. When using the third harmonic of the radiation, a 1% decay of the peak means that a phase error of up to 2º is allowed.

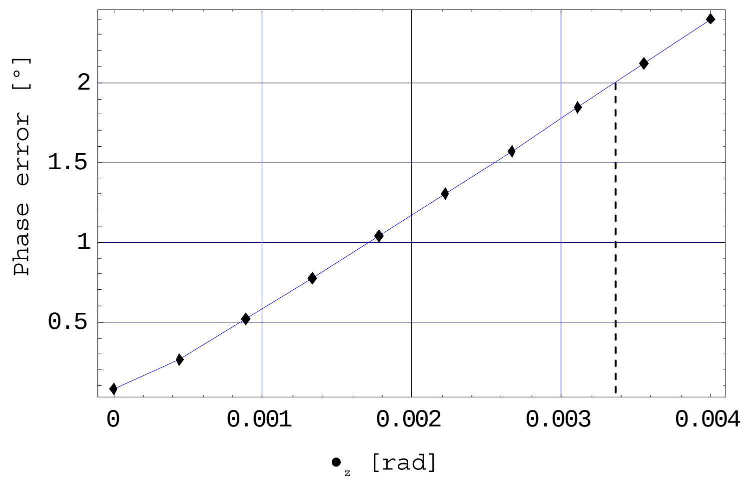

Figure 5: *Phase error vs. tapering angle.*

Following the criterion defined above, the tolerance for the θ_z yaw is *3.4 mrad*. However, beam dynamics calculations give a more restrictive value. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature.

3.1.2.2 φ_z

If both lower and upper beams are parallel but the mid plane is not aligned to the electron beam, we loss periodicity, and also multipolar components arise at the extremities of the insertion device. Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature.

3.1.3 Roll

Figure 5 shows schematically the definition of the roll, the rotation plane is perpendicular to the longitudinal axis (*y* axis in our reference system).

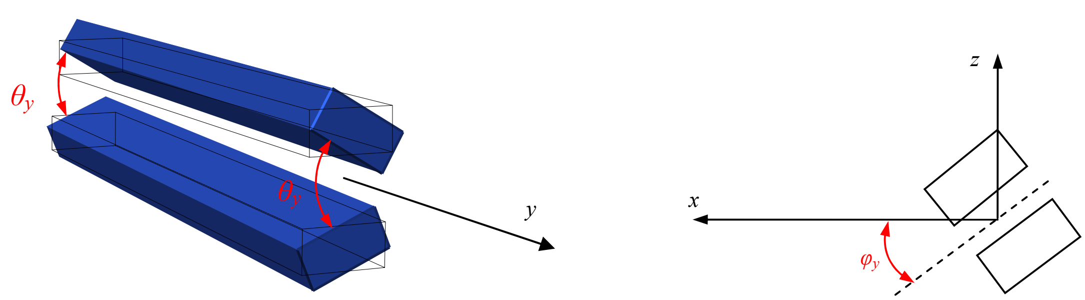

Figure 6: *Roll angles θ_y and φ_y definition.*

A roll of the beams can be due to a bad mounting or to the action of the magnetic forces.

3.1.3.1 θ_y

In this case, the phase error is almost not influenced by this parameter, all periods are still the same and the magnetic field on axis almost does not change. The main effect is out of axis, a magnetic field quadrupole is introduced in each pole. This will affect the machine through the expression given in (1). Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature.

3.1.3.2 φ_y

This may be produced by a bad alignment of the undulator. This parameter does not influence the phase error neither the effect of the machine. By it self it only introduces a change in the polarization, this effect can be avoided by an appropriated calibration of the undulator in the commissioning.

3.2 Beam position

As in the case of the parallelism, the beams position can be defined with six degrees of freedom. For each of the three main directions, there is one degree of freedom per each one of the two beams. Again the two degrees of freedom per direction can be reorganized into two more suitable variables. One variable is the separation between the two arrays, and the other the separation of the mid plane with the electrons orbit.

3.2.1 Vertical direction

The two variables that we will treat are the gap error and the vertical centring of the undulator.

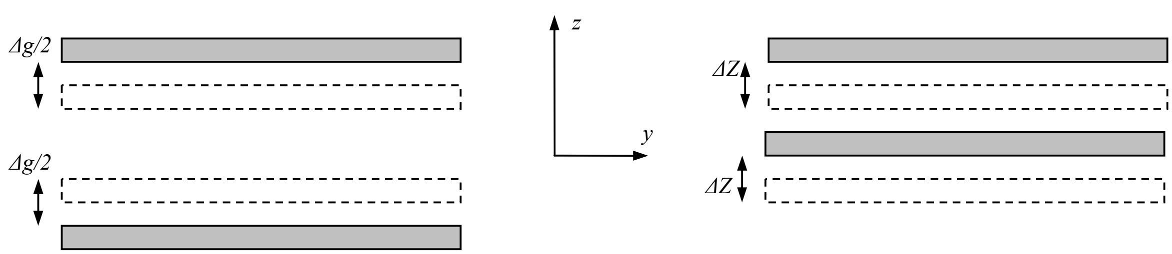

Figure 7: *Schematical definition of the gap error Δg and the global vertical error ΔZ.*

3.2.1.1 Gap error

Each one of the four motors dedicated to the gap movement has a linear absolute encoder associated. What matters to the experimentalists is the repeatability, this means, the error that one will have when moving the gap and returning it to the previous position. This error is generated by the repeatability of the reading of the encoders and by the non elastic behaviour of the beam (the encoder will read the position of one point of the beam, it is not sensible to a plastic bending of the beams).

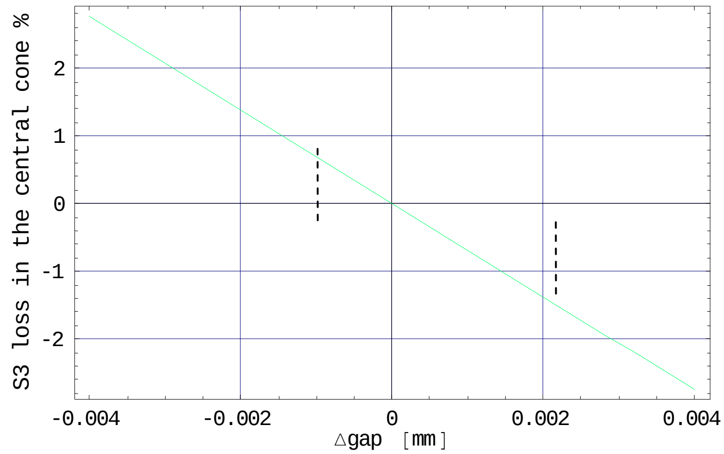

***Figure 8**: s3 loss in the central cone vs. phase error.*

Form the data shown in the previous graph we deduce a tolerance for the gap movement of *1.5 μm*.

3.2.1.2 Vertical centring

The periodicity remains unaffected by this type of error, the vertical magnetic field will increase, a longitudinal magnetic field will appear and a gradient respect to the vertical direction will also appear. Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature.

3.2.2 Longitudinal direction

The global longitudinal position of the undulator is not an issue, and then the only important parameter regarding the longitudinal direction is the longitudinal facing.

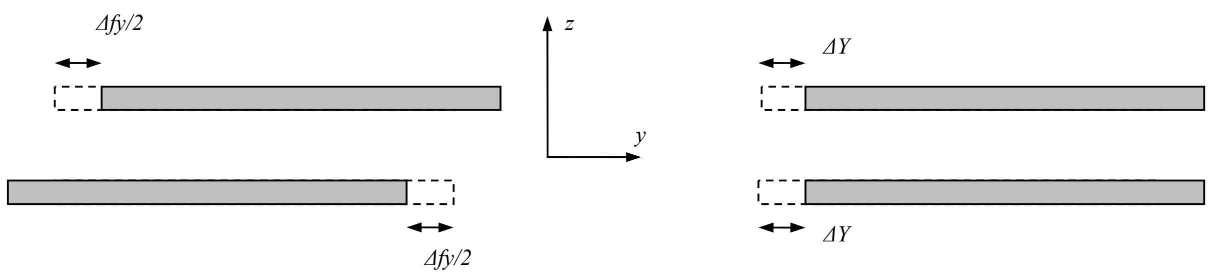

***Figure 9:** Schematically defined longitudinal facing error Δfy and global longitudinal error ΔY.*

3.2.2.1 Longitudinal facing

This error does not affect the periodicity of the magnetic field; hence optical phase error is not a good function of merit in this case. The distribution of the field is affected by this facing error, mainly; a gradient appears in the vertical field and the horizontal field is decreased. If we can not control this error, and it changes each time we change the phase or the gap, we will have an uncontrolled flux oscillation. The most critical is *s1* in vertical polarization.

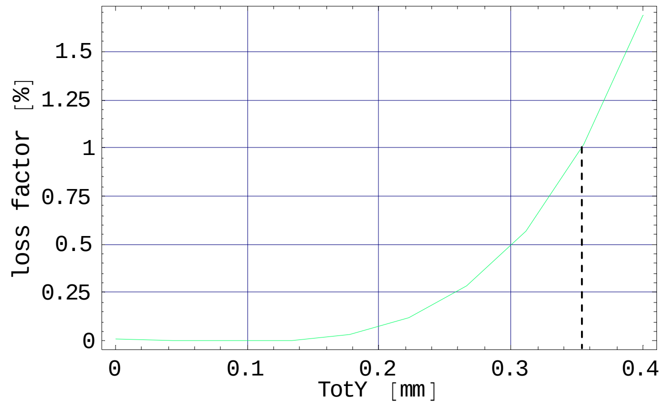

***Figure 8**: s1 loss in the central cone vs. Δfy/2*

This establishes a tolerance of 350 µm for *Δfy/2*. This type of error will also affect the machine through the expression given in (1). Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature, which is more restrictive than the number obtained here.

3.2.2.2 Longitudinal centring

This type of error does not affect the periodicity neither the effect on the machine. We do not tolerance it.

3.2.3 Horizontal direction

Here a global horizontal misalignment of the undulator and a horizontal phasing error are treated separately.

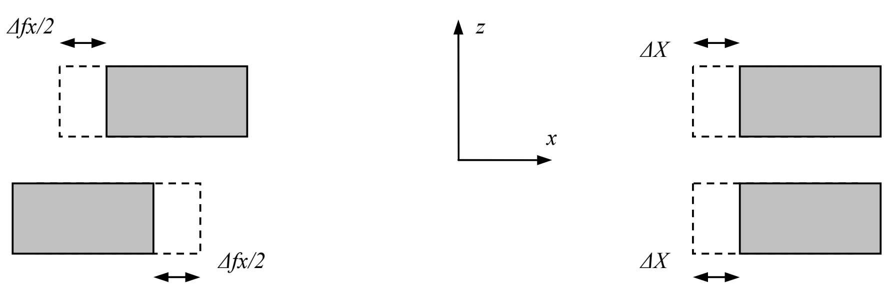

***Figure 10:** Schematically defined horizontal facing error Δfx and global longitudinal error ΔY.*

3.2.3.1 Horizontal facing

This error does not affect the periodicity of the magnetic field; hence optical phase error is not a good function of merit in this case. The distribution of the field is affected by this facing error, mainly; the vertical peak field is increased and shifted in the longitudinal direction and the horizontal field is decreased and it's roll of is decreased. If can not control this effect, it will generate an uncontrolled change of polarization. The most critical is *s1* in vertical polarization.

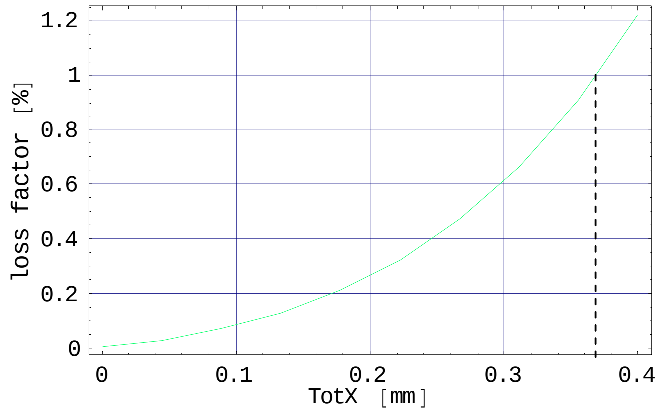

Figure 8*: s1 loss in the central cone vs. Δfx/2*

This establishes a tolerance of 365 µm for *Δfx/2*. However, this type of error will also affect the machine through the expression given in (1). Beam dynamics calculations are required to refine this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature, which is more restrictive than the number obtained here.

3.2.3.2 Horizontal centring

This error does not affect the periodicity of the magnetic field; hence optical phase error is not a good function of merit in this case. The distribution of the field is affected by this positioning error, the field distribution is shifted at one side, and this implies a reduction of the horizontal field and a linear term on it. If can not control this effect, it will generate an uncontrolled change of polarization. The most critical is *s1* in vertical polarization.

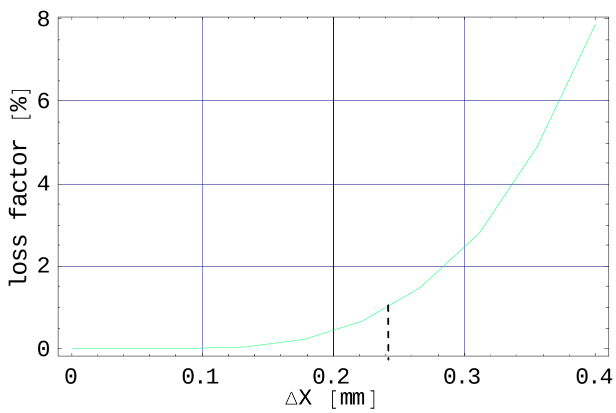

Figure 8*: s1 loss in the central cone vs. ΔX*

This establishes a tolerance of 240 µm for *ΔX*. This type of error will also affect the machine through the expression given in (1). Beam dynamics calculations are required to find this tolerance. This calculation is out of the scope of this document. In table 3 we give the number given usually in the literature, which is more restrictive than the number obtained here.

3.3 Phase error

This error can't be included in the beam's movement tolerances, but is important to set the properties of the motors and the cinematic chain that links them to the phase movement. Again, the error of the encoder's reading and the plastic deformation of the structure will be the cause of such error. The most critical point is the circular polarization point, again the s3 stokes parameter will be used as cost function. We will not allow errors above the 1% in *s3*.

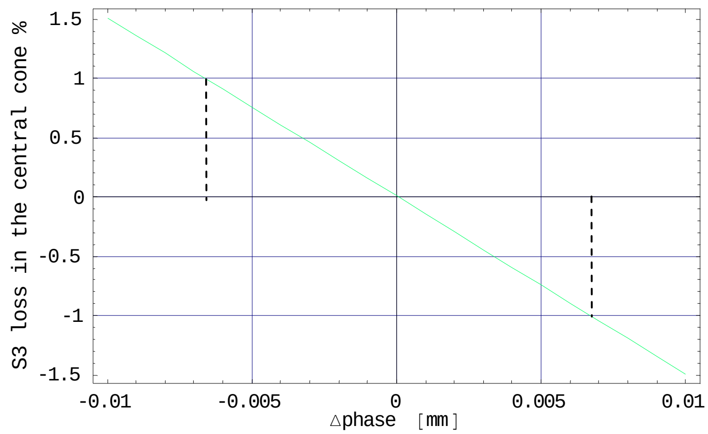

Figure 11*: s3 loss in the central cone vs. phase error.*

With the chosen restrictions, the repeatability for the phase movement should not exceed *7 μm*.

3.4 Block positions

The roughness of the different surfaces and mounting errors will produce random displacements of the blocks centres in all three directions. Again, this will have mainly an impact on the phase error. One parameter that could describe the roughness is the maximum bloc displacement (a flat displacement distribution is assumed), but the phase error not only depends on the block displacements but also on how these displacements are distributed all along the insertion device. To avoid this dependence, for each maximum block displacement we will generate 100 randomly chosen displacements distributions. The cost function that we will consider is the maximum phase error generated in this set of 100 cases. Also in this case we will allow a maximum phase error of 2º.

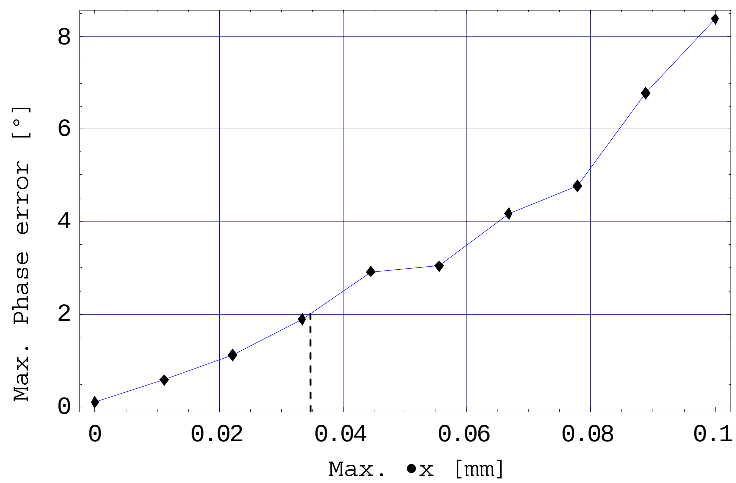

Figure 12*: Maximum phase error vs. maximum block horizontal off centre.*

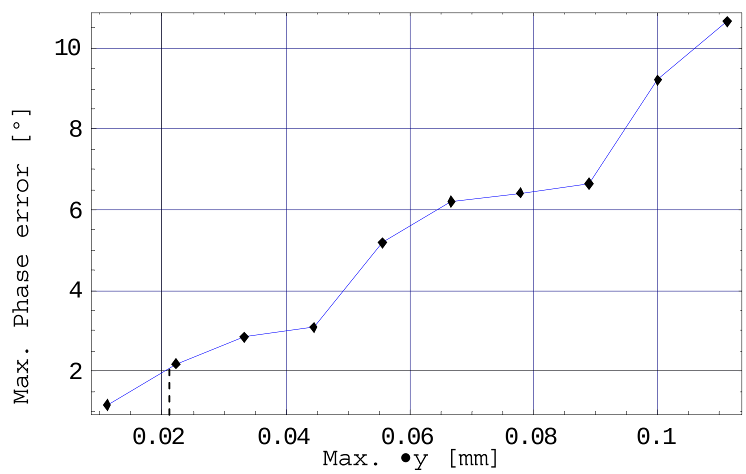

Figure 13*: Maximum phase error vs. maximum block longitudinal off centre.*

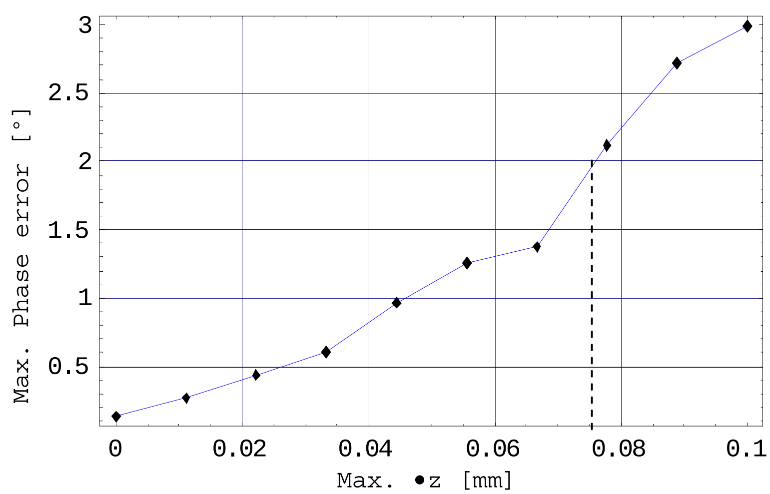

Figure 14*: Maximum phase error vs. maximum block vertical off centre.*

From that graphs one can deduce the tolerances of the system:

Δx [mm]	**Δy [mm]**	**Δz [mm]**
0.035	0.020	0.078

***Table 1**: Block centring tolerances.*

3.5 Block dimensions

The magnets suppliers will have limits for they tolerances on the blocks dimensions. In this section we will evaluate how this can impact the undulator performance. Again, we will assume a set of 100 flat distributions of block size errors. The cost function that will evaluate the how harmful is each maximum block size error is the maximum phase error of the 100 cases simulated. Also in this case we will allow a maximum phase error of 2º.

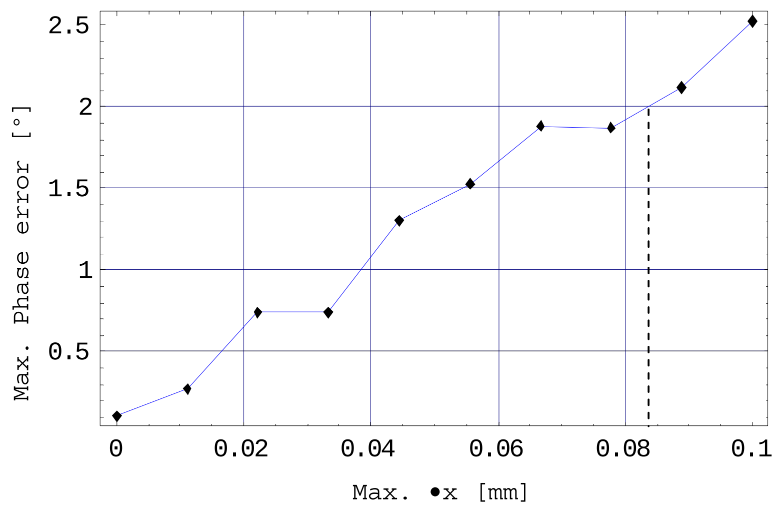

***Figure 15**: Maximum phase error vs. maximum block horizontal size error.*

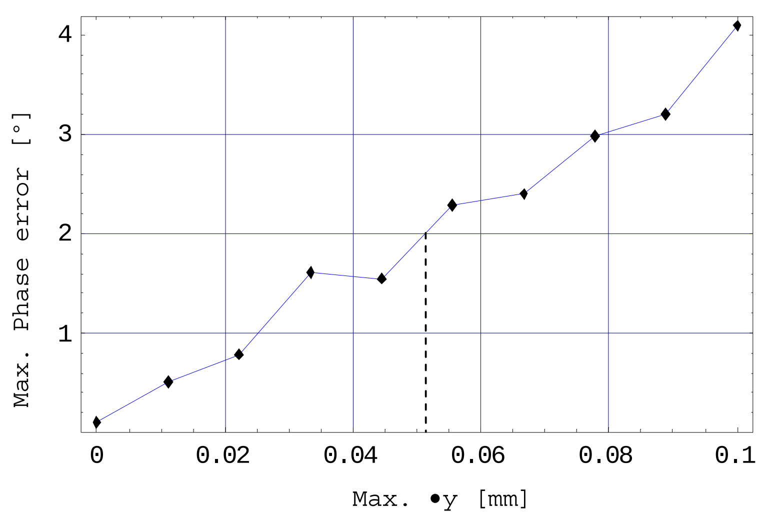

***Figure 16**: Maximum phase error vs. maximum block longitudinal size error.*

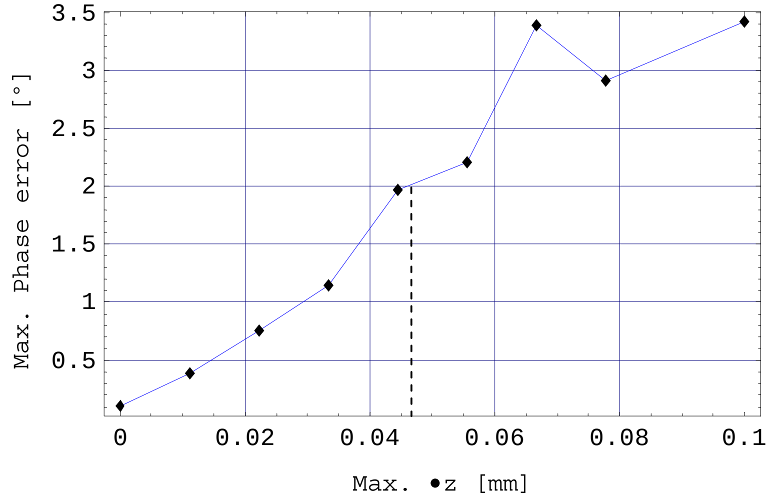

Figure 17*: Maximum phase error vs. maximum block vertical size error.*

From that graphs one can deduce the tolerances of the system:

Δx [mm]	Δy [mm]	Δz [mm]
0.082	0.050	0.043

Table *: Block size tolerances.*

3.6 Blocks magnetic properties

In general, the direction of magnetization of the blocks won't be absolutely parallel to the ideal direction. Minor components perpendicular to the main axis of magnetization can affect directly the periodicity along the undulator. Also not all block will have exactly the same magnetization, a given distribution of weak and strong magnets along the undulator will affect the periodicity of the magnetic field in the central orbit. Finally some calculations have to be performed to ensure that the magnets will not be demagnetized, the demagnetizing field have to be calculated.

3.6.1 Angle of magnetization

We will choose spherical coordinates to describe this error: polar angle θ has a flat distribution between 0 and a given maximum error (this angle is defined respect to the direction of magnetization of each block), while the azimuthal angle is left to be randomly distributed between –180 and 180 degrees. As the loss of periodicity is the main effect, we will use again the Phase error as cost function. Again, 100 randomly chosen cases are generated for each maximum polar angle error allowed.

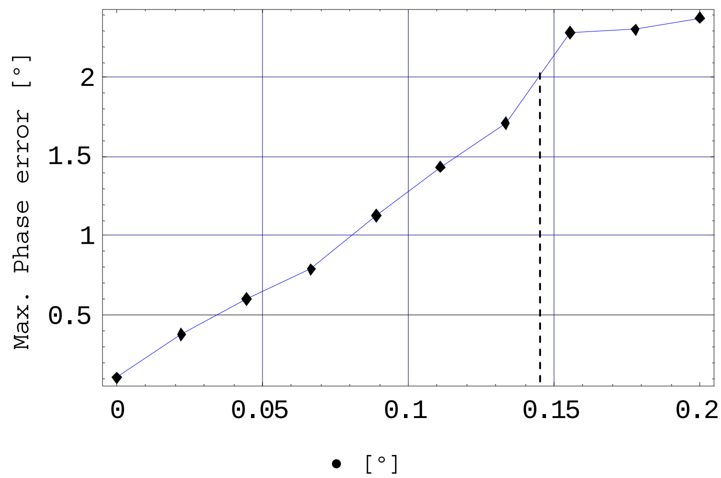

Figure 18*: Maximum phase error vs. maximum block magnetization angle error.*

From the graph one can deduce the tolerance of the system to the magnetization angle: *0.145 º*. Usual manufacture tolerances are around 1.5º. It is not simple to predict in advance which will be the relaxation in this tolerance that an appropriate sorting will bring.

Taking the maximum phase error of a set of 100 cases simulates a situation where we are blind to the distribution of blocks. The previous result indicates that to be insensible to the magnetization angle error of the blocks, this error has to be below 0.145º, which is practically impossible. To simulate the sorting stage, we will take the minimum phase error of the 100 cases set.

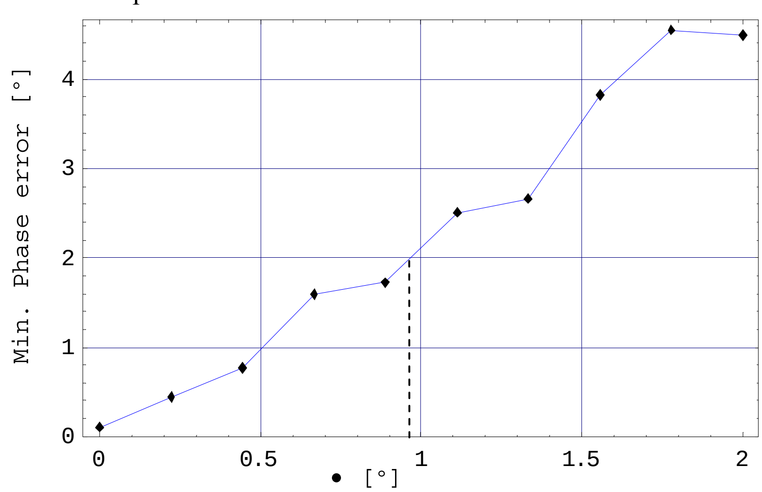

Figure 19*: Minimum phase error vs. maximum block magnetization angle error.*

With this new cost function, the limit of 2º for the optical phase error leads to an allowed maximum magnetization angle error of 0.95º, which is much closer to the usual tolerances, typically between 1º and 3º.

3.6.2 *Magnetization*

The magnetic field used to magnetize the blocks may have a random error component. The blocks may present different microscopic structures. These small differences make that, at a certain level, blocks present different magnetizations. This will affect again the periodicity of the magnetic field at the central orbit. The same procedure than with the angle will be applied, the cost function is defined as the maximum phase error of a set of 100 cases with a given maximum magnetization error.

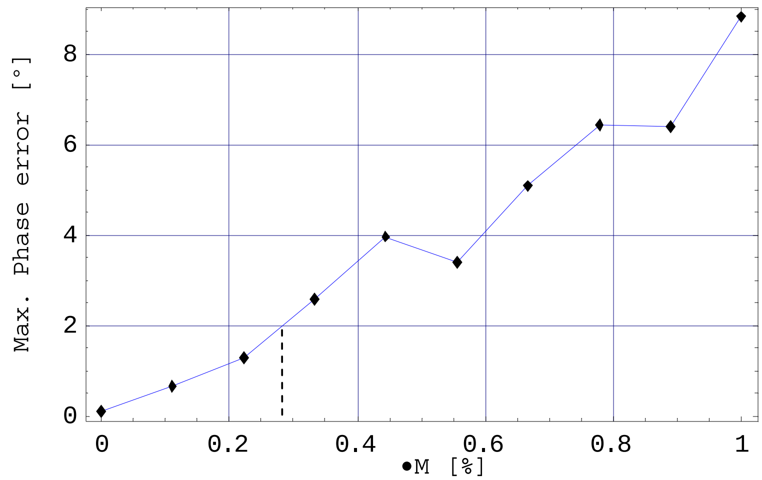

***Figure 20**: Maximum phase error vs. maximum block magnetization angle error.*

Following the criterion above described lead us to a tolerance in the magnetization error of *0.27 %*. This value is quite below the 1% which is usually guaranteed for the block manufacturers. Again, we can't ignore this magnitude just by setting the tolerances; we will assume that the minimum phase error of 100 cases is a representative value of the minimum achievable optical phase error after sorting.

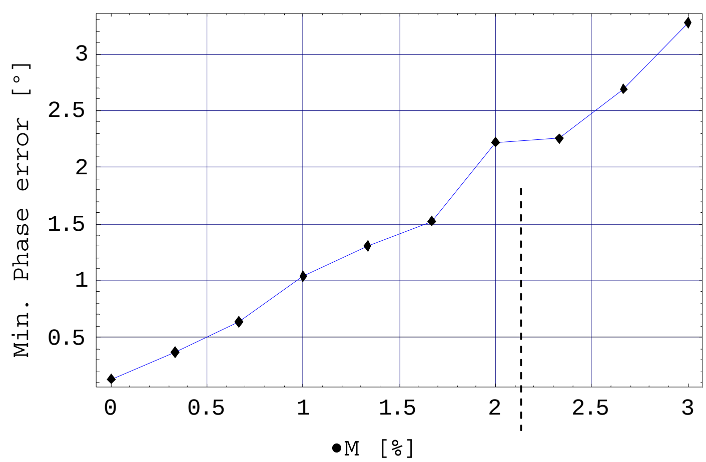

***Figure 21**: Minimum phase error vs. maximum block magnetization angle error.*

Also in this case, we recover much more reasonable values for the maximum allowed magnetization error. Tolerance is set to 1.9%.

3.6.3 Coercitivity

The maximum demagnetizing field has to be calculated. In the case of the Apple, it is not clear, a priori, which is the phase and gap configuration that gives the worst demagnetising field in the magnets. After some comparisons, one can see that at maximum gap and zero phase the demagnetizing fields are maximal. For the vertical polarized blocks, the most dangerous zone is the plane facing outside the gap, while for the horizontally polarized blocks; the most dangerous zone is the plane facing the gap.

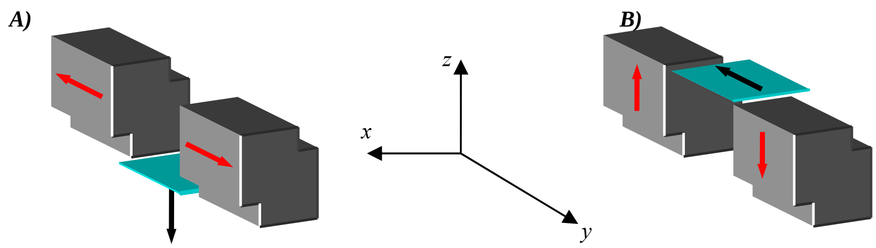

Figure 22: *A) Blocks that generate the most of the demagnetizing field of a vertically magnetized bloc. B) Blocks that generate most of the demagnetizing field of a horizontally magnetized bloc. In blue the plane where the demagnetizing field is calculated, in black the direction of the non demagnetizing field.*

Next figures show the values of the demagnetizing field in the most critical surfaces for each type of magnet.

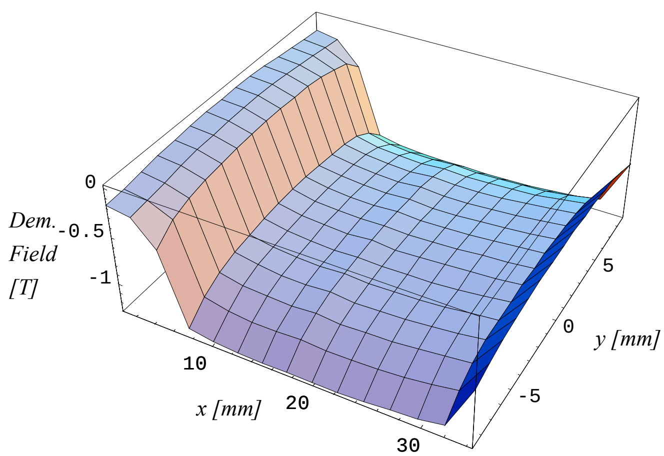

Figure 23: *Demagnetizing field in the plane facing outside the gap of a vertically magnetized block. A negative sing indicates that the field has an opposite direction to the magnetization.*

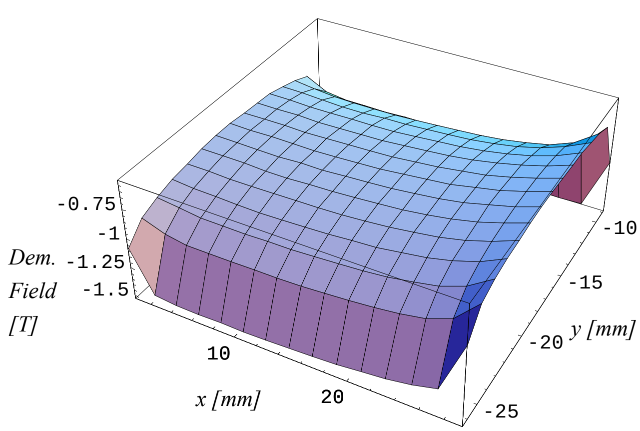

Figure 24: *Demagnetizing field in the plane facing the gap of a horizontally magnetized block. A negative sing indicates that the field has an opposite direction to the magnetization.*

Form the data exposed here we know that the magnets are exposed to demagnetizing fields up to 1.5 T.

4 Summary of tolerances

In Table 3 below we present the mechanical and magnetic tolerances required for Apple-II devices designed to feed XMCD and PEEM beamlines at ALBA. Red figures correspond to tolerances taken from the literature referred in each case.

Error		Cost function	Maximum allowance in cost function	Tolerance	Reference
Beam Parallelism	θ_x	Optical Phase error	2 º	*65 μrad*	
	φ_x			*100 μrad*	[6]
	θ_y			*300 μrad*	[6]
	φ_y	-	-	-	
	θ_z			*400 μrad*	[6]
	φ_z			*400 μrad*	[6]
Beam Position	Gap error	S3	1 %	*1.5 μm*	
	Vertical centring			*10 μm*	[6]
	Long. facing			*100 μm*	[7]
	Long. centring	-	-	-	
	Hor. facing			*20 μm*	[6]
	Hor. centring			*20 μm*	[6]
Undulator Phase		S3	1 %	*7 μm*	
Block Position	Δx	Optical Phase error	2 º	*35 μm*	
	Δy	Optical Phase error	2 º	*20 μm*	
	Δz	Optical Phase error	2 º	*78 μm*	
Block dimensions	Δx	Optical Phase error	2 º	*82 μm*	
	Δy	Optical Phase error	2 º	*50 μm*	
	Δz	Optical Phase error	2 º	*43 μm*	
Block magnetic properties	Angle	Optical Phase error	2 º	*0.95 º*	
	Magnetization	Optical Phase error	2 º	*1.9 %*	
	Coercitivity	-	-	*15 kOe*	

Table 3: *Tolerances for the HU 71*