PHASE SHIFTERS FOR THE SPARC UNDULATOR SYSTEM

Giovanni Parisi, Franco Ciocci, Giuseppe Dattoli, Luca Giannessi*, Gueorgui Kirilov Voykov
ENEA, Centro Ricerche Frascati, C.P. 65, 00044 Frascati, Italy

Abstract

In the framework of the SPARC FEL experiment [1], a 14-m long undulator divided into six segments is presently under construction (by ACCEL Instruments GmbH). In order to correct the phase difference between the electron beam and the radiation at the end of each undulator segment, a tunable phase shifter is under development.

In this paper we present results from beam dynamics simulation, which show the impact of the phase mismatch on the FEL, and a preliminary design of the phase shifter device for SPARC.

INTRODUCTION

In a single-pass FEL designed with segmented undulator, the gaps between each undulator segment introduce a phase shift between the electron transverse velocity and the phase of the electromagnetic field. Such a phase mismatch causes the electrons to momentarily gain energy from the radiation field, interrupting the amplification process. The phase shift ϕ induced by a drift L_d between two segments is a function of the undulator K parameter

$$\phi = \frac{L_d}{2\gamma^2 \lambda_0} = \frac{L_d}{\lambda_u \left(1 + K^2/2\right)} \qquad (1)$$

The SPARC undulator [2] is a variable gap device where the K parameter may be varied in the range indicated in Tab. 1, which lists the SPARC undulator parameters.

Table 1: Main SPARC undulator parameters

Period length (mm)	28
Periods per segment	77
Segment length (mm)	2156
Undulator segments	6
Gap between segments (mm)	392
Undulator strength K	2.3 – 0.3

The main effect of a phase mismatch on the FEL dynamics is an increase of the saturation length[3]. In order to compensate the phase error between two undulator segments in a variable gap device, a variable phase shifter is required. In this contribution we have analysed the effects of phase mismatch at SPARC and we present the design of compact phase shifters based on permanent magnets.

EFFECTS OF PHASE MISMATCH

The effect of a phase mismatch at the five breaks between the six undulators of the SPARC FEL is shown in Fig. 1. The time dependent simulation has been obtained with PERSEO[4] with the electron beam parameters listed in Tab. 2. The breaks between the undulators have been simulated by multiplying the laser field by a phase factor $\exp(i\phi)$ at each break location.

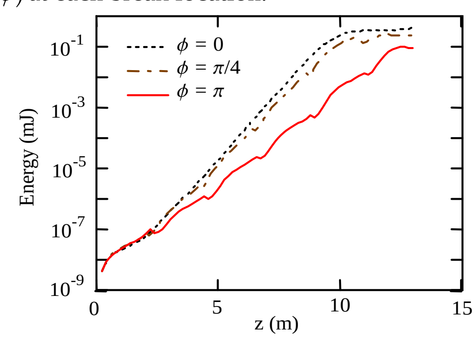

Figure 1: Energy along the SPARC undulator for different phase shifts ϕ at the gaps, in <u>SASE mode</u> (λ = 500 nm).

Table 2: Beam parameters of the SPARC FEL operating in SASE mode.

Resonant wavelength (nm)	500
Peak current (A)	110
Beam energy (MeV)	155.3
Energy spread (%)	0.1
Emittance (mm-mrad)	1
Undulator strength K	2.14

The effect of the phase mismatch is that of increasing the saturation length, and a phase mismatch of π is almost sufficient to inhibit the saturation process within the SPARC undulator length.

Phase mismatches are even more effective in the case of seeded operation. In Fig. 2 it is shown the case of the SPARC FEL seeded at 160 nm. The parameters used in this simulation are listed in Tab.3. It can be observed that a phase mismatch of π induces a loss of about two orders of magnitude in the pulse energy. A phase mismatch has also significant effects on the spectrum of the seeded FEL source, which is not any more resembling those of the input seed (see Fig. 5).

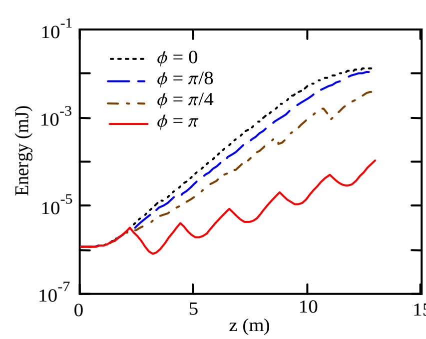

Figure 2: Energy along the SPARC undulator for different phase shifts ϕ at the gaps, in <u>seeded mode</u> (λ = 160 nm, 15 kW input power, 100 fs pulse duration).

* giannessi@frascati.enea.it

Table 3: Parameters of the seeded mode (first case)

Resonant wavelength (nm)	160
Energy spread (%)	0.1
Undulator strength K	1.226
Seed wavelength (nm)	160
Seed pulse energy (nJ)	1.7
Seed pulse duration (fs)	100

Phase shifters are required to compensate the phase mismatch in order to avoid the above mentioned problems, but may be used to add further flexibility to the undulator as it will be shown in the following example. Phase shifter can be indeed exploited to balance the growth of different harmonics of the FEL resonant wavelength [5]. The SPARC undulator may be seeded at 88 nm (9^{th} harmonic of the Ti:Sa laser) which corresponds to the third harmonic of the undulator set with the fundamental resonance tuned at 264 nm. The parameters used in the simulation of this example are listed in Tab. 4.

Table 4: Parameters of the seeded mode (second case)

Resonant wavelength (nm)	264
Peak current (A)	110
Beam energy (MeV)	200
Energy spread (%)	0.04
Undulator strength K	1.945
Seed wavelength (nm)	88
Seed pulse energy (nJ)	0.5
Seed pulse duration (fs)	100

In Fig. 3 it is shown that the growth of the fundamental harmonic (dashed line) may be suppressed by phase shifts which are calculated to leave the third harmonic unperturbed. The third harmonic operates in seeded mode, with the seed at the wavelength of 88 nm. Seeding at this wavelength would not be otherwise possible because the SASE growth of the fundamental approaching saturation faster than the third harmonic would overwhelm the effect of the seed at the third harmonic.

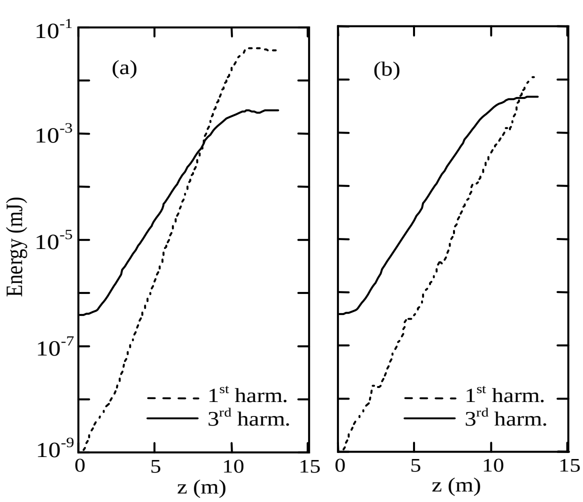

Figure 3: Pulse energy along the SPARC undulator in seeded mode at the third harmonic (λ = 88 nm, corresponding to a FEL resonance at 264 nm). In (a) phase does not change at each gap. In (b) phase shifts $\phi = \pm 2\pi/3$, with alternated sign, are introduced at each gap.

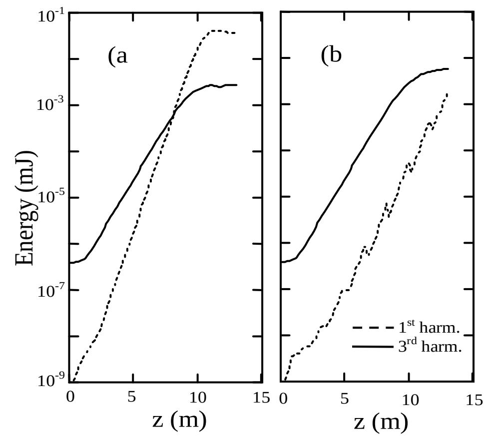

Figure 4: Pulse energy vs. longitudinal coordinate along the undulator. In (a) phase does not change along the undulator. In (b) phase shifts $\phi = \pm 2\pi/3$ every 30 periods, with alternated sign, are introduced.

The gain length at SPARC is of about 60cm. In this condition a phase shift imposed at the undulator gaps, located at approximately 2.4 m of distance is only partially effective in suppressing the radiation at the fundamental harmonic. In fig.4 it is shown an example where phase shifts are located at every 30 periods and the fundamental harmonic suppression is more evident. In fig.5 it is shown the spectrum in this latter case at the undulator exit for the fundamental and the third harmonic with phase shifts on and off. With the shifts on SASE at the fundamental is suppressed and the third harmonic spectrum reproduces the seed spectrum.

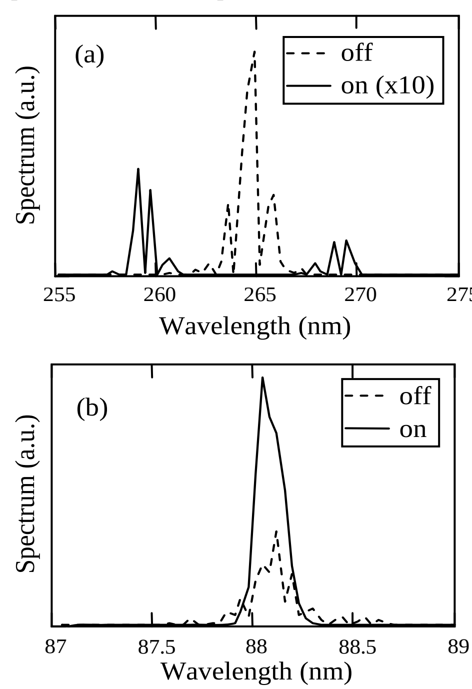

Figure 5: First (a) and third (b) harmonic spectrum at the end of the undulator with (continuous line) and without (dashed line) phase shifts. In (a) the first harmonic spectrum suppressed by the shifts has been multiplied by a factor 10.

PHASE SHIFTER'S REQUIREMENTS

A phase shift is obtained by a magnetic chicane that delays the beam due to a longer path, which in principle may be realized as in the main undulator, with the same kind of permanent magnets, in a similar arrangement. The undulator is indeed capable of inducing a phase advance of 2π for each period. The possibility to vary the gap of this device, i.e. the electron beam path length, independently from that of the undulator allows to compensate for a given phase difference. The main requirement for such a phase corrector is that the field integrals must vanish at any gap. We have considered two magnetic configurations capable of adjusting the phase and to fulfil the requirements in terms of field integrals. Both the phase shifters consists of two groups of permanent magnets, arranged as in the main undulator in a variable gap magnet assembly. The simplest way to get this is to use a whole undulator period (four magnets). The period of the undulator is 28 mm and it consists of four magnets with different magnetization axes; each magnet is 6.95 mm long and the magnets are assumed to be separated by a 50 μm gap.

Due to symmetry reasons, it is necessary to start and terminate the period with a lower field. We have analysed two different field terminations: in the first one, the ending magnets have the same width but a reduced height (i.e. horizontally cut); in the second one, they are shorter (i.e. vertically cut). Both solutions are analysed hereafter.

FIRST CONFIGURATION

In order to make the first and second field integral equal to zero, a possibility is to model the phase shifter terminations in a typical 25%-25%-75%-75% way, as it is shown in Fig.6. In this case at least seven magnets are needed to fulfil the requirement on field integrals. Since only three magnets are available at each side of the device, we used a 25%-37%-75% shaping and managed to get the first and second field integral equal to zero at the nominal gap (9.3 mm); the second field integral is still slightly gap dependent, but it remains within the tolerances. Simulations were performed with RADIA code [6].

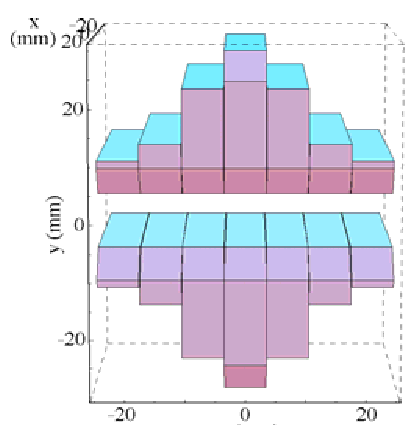

Figure 6: First configuration for the phase shifter (seven horizontally cut magnets); the total length is 49 mm.

The vertical component of the magnetic field at the nominal gap, as well as the first and second field integrals, are shown in Figs.7 and 8.

The second field integral and the achievable phase correction as a function of the gap are shown in Figs. 9 and 10. Notice that increasing the gap from 9.3 to 24 mm allows to shift the phase by a whole period (6.28 rad).

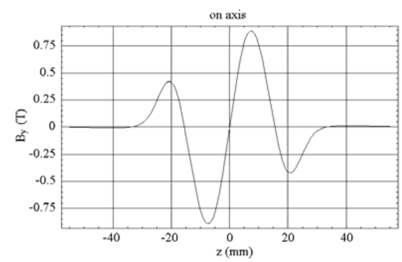

Figure 7: Vertical component of the magnetic field.

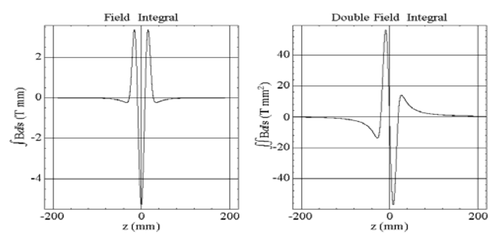

Figure 8: First and second field integrals along axis.

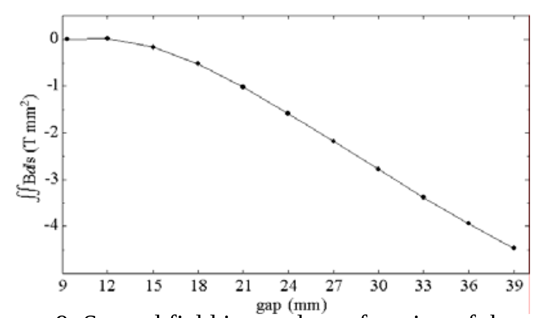

Figure 9: Second field integral as a function of the gap.

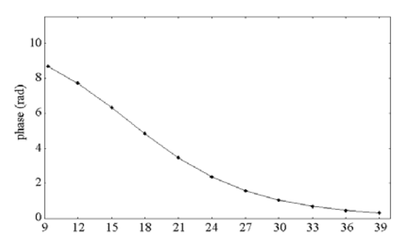

Figure 10: Phase correction as a function of the gap.

SECOND CONFIGURATION

The second possibility consists in assuming thinner magnets for the terminations. In this case only five magnets (rather than seven) are needed to fulfil the requirement on field integrals. Setting the length of the ending magnet (at both sides) to the 70.5% of the nominal one, i.e. 4.95 mm (see Fig. 11), it ensures to get the first and the second field integral equal to zero at the nominal gap. As in the previous case we have a slight dependence of the second field integral with the gap, but it remains within the tolerances.

The vertical component of the magnetic field at the nominal gap, as well as the consequent first and second field integrals, are shown in Figs. 12 and 13.

The second field integral and the achievable phase correction as a function of the gap are shown in Figs. 14 and 15. In this case, increasing the gap from 8.95 to 26 mm allows to shift the phase by a whole period.

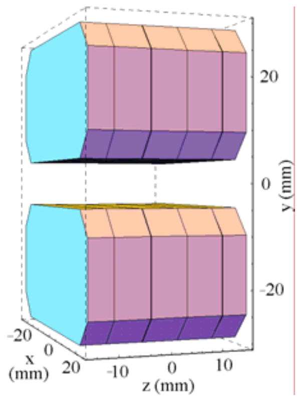

Figure 11: Second configuration for the phase shifter (five horizontally cut magnets); the total length is 31 mm.

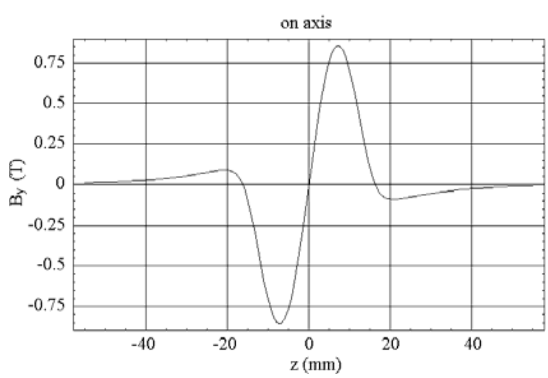

Figure 12: Vertical component of the magnetic field.

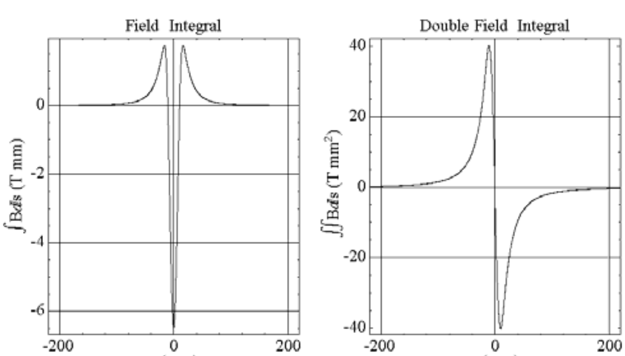

Figure 13: First and second field integrals along axis.

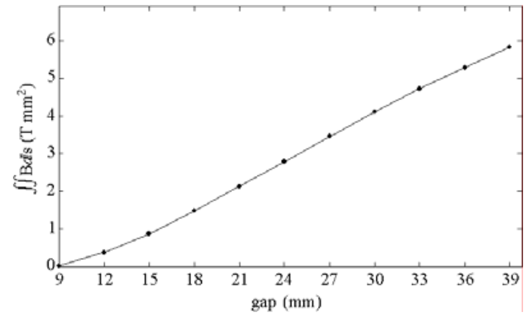

Figure 14: Second field integral as a function of the gap.

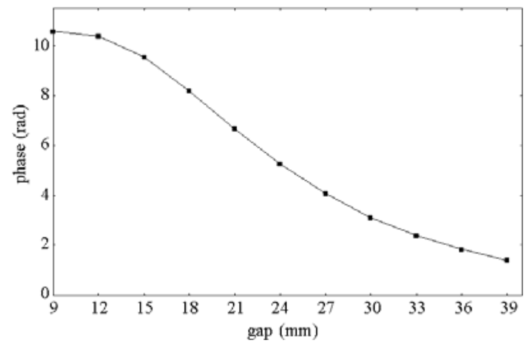

Figure 15: Phase correction as a function of the gap.

CONCLUSIONS

Two preliminary designs of the phase shifters have been proposed. They consist of two groups of permanent magnets, arranged as in the main undulator, in a variable gap assembly. Adjusting the gap allows to correct any electron-radiation phase difference.

Both configurations allow to fulfil the requirements in term of phase range and vanishing field integrals. The first one, made of seven couples of magnets, has a total length of 49 mm; the second one, made of five couples of magnets, has a total length of 31 mm and therefore looks more attractive.

ACKNOWLEDGEMENTS

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