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SPARX Simulations with GENESIS 1.3

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Abstract

The aim of this study is to find the FEL working point. At this regard, we performed simulations at different energy, wavelength, peak current and energy spread, using a 3D simulation code, called GENESIS 1.3.
We present a scheme which shows three different suggestions for our purposes:

1. We studied a machine which worked at 2 GeV and was able to produce two different wavelength, a) 10 nm and b) 1.5 nm, using two planar undulators with λ_u=4 cm and λ_u=3 cm, respectively. For this situation we also present a time-dependent simulation and we report the power spectrum for three different positions within the undulator.
2. In this section we study the possibility of getting 10 nm with 1 GeV and 1.5 nm with 2.5 GeV. For the latter case, we present two kinds of external strong focusing, a combined function undulator and a separated function undulator.
3. A further suggestion is working at one energy, 2.5 GeV, for both wavelengths, and an undulator magnet with λ_u=4 cm.

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1. E=2 GeV

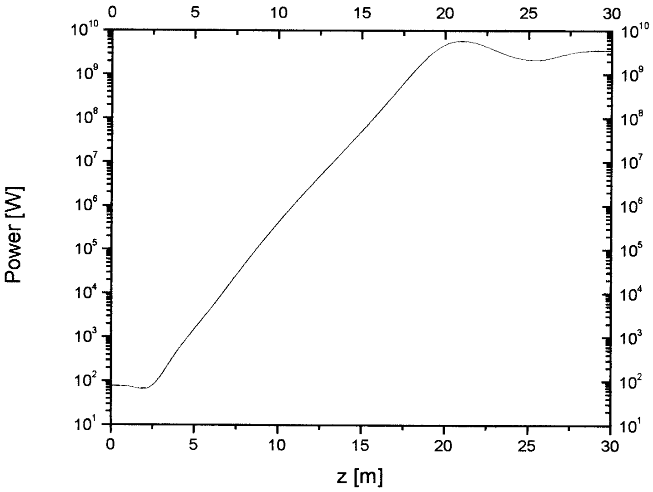
a) λ_r=10 nm

As first step, we used Saldin's theory to verify the goodness of the chosen parameters, and we found an agreement at 10 nm with the following set of values:

Table1

E [GeV]	2
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2
λ_u [cm]	4
K	3.649
Gap [mm]	11

The radiation power along the undulator axis z has been obtained by GENESIS 1.3 in the steady state regime and is shown on end.

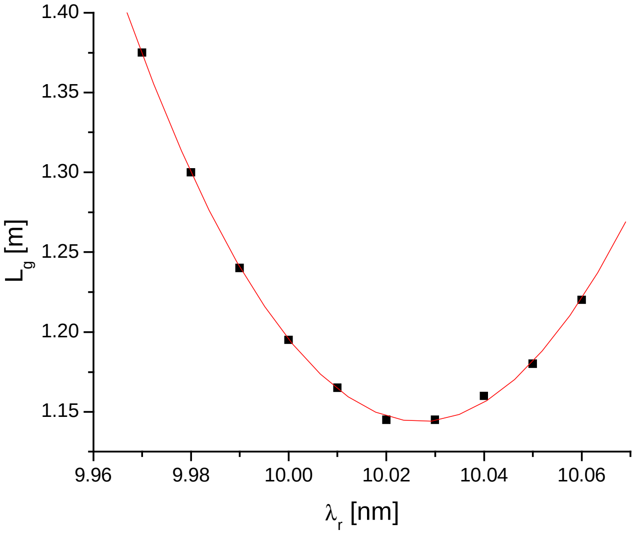


Saturation is reached at z_{sat}=23.9 m with a power of 4.889 GW, using a single-segment combined function undulator, whose cell length and quadrupole gradient are λ_{FODO}=1 m and g=11 T/m, respectively.

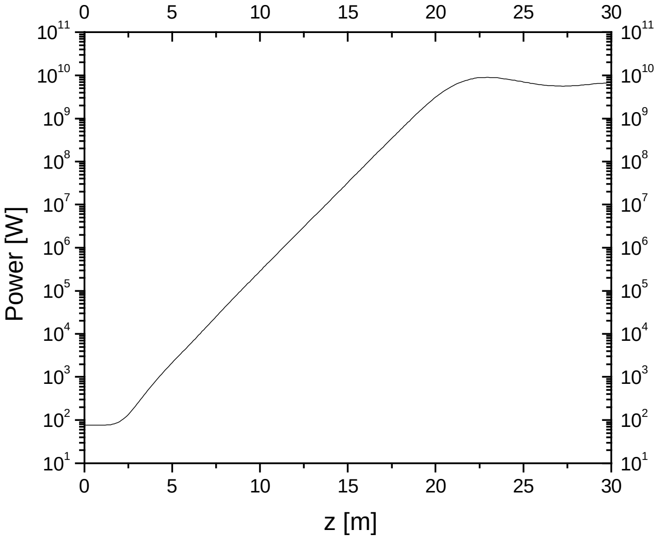
Since the code has been used in time-independent mode, in order to reduce CPU time, we have excluded the fluctuation due to SASE process, thus we are in an FEL amplifier configuration, but the seed we simulated is the spontaneous radiation.

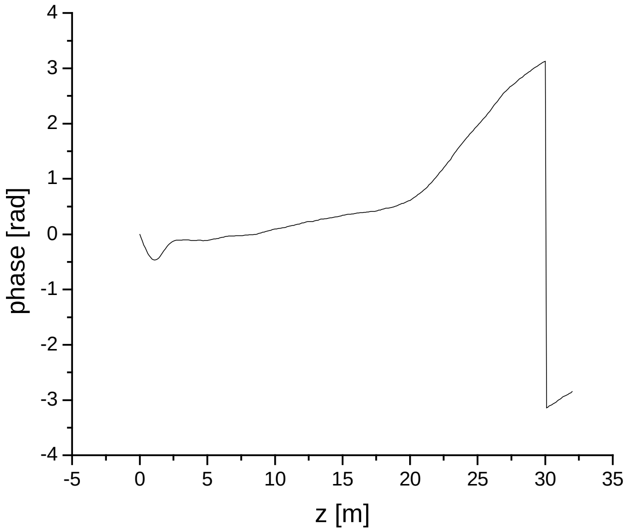
For this reason, we found the optimum wavelength, corresponding to the minimum gain length, by scanning in wavelength near the resonance:

λr [nm]	Lsat [m]	Lg [m]	Psat [W]
9.97	27.5	1.375	1.7301E+09
9.98	26	1.300	2.5966E+09
9.99	24.8	1.240	3.5257E+09
10	23.9	1.195	4.8888E+09
10.01	23.3	1.165	6.2615E+09
10.02	22.9	1.145	8.0488E+09
10.03	22.9	1.145	9.6188E+09
10.04	23.2	1.160	1.1202E+10
10.05	23.6	1.180	1.2453E+10
10.06	24.4	1.220	1.31E+10



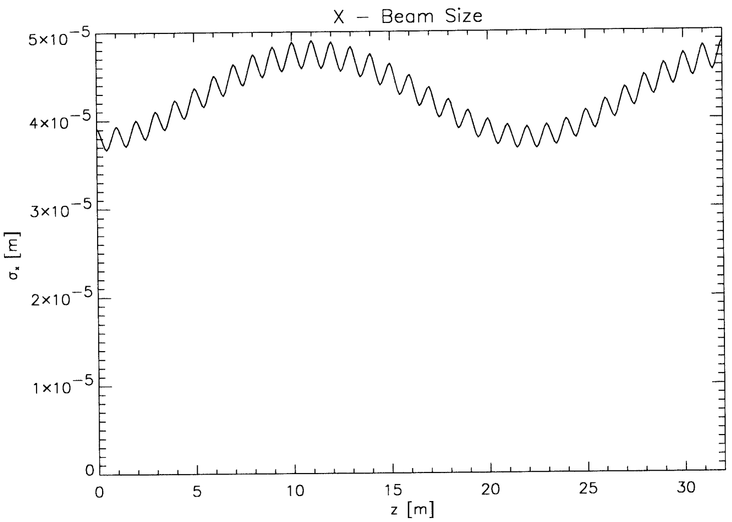
The minimum gain length is achieved with the optimum wavelength $\lambda_{r(optimum)}$=10.027 nm, corresponding to a frequency of $2.99 \cdot 10^{16}\,Hz$. Therefore GENESIS simulation, performed with such a optimum value, has produced the following curves for the radiation power and phase at the undulator axis:

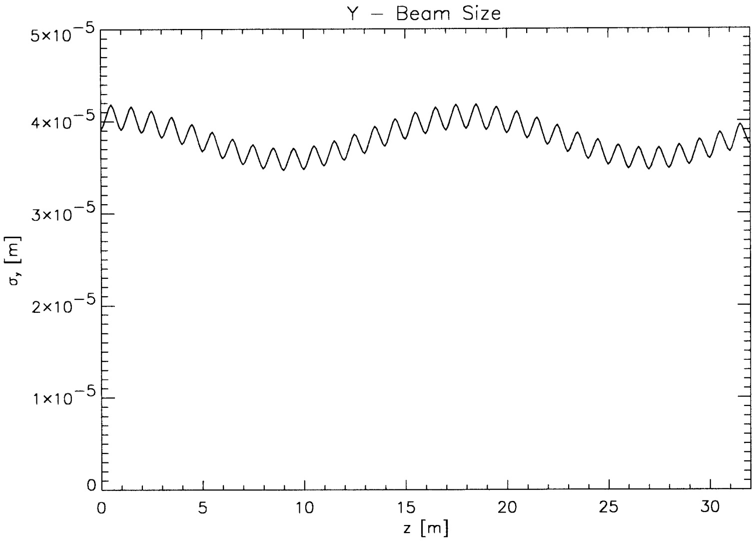




As can be noticed, the saturation power at the optimum wavelength is slightly higher and the saturation length slightly shorter than those at the nominal resonant wavelength. Moreover, with this optimum wavelength, no change in the electron ponderomotive phase is observed and the micro-bunching is still driven by the radiation field and, as a consequence, the interaction between the electron beam and the radiation field is much stronger.

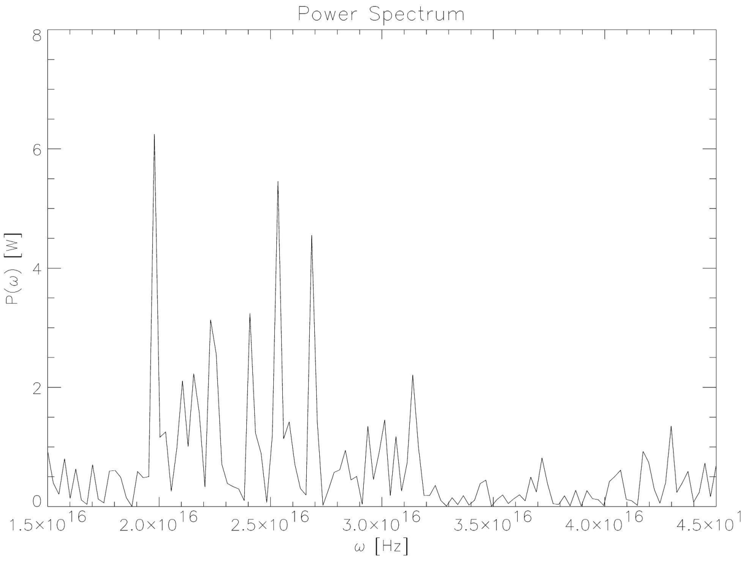
The following figures show the rms beam size, in x and y direction, along the undulator axis:





The low-frequency oscillation is due to the betatron oscillation, while the high-frequency oscillation is due to the external strong focusing generated by a combined function undulator, whose FODO cell length is as long as the oscillation period, that is 1 m.

For the present case, we performed time-dependent simulation thus we display in the next figures the power spectrum at three different positions within the undulator: at the entrance , at an intermediate position and at the exit of the undulator, respectively:



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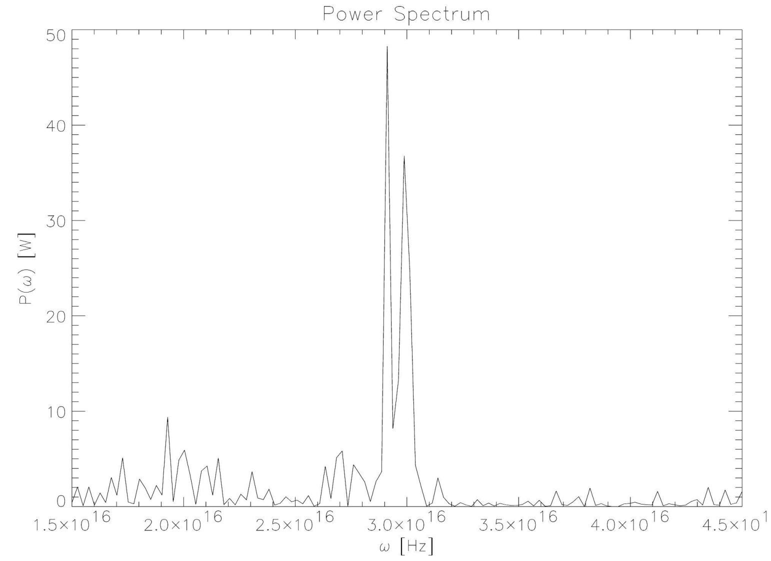
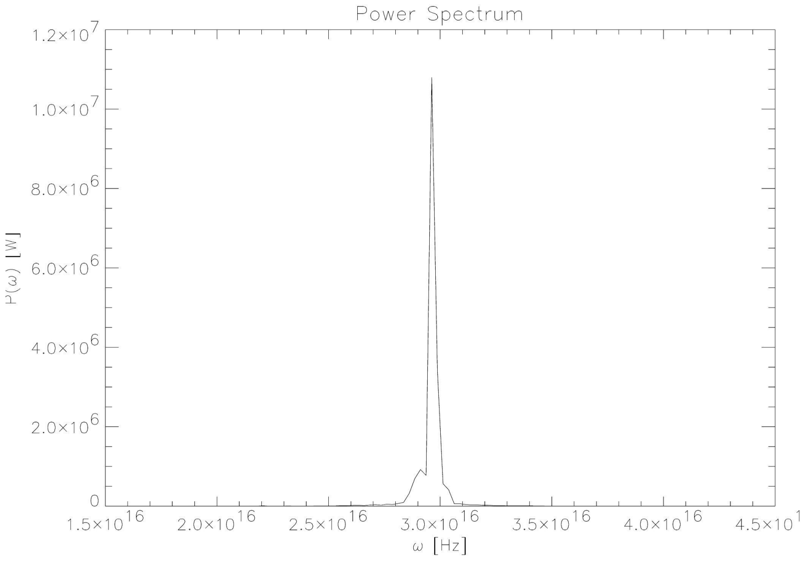




As can be seen, at the undulator exit, the power spectrum is fully localized around the resonance frequency, that is roughly $2.97 \cdot 10^{16}\,Hz$, corresponding to a resonance wavelength slightly greater than the nominal one and practically equal to that for which the minimum gain length is achieved in the steady state simulation.

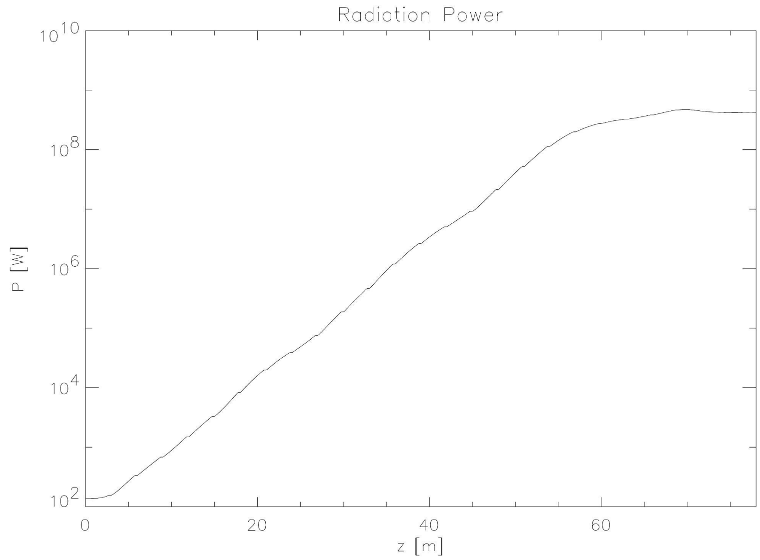
b) λ_r=1.5 nm

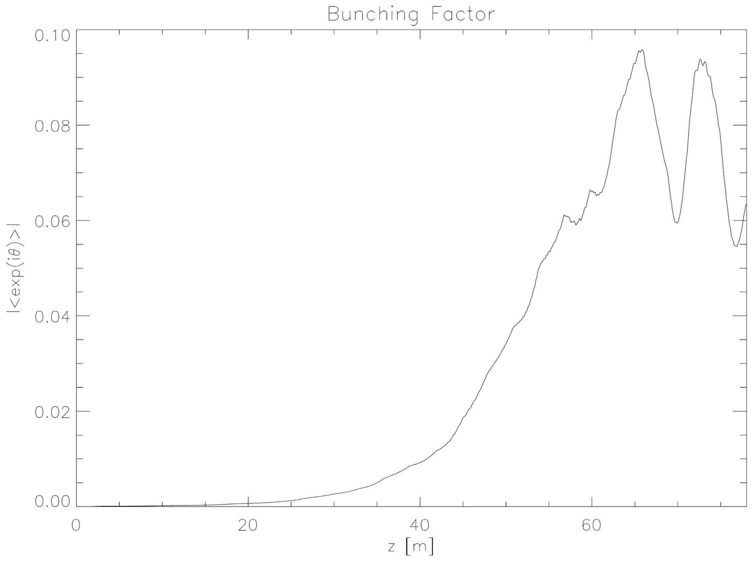
For the case at 1.5 nm, we used the same procedure and we first applied Saldin's theory with the following parameters:

Table2

E [GeV]	2
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2
λ_u [cm]	3
K	1.031
Gap [mm]	16

As a result, we noticed a very strong discrepancy between the resonant wavelength we would and could have had, in accordance with Saldin's theory. However, we executed GENESIS' simulation and we obtained the following results for the radiation power and the bunching factor, respectively:





Saturation is reached at roughly 65 m with a saturation power less than 10^9 W.

2.

a) E=2.5 GeV - λ_r=1.5 nm – I=2.5 kA

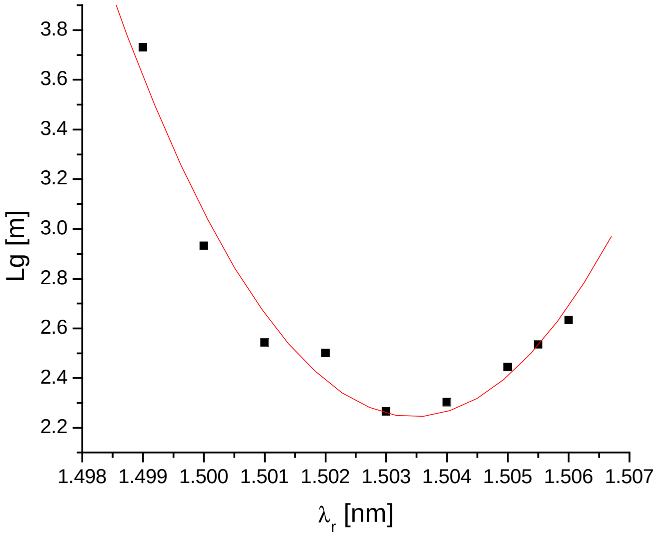
Since we did not succeed in obtaining a good saturation curve at 1.5 nm with the set of parameters listed in Table 2, we increased the energy up to 2.5 GeV and we varied the peak current and the energy spread, in order to find a better condition, obtained with the values shown in Table 3:

Table3

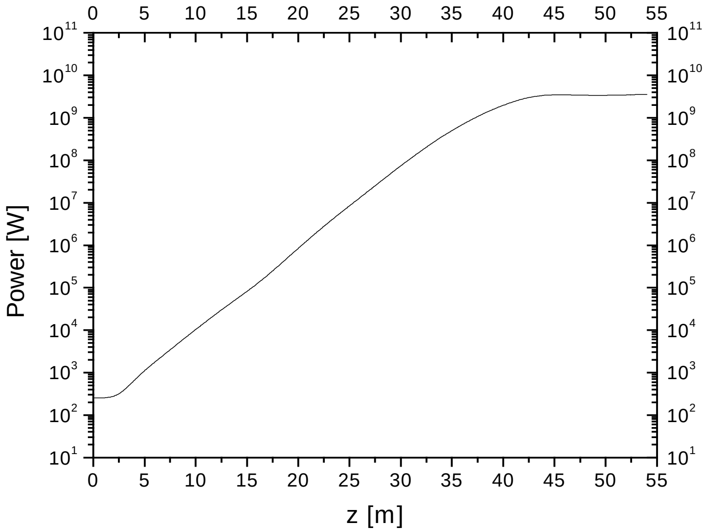
E [GeV]	2.5
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2.5
λ_u [cm]	3
K	1.669
Gap [mm]	12

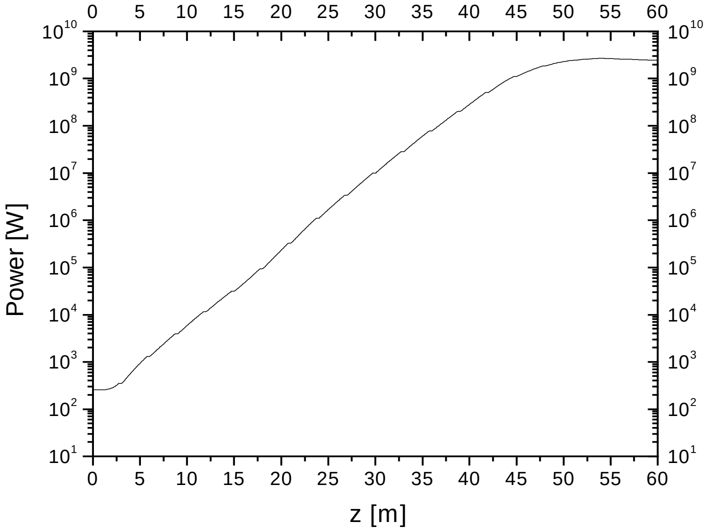
Then we looked for the optimum wavelength by scanning near the resonance and we found the following results:

λr [nm]	Lsat [m]	Lg [m]	Psat [W]
1.49900	74.625	3.73125	3.9634E+08
1.50000	58.65	2.9325	6.1431E+08
1.50100	50.85	2.5425	1.3531E+09
1.50200	50.025	2.50125	2.4257E+09
1.50300	45.3	2.265	3.1615E+09
1.50400	46.05	2.3025	3.8457E+09
1.50450	48.45	2.4225	3.9349E+09
1.50500	48.9	2.445	4.1568E+09
1.50550	50.7	2.535	4.2373E+09
1.50600	52.65	2.6325	4.0740E+09

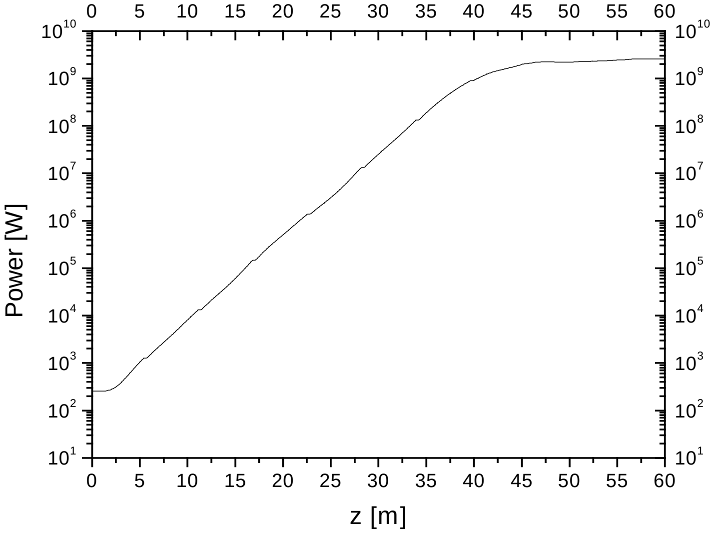


The minimum gain length is obtained with an optimum wavelength of roughly 1.503 nm. The two following pictures show the radiation power along the undulator axis for a single-segment and a multi-segment undulator, respectively. In the latter case, we have assumed a gap of 30 cm between each segment forming the undulator magnet.





In what follows we show the results attained at the same wavelength with a standard FODO lattice, whose cell length is 6.6 m long. As we can see, we reach roughly the same saturation power but with a slightly shorter saturation length. The x-beam and y-beam pictures show the motion of the electron beam in x and y direction, respectively, with an oscillation period as long as the FODO cell length.


Power [W]
z [m]
0
5
10
15
20
25
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35
40
45
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55
60
10^{1}
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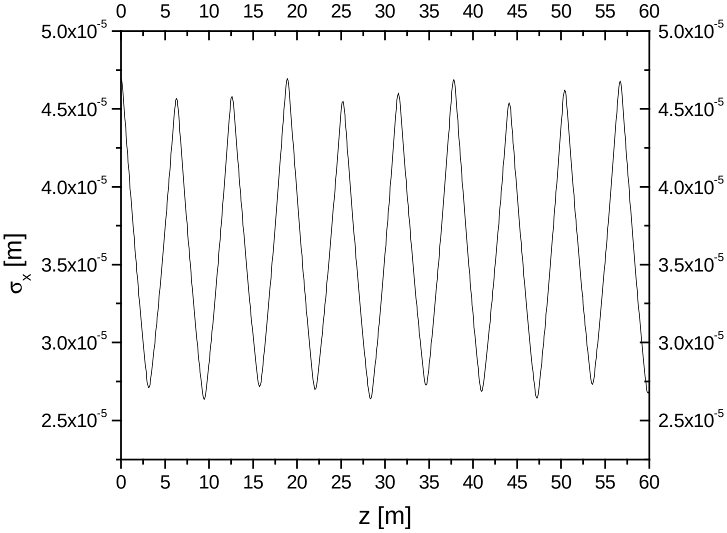
σ_x [m]
z [m]
0
5
10
15
20
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50
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$2.5\text{x}10^{-5}$
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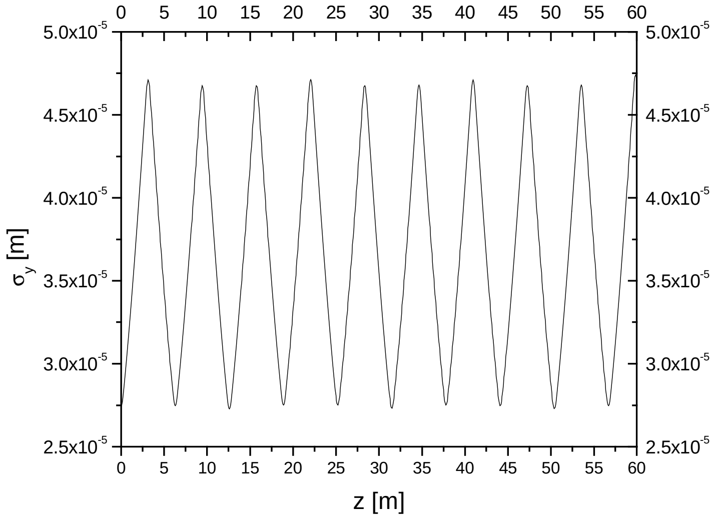
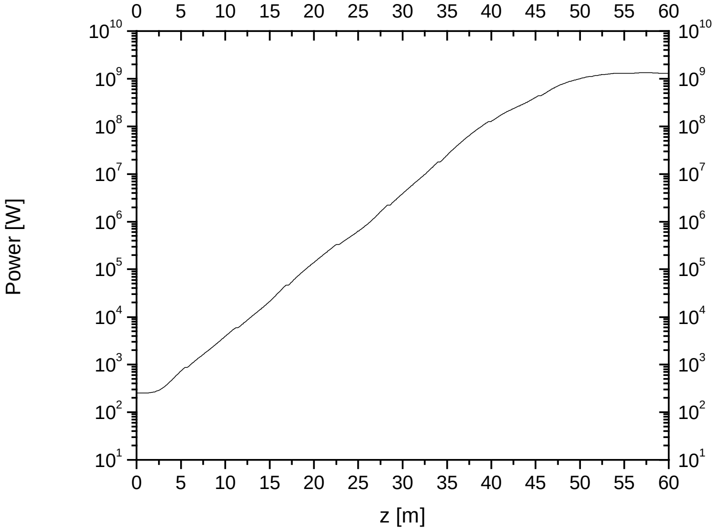
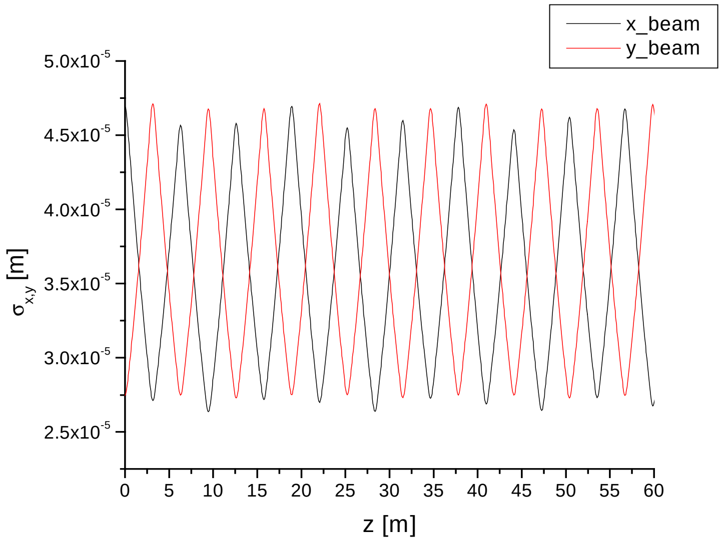


b) E=2.5 GeV - λ_r=1.5 nm – I=2 kA

Then, we performed a further simulation at this wavelength with a lower peak current, I=2 kA. Saturation has been reached within an undulator 60 m long, as shown in the following pictures displaying radiation power, x and y beam size, respectively:





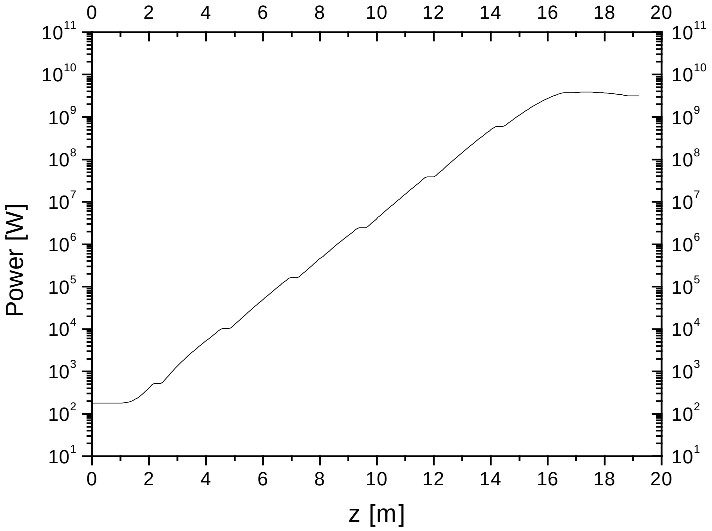
c) E=1 GeV - λ_r=10 nm – I=2 kA

At this point, we performed simulations at 1 GeV to get 10 nm with parameters shown in Table 4:

Table4

E [GeV]	1
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2
λ_u [cm]	3
K	1.762
Gap [mm]	11

Using the same procedure we found the optimum wavelength, $\lambda_{r(optimum)}$=10.0246 nm, and we run GENESIS with this value. On end, we display the results: saturation is reached at z_{sat}=17.4 m and the saturation power is P_{sat}=3.89 GW.



3. E=2.5 GeV

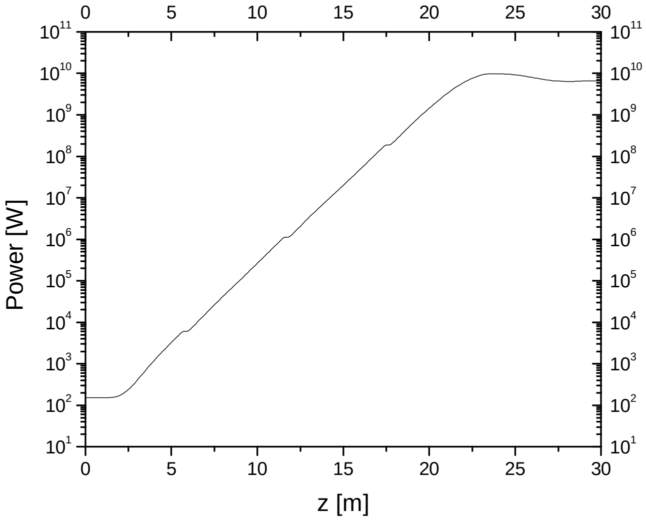
a) λ_r=10 nm

We also executed simulations at 2.5 GeV in order to get 10 nm. The parameter's list is shown in Table 5:

Table5

E [GeV]	2.5
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2
λ_u [cm]	4
K	4.864
Gap [mm]	8.469

The saturation curve is displayed in the following picture:



b) λ_r=1.5 nm

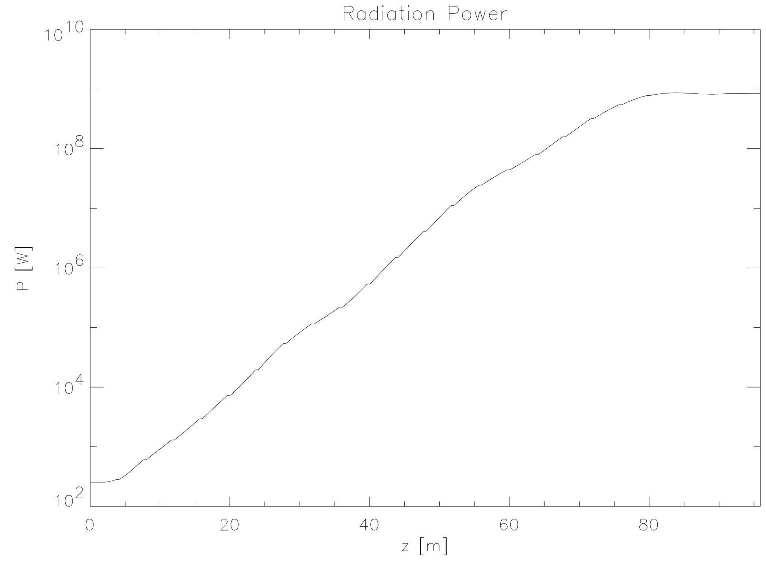
Finally, in what follows we show the results of simulations at the same energy, peak current, energy spread and undulator period for 1.5 nm:

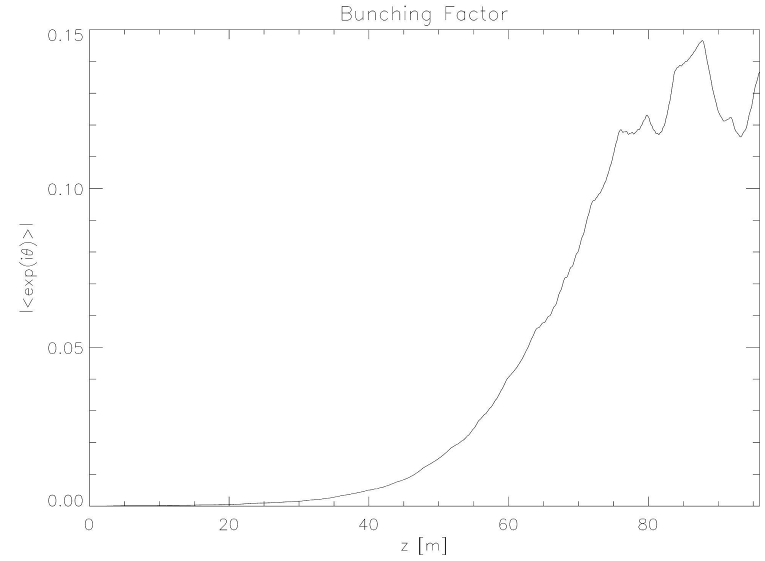
Table6

E [GeV]	2.5
$\Delta\gamma/\gamma$ [%]	0.1
I [kA]	2
λ_u [cm]	4
K	1.261
Gap [mm]	22

The following picture display the radiation power and the bunching factor. The saturation length is roughly 85 m and the saturation power is nearly 1 GW.

As in the case 1.b), the saturation curve presents an irregular gear. It seems that each segment forming the undulator contributes with a different gain.





Finally, we summarize our results for the <u>10 nm case</u> in Table 7 and for the <u>1.5 nm case</u> in Table 8:

Table7: λ_r=10 nm

E [GeV]	I [kA]	L_{sat} [m]	P_{sat} [GW]
1	2	17.4	3.89
2	2	22.9	~ 8
2.5	2	~ 25	~ 8

Table8: λ_u=1.5 nm

E [GeV]	I [kA]	L_{sat} [m]	P_{sat} [GW]
2	2	~65	<1
2.5	2	~ 55	~ 1.5
2.5	2.5	45.3	3.16

We conclude the better solution, in terms of saturation length, seems to be the one at two energies, 1 GeV and 2.5 GeV, in order to get 10 nm and 1.5 nm, respectively.

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