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Optimal focusing lattice for XFEL undulators: Numerical simulations

17.12.2007

Table 1. Electron beam parameters at the entrance of the SASE1 and SASE2 undulators

Electron energy [GeV]	17.5
Emittance [mm-mrad]	1.4
Bunch length (RMS) [micron]	25
Bunch charge [nC]	1
Peak current [kA]	5
Energy spread [MeV]	1.5

Table 2. European XFEL SASE1 FEL design parameters

Resonant radiation wavelength [nm]	0.1
K value	3.3
Period length [cm]	3.56
Segment length [m]	5
Number of segments	33
Segment interval [m]	6.1
Total length [m]	201.3
Lattice type	FODO

Table 3. European XFEL SASE2 FEL design parameters

Resonant radiation wavelength [nm]	0.1	0.4
K value	2.8	6.1
Period length [cm]	4.8	4.8
Segment length [m]	5	5
Number of segments	42	42
Total length [m]	256.2	256.2
Lattice type	FODO	FODO

L=12.2 (m)		λ=0.1 (nm)				
μ (deg)	$\beta_{av}\approx$	$P_{\max}\approx$	$L_{sat}\approx$	$\rho\approx$ $(\times10^{-4})$	$\Delta\lambda/\lambda\approx$ $(\times10^{-3})$	$Br\approx$ $(\times10^{33})$
90	10.1667	0.383153	>256.2	6.6670	1.5497	0.57109
50	14.9778	1.336	248.992	5.8446	1.3253	1.30847
42	17.4521	1.64765	>256.2	5.5627	1.2515	1.70791
30	23.8552	9.10088	>256.2	5.0106	1.1113	2.7604
27	26.3847	11.1637	248.992	4.8401	1.0691	3.15798
25	28.4169	14.0598	>256.2	4.7234	1.00679	3.44797
20	35.3119	20.473	251.684	4.3974	0.96194	4.32069
15	46.8695	24.954	255.092	3.9997	0.86830	5.4523
10	70.0792	25.0649	250.1	3.4975	0.75309	6.81157
7	99.9829	20.9841	>256.2	3.1067	0.66539	7.65791
	46	**24.4265**	**242.892**	**4.0232**	**0.87378**	**5.8513**

L=24.4 (m)		λ=0.1 (nm)				
μ (deg)	$\beta_{av}\approx$	$P_{\max}\approx$	$L_{sat}\approx$	$\rho\approx$ $(\times10^{-4})$	$\Delta\lambda/\lambda\approx$ $(\times10^{-3})$	$Br\approx$ $(\times10^{33})$
90	20.3333	3.85381	>256.2	5.2855	1.1804	2.19042
50	29.9556	15.4353	>256.2	4.6445	1.0214	3.65132
42	34.9042	20.3223	>256.2	4.4138	0.96586	4.27497
30	47.7104	25.075	248.992	3.9763	0.86286	5.51899
27	52.7693	26.3945	255.092	3.8447	0.83240	5.89058
25	56.8338	25.7443	248.992	3.7496	0.81054	6.15327
20	70.6238	24.8764	>256.2	3.4877	0.75088	6.83569
15	93.7391	21.96	>256.2	3.1744	0.68049	7.53049
10	140.1583	14.8992	>256.2	2.7755	0.59214	8.13591
7	199.9659	7.25432	>256.2	2.4654	0.52434	8.32688
	46	**23.979**	**248.224**	**4.0247**	**0.87412**	**5.38088**

L=12.2 (m)	Lq=0.384 (m)	λ=0.4 (nm)				
μ (deg)	$\beta_{av} \approx$	$P_{\max} \approx$	$L_{sat} \approx$	$\rho \approx$ $(\times 10^{-4})$	$\Delta\lambda/\lambda \approx$ $(\times 10^{-3})$	$Br \approx$ $(\times 10^{33})$
90	10.1667	78.0209	91.788	10.672	2.2842	1.71017
50	14.9778	117.704	97.984	9.3735	1.9934	2.00178
42	17.4521	112.677	192.111	8.9155	1.8920	2.09334
30	23.8552	109.048	120.892	8.0318	1.6978	2.25104
27	26.3847	105.348	123.632	7.7682	1.6402	2.29313
25	28.4169	103.047	123.728	7.5783	1.5988	2.32202
20	35.3119	95.7084	130.02	7.0459	1.4831	2.39667
15	46.8695	87.2659	136.168	6.4178	1.3473	2.47259
10	70.0792	77.918	159.176	5.6098	1.1735	2.55002
7	99.9829					
	15	**116.308**	**90.392**	**9.3714**	**1.9929**	**2.00222**

L=24.4 (m)		λ=0.4 (nm)				
μ (deg)	$\beta_{av} \approx$	$P_{\max} \approx$	$L_{sat} \approx$	$\rho \approx$ $(\times 10^{-4})$	$\Delta\lambda/\lambda \approx$ $(\times 10^{-3})$	$Br \approx$ $(\times 10^{33})$
90	20.3333	96.952	102.592	8.4777	1.7956	2.17464
50	29.9556	97.864	122.192	7.4493	1.5707	2.34098
42	34.9042	93.9832	128.58	7.0749	1.4894	2.3928
30	47.7104	85.5159	136.888	6.3791	1.3389	2.47684
27	52.7693	82.8459	145.196	6.1677	1.2934	2.49908
25	56.8338	82.6747	149.28	6.0169	1.2609	2.51398
20	70.6238	77.1548	159.704	5.5959	1.1705	2.55114
15	93.7391	70.0077	177.812	5.0921	1.0626	2.58618
10	140.158					
7	199.966					

Estimation of the FEL brightness from using GENESIS time –dependent simulations

Sat. length is calculated as weighted average over the bunch.

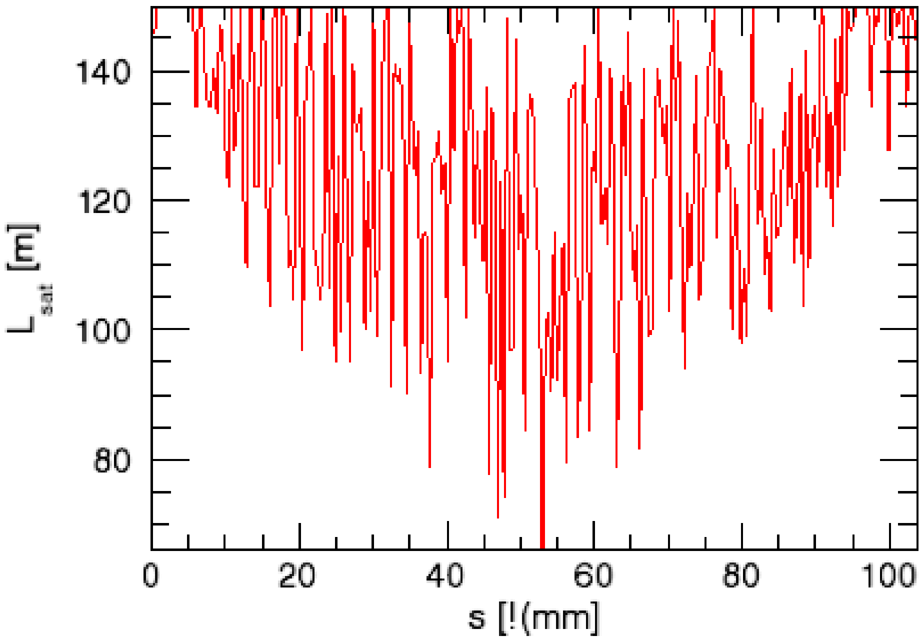
$$L_{Sat} = \frac{\int_{s_1}^{s_2} L_{Sat}(s) P_{Sat}(s) ds}{\int_{s_1}^{s_2} P_{Sat}(s) ds}$$

The maximum power, rad. size, rad. divergence are calculated similarly at L_{Sat} distance.

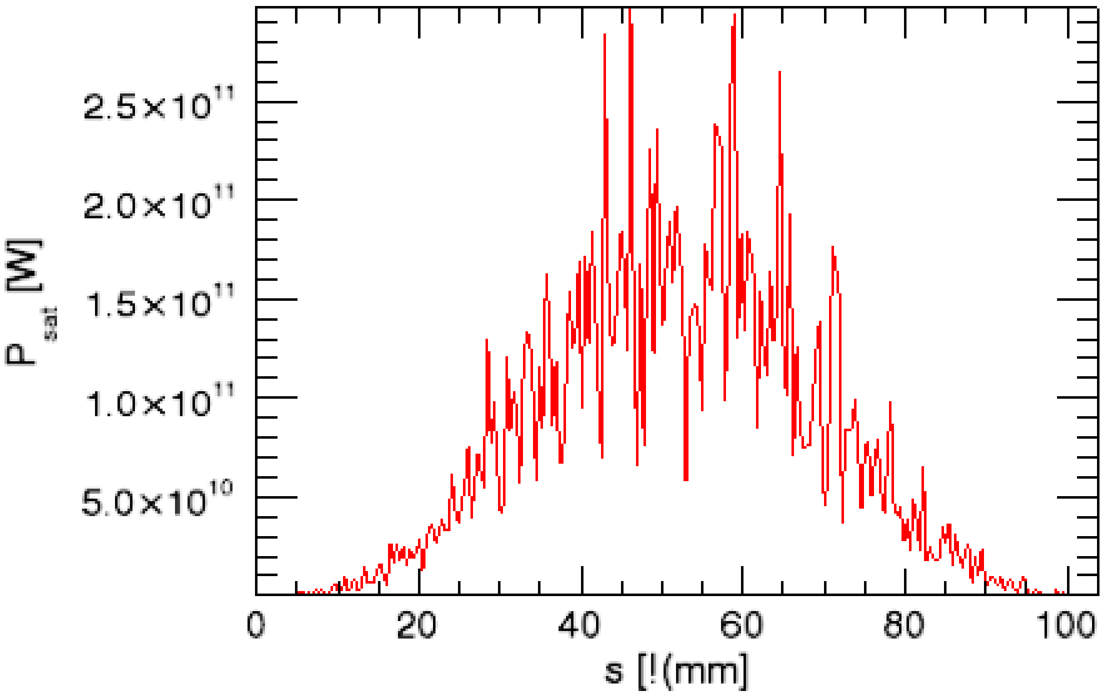
$$P_{\max} = \left. \frac{\int_{s_1}^{s_2} P(s) ds}{(s_2 - s_1)} \right|_{@L_{Sat}} \qquad \sigma_R = \left. \frac{\int_{s_1}^{s_2} \sigma_R(s) P(s) ds}{\int_{s_1}^{s_2} P(s) ds} \right|_{@L_{Sat}}$$

FEL peak Brightness/Brilliance in the units of (Photons/sec/ mm^2 /$mrad^2$/0.1%bw) is calculated as:

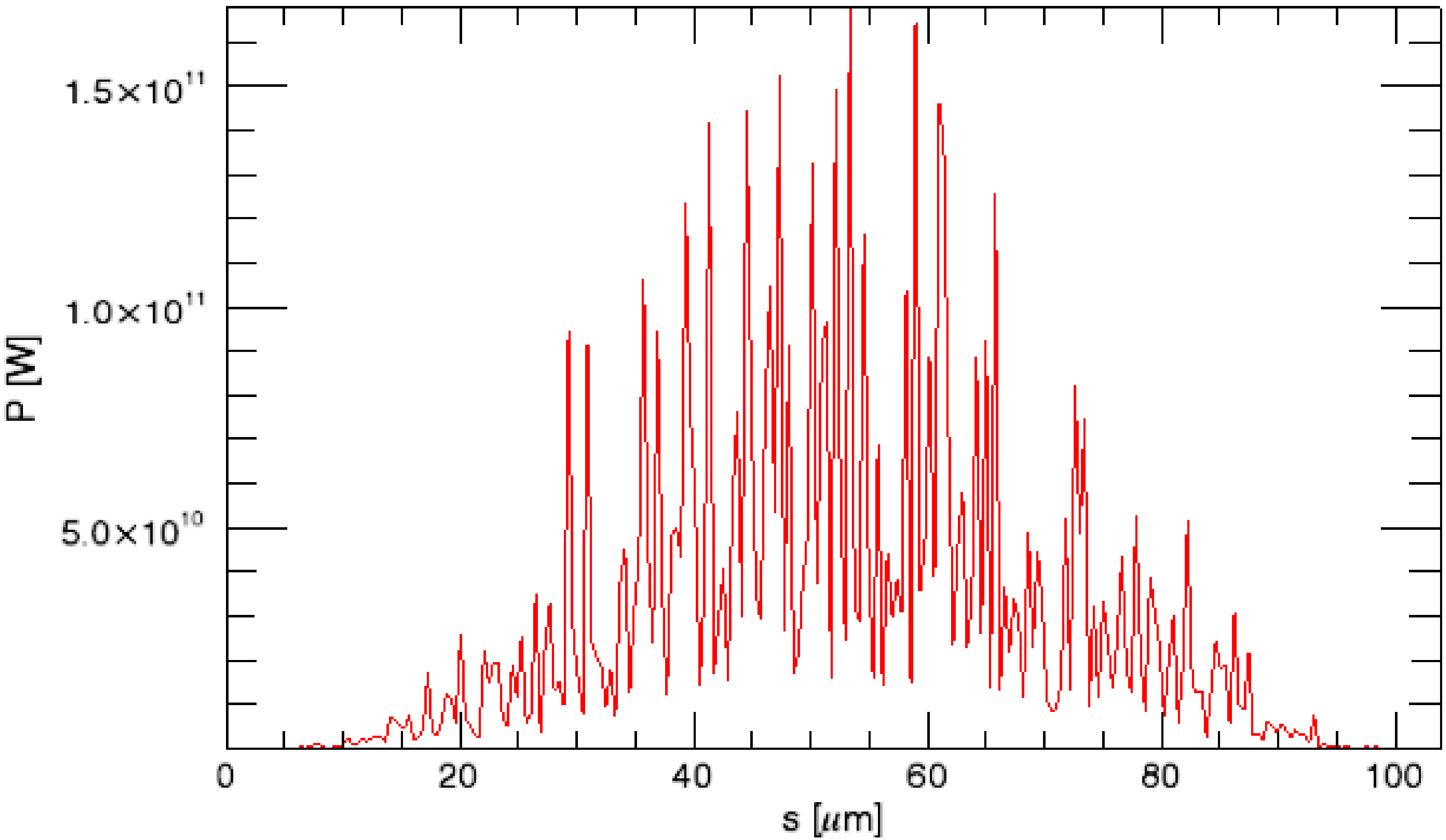
$$Br = \frac{P_{\max} / E_{ph}}{(2\pi)^2 \sigma_R^2 \sigma_{R'}^2 \cdot 0.1\% bw}$$



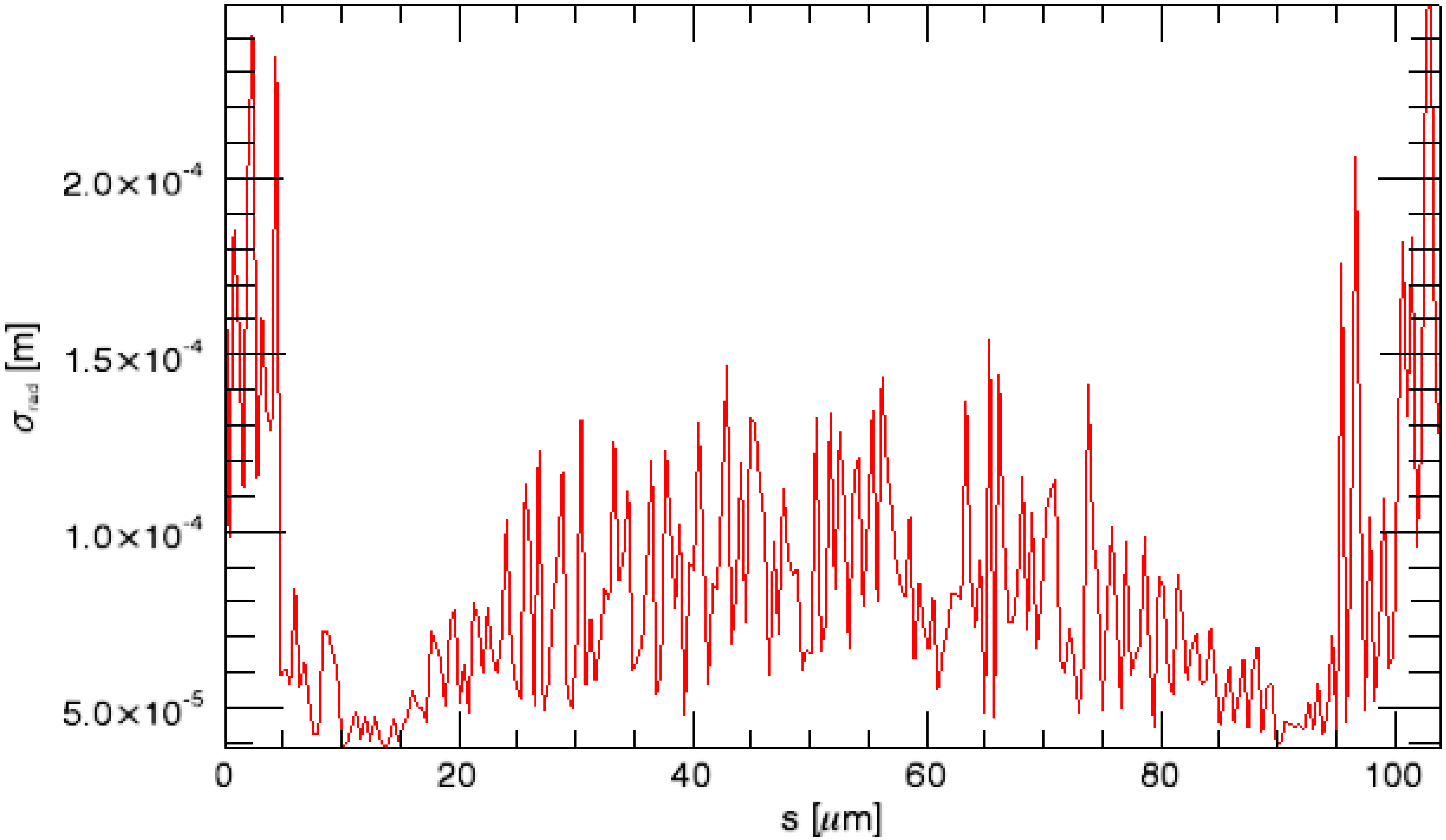
Saturation length distribution along the bunch for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.



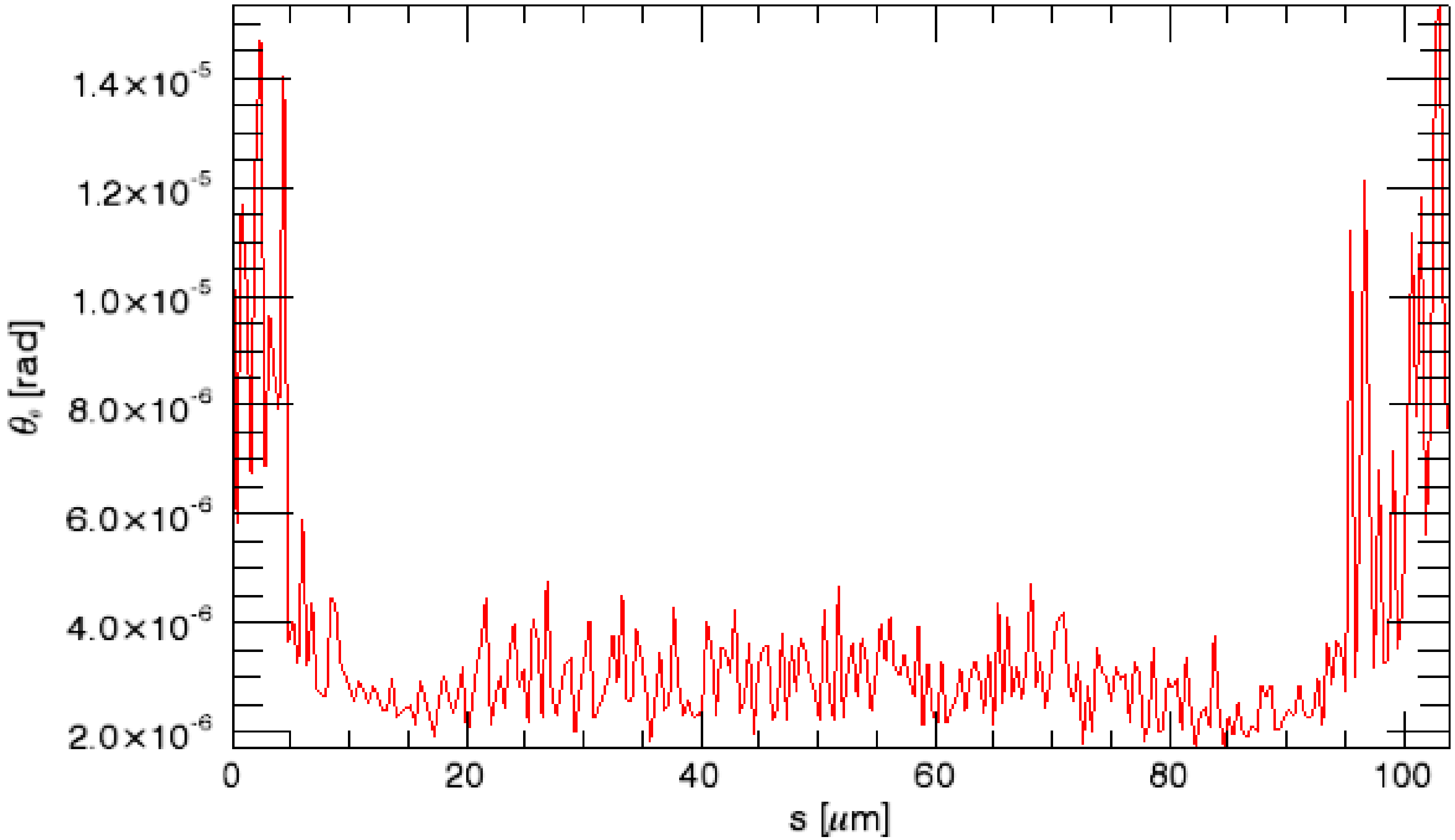
Saturation power distribution along the bunch for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.



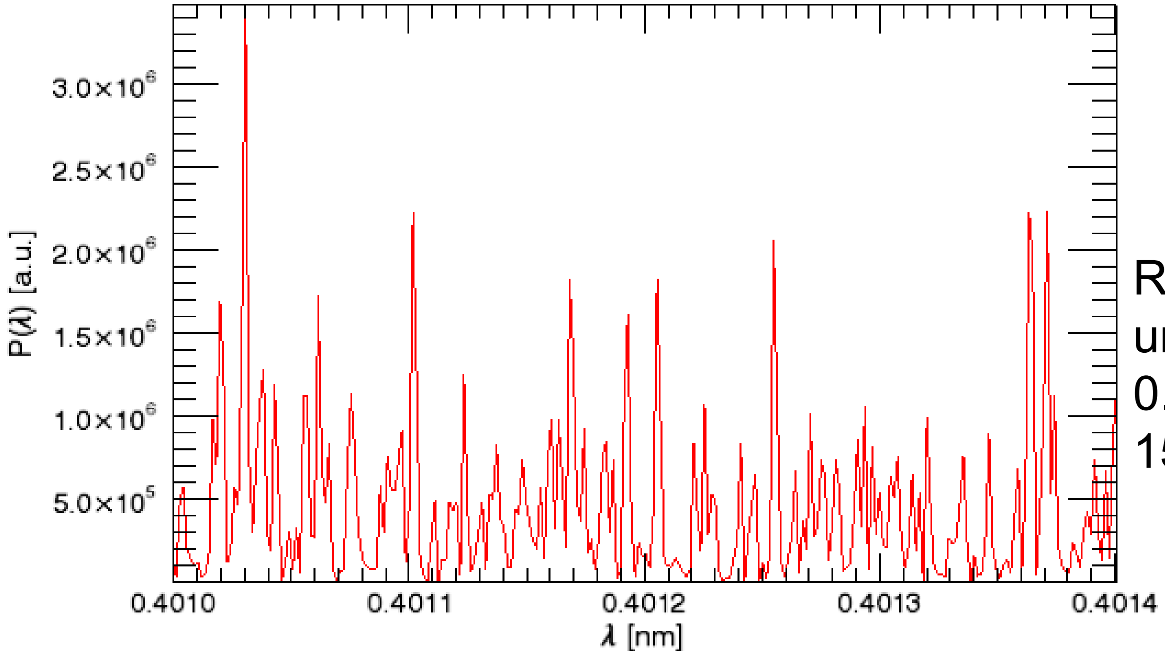
Power distribution along the bunch @L_{sat} =120m for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.



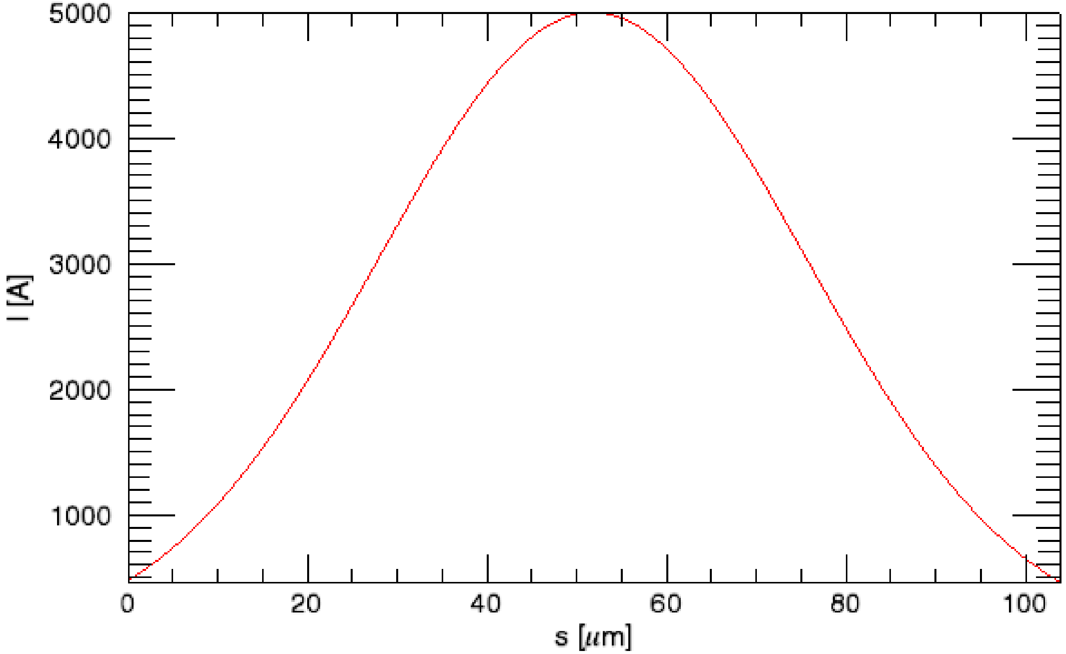
Radiation size distribution along the bunch @L_{sat} =120m for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.



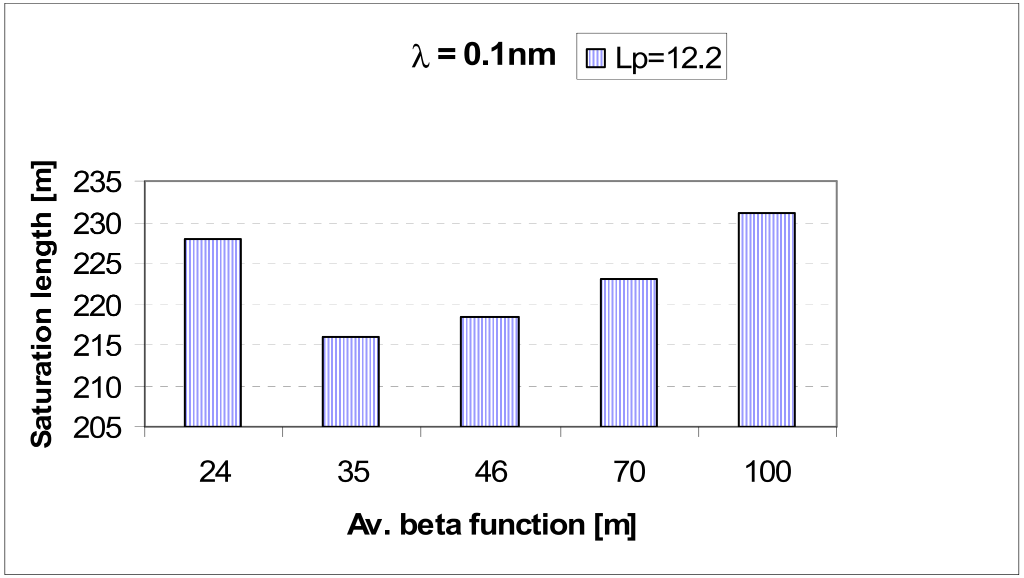
Radiation divergence angle distribution along the bunch @L_{sat} =120m for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.



Radiation spectrum for SASE2 undulator tuned to wavelength 0.4nm; Average beta function is 15m.

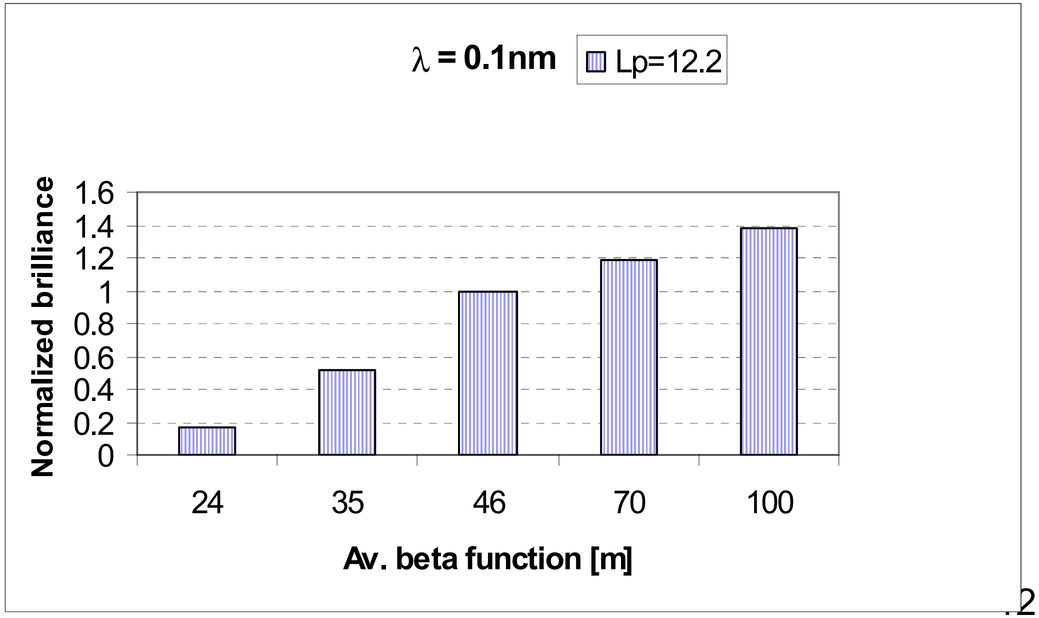


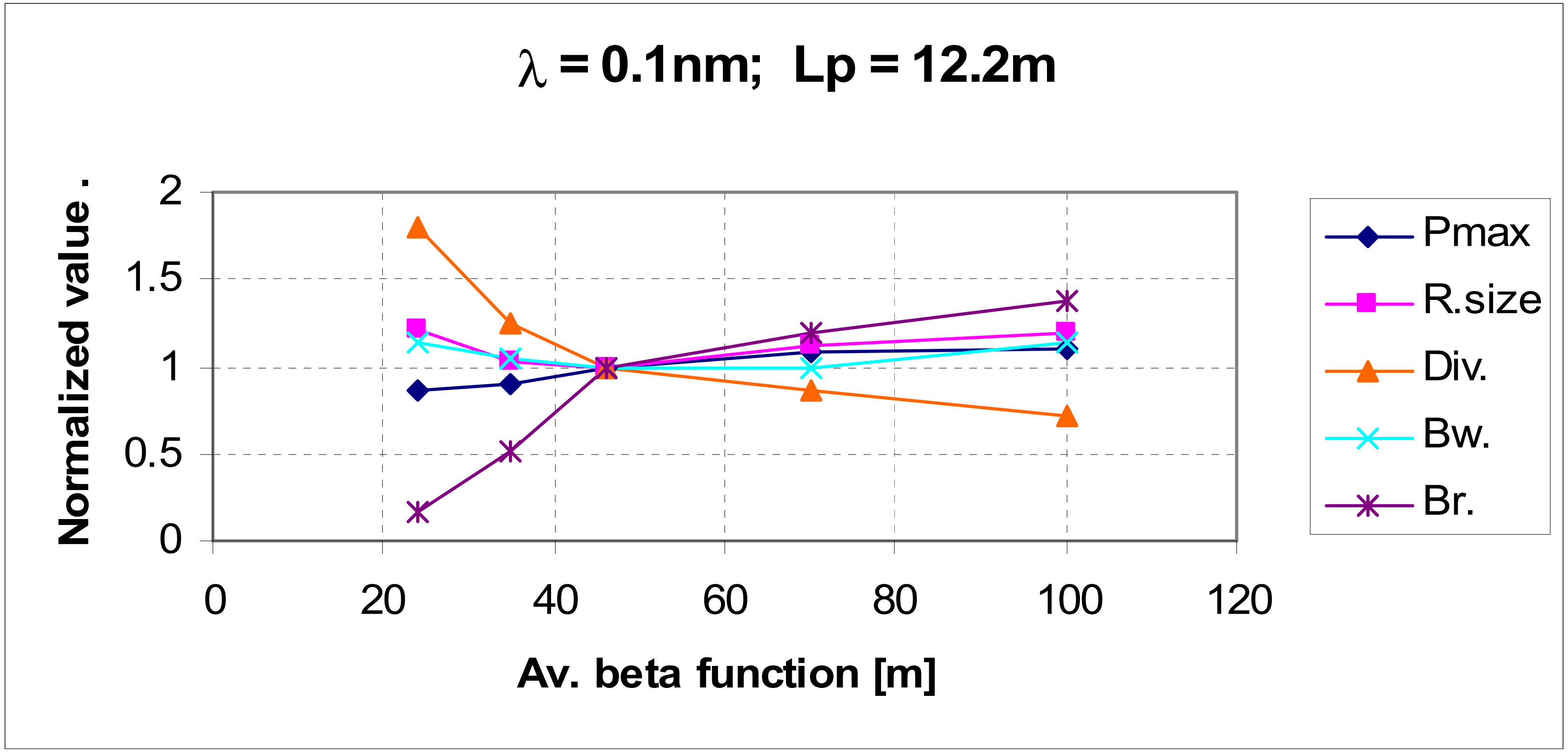
Bunch current longitudinal profile



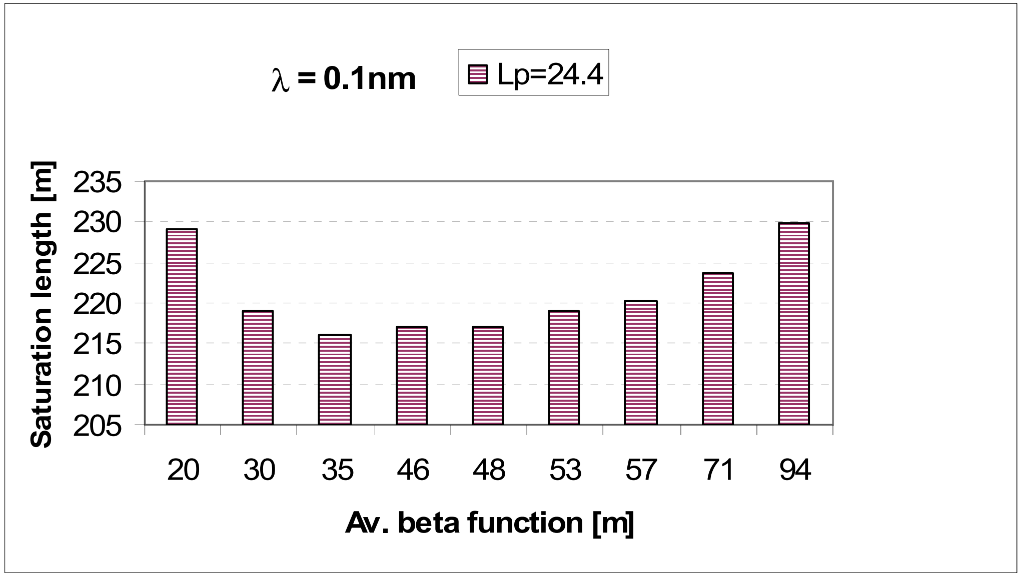
Saturation length dependence on the average beta function for the SASE2 undulator tuned to wavelength 0.1nm; Current design value for the av. beta is 46m.

Dependence of the brilliance/brightness on the average beta function for the SASE2 undulator tuned to wavelength 0.1nm; Current design value for the av. beta is 46m.



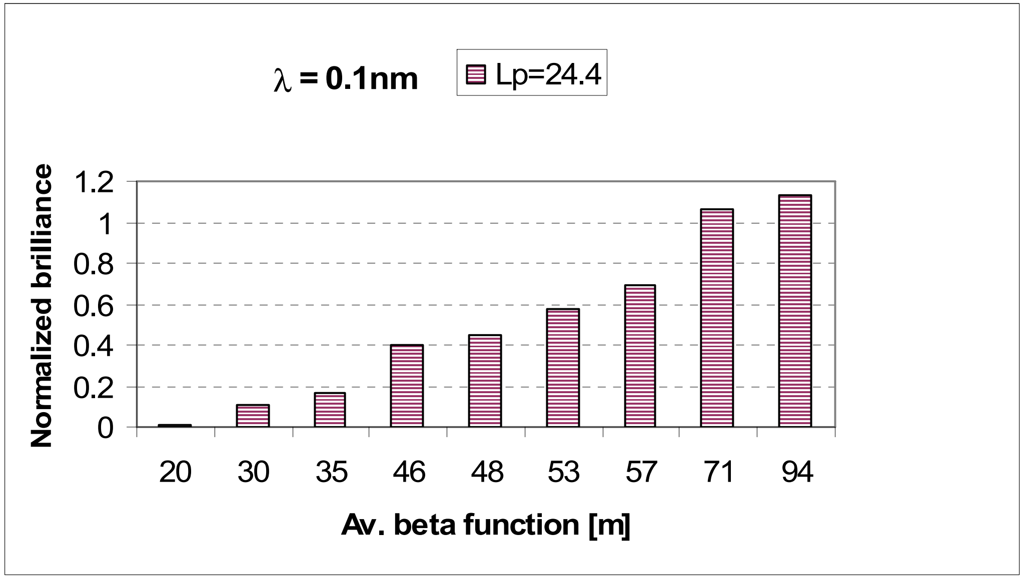


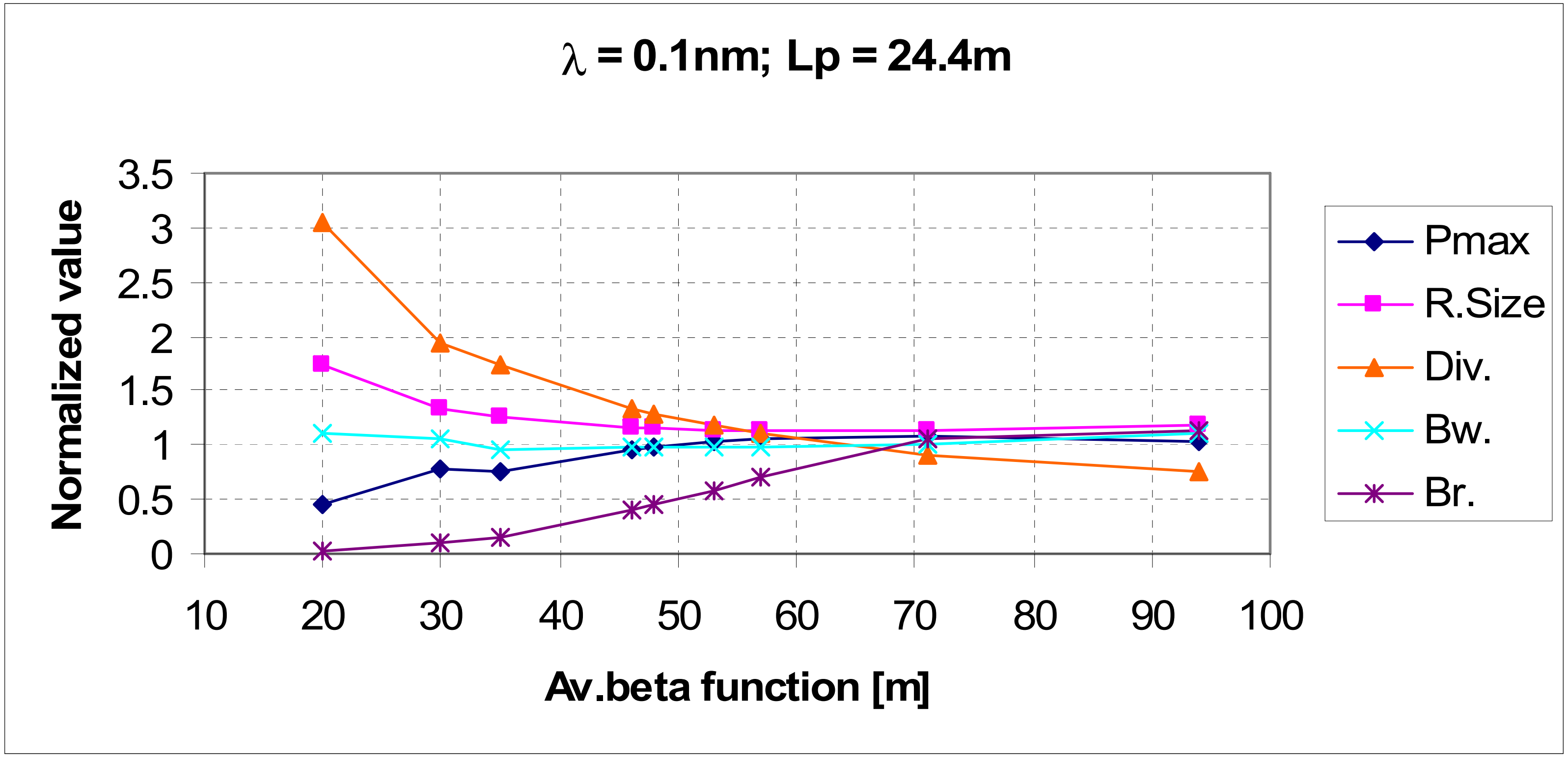
SASE2 undulator radiation parameters (maximum power, radiation size and divergence, badwidth and brightness/brilliance) dependence on the average beta function. All parameters are normalized to those corresponding to lattice current design parameters: 12.2 FODO period length and 46m average beta function.



Saturation length dependence on the average beta function for the SASE2 undulator tuned to wavelength 0.1nm; FODO period length is 24.4m Current design value for the the period length is 12.2m.

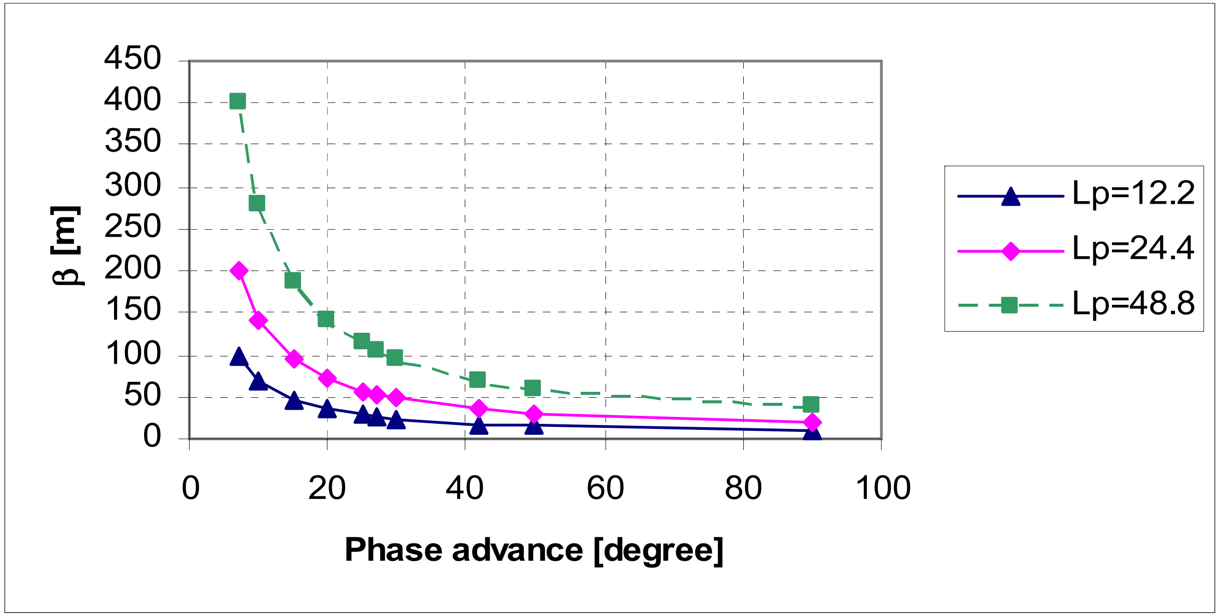
Dependence of the brilliance/brightness on the average beta function for the SASE2 undulator tuned to wavelength 0.1nm; FODO period length is 24.4m Current design value for the of the period length is 12.2m.

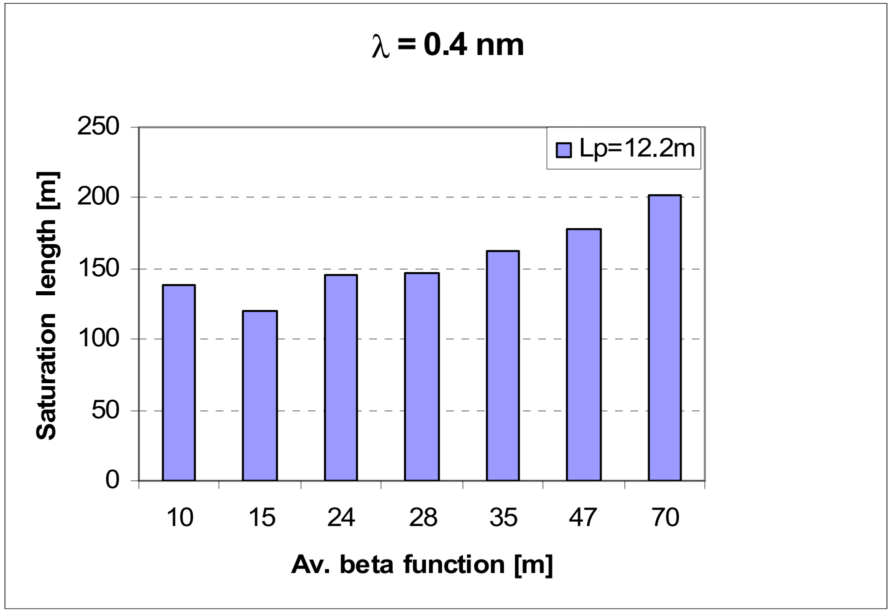




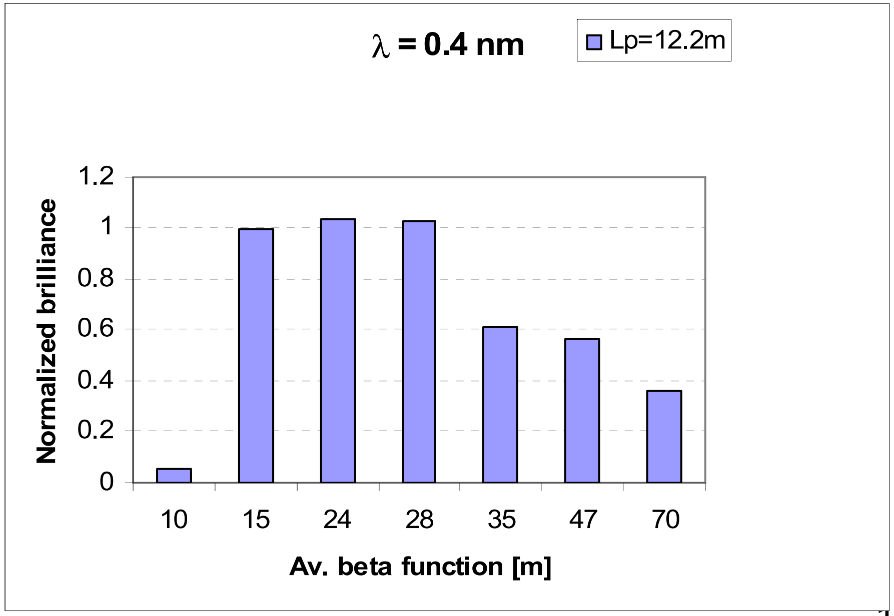
SASE2 undulator radiation parameters (maximum power, radiation size and divergence, badwidth and brightness/brilliance) dependence on the average beta function. All parameters are normalized to those corresponding to the lattice current design parameters: 12.2m FODO period length and 46m average beta function.

Mu/deg	Mu/rad	B_24.4	B_12.2	B_36.6	B_48.8
90	1.570795	20.33334	10.16667	30.50001	40.66668
50	0.872664	29.95564	14.97782	44.93346	59.91128
42	0.733038	34.90421	17.4521	52.35631	69.80841
30	0.523598	47.71038	23.85519	71.56557	95.42076
27	0.471239	52.76934	26.38467	79.15401	105.5387
25	0.436332	56.83381	28.4169	85.25071	113.6676
20	0.349066	70.62382	35.31191	105.9357	141.2476
15	0.261799	93.73905	46.86953	140.6086	187.4781
10	0.174533	140.1583	70.07917	210.2375	280.3167
7	0.122173	199.9659	99.98293	299.9488	399.9317

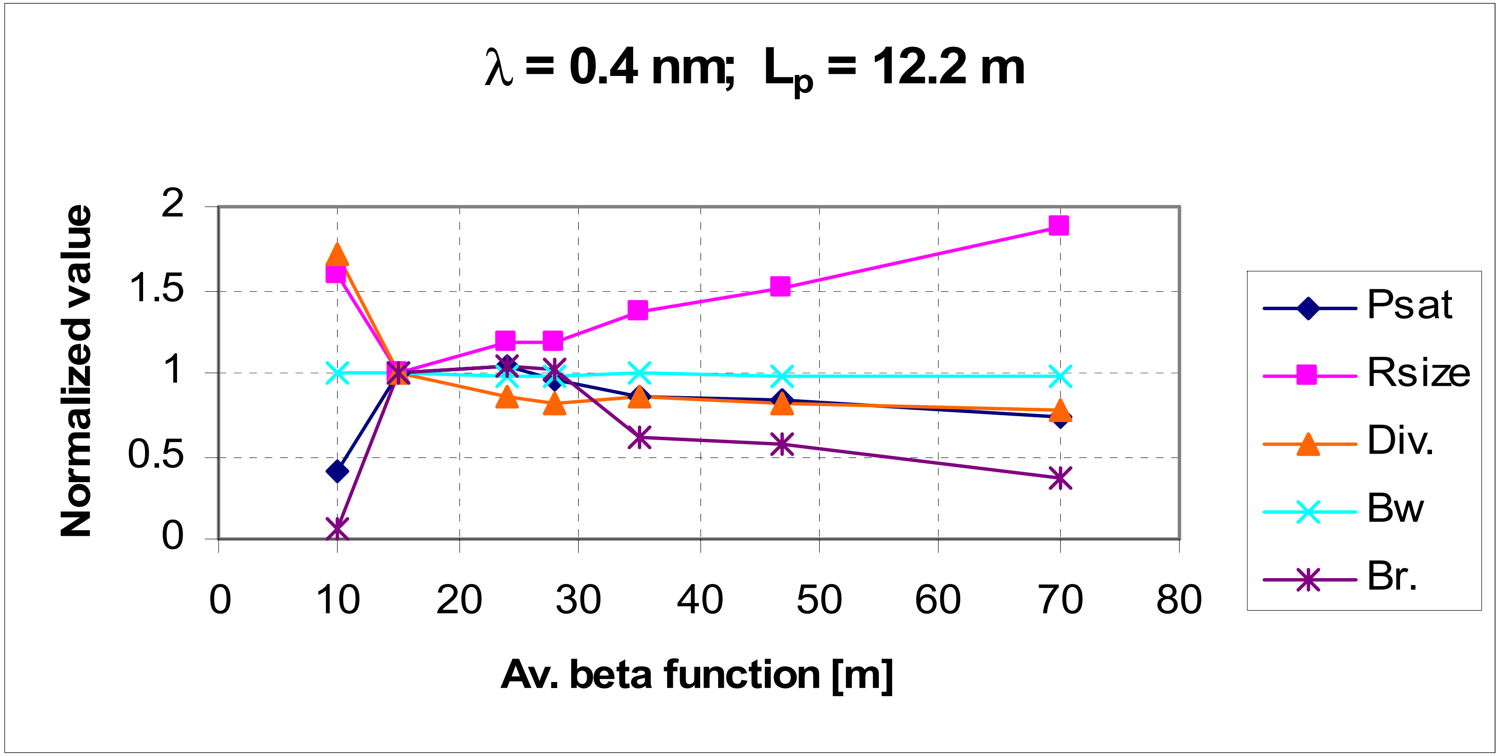




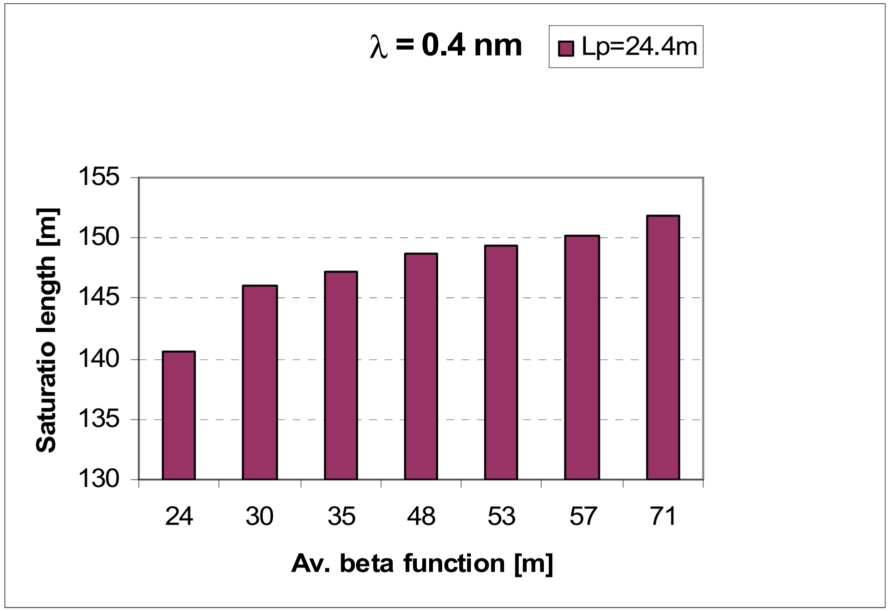
Saturation length dependence on the average beta function for the SASE2 undulator tuned to wavelength 0.4nm; Current design value for the av. beta is 15m.



Dependence of the brilliance/brightness on the average beta function for the SASE2 undulator tuned to wavelength 0.4nm; Current design value for the av. beta is 15m.

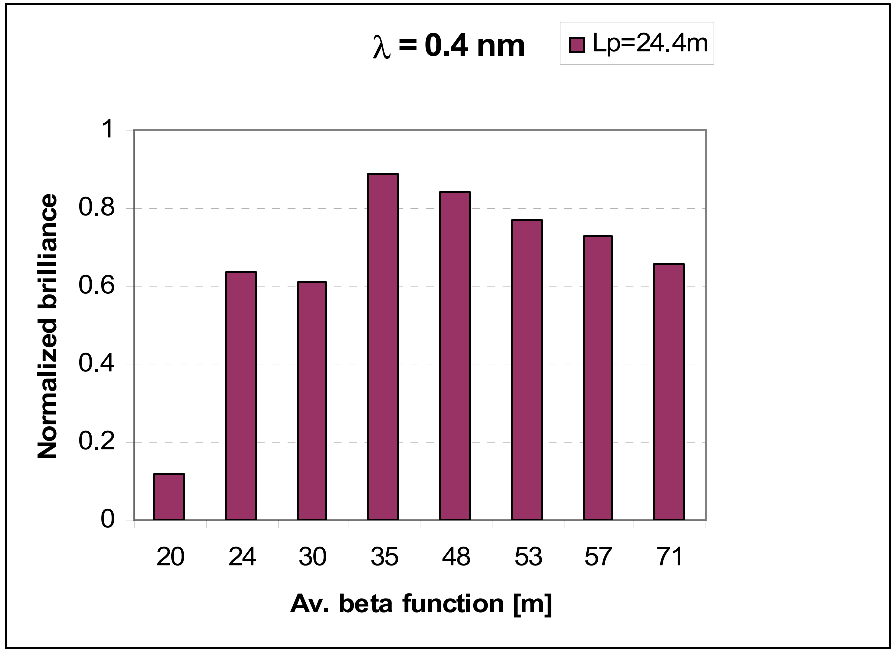


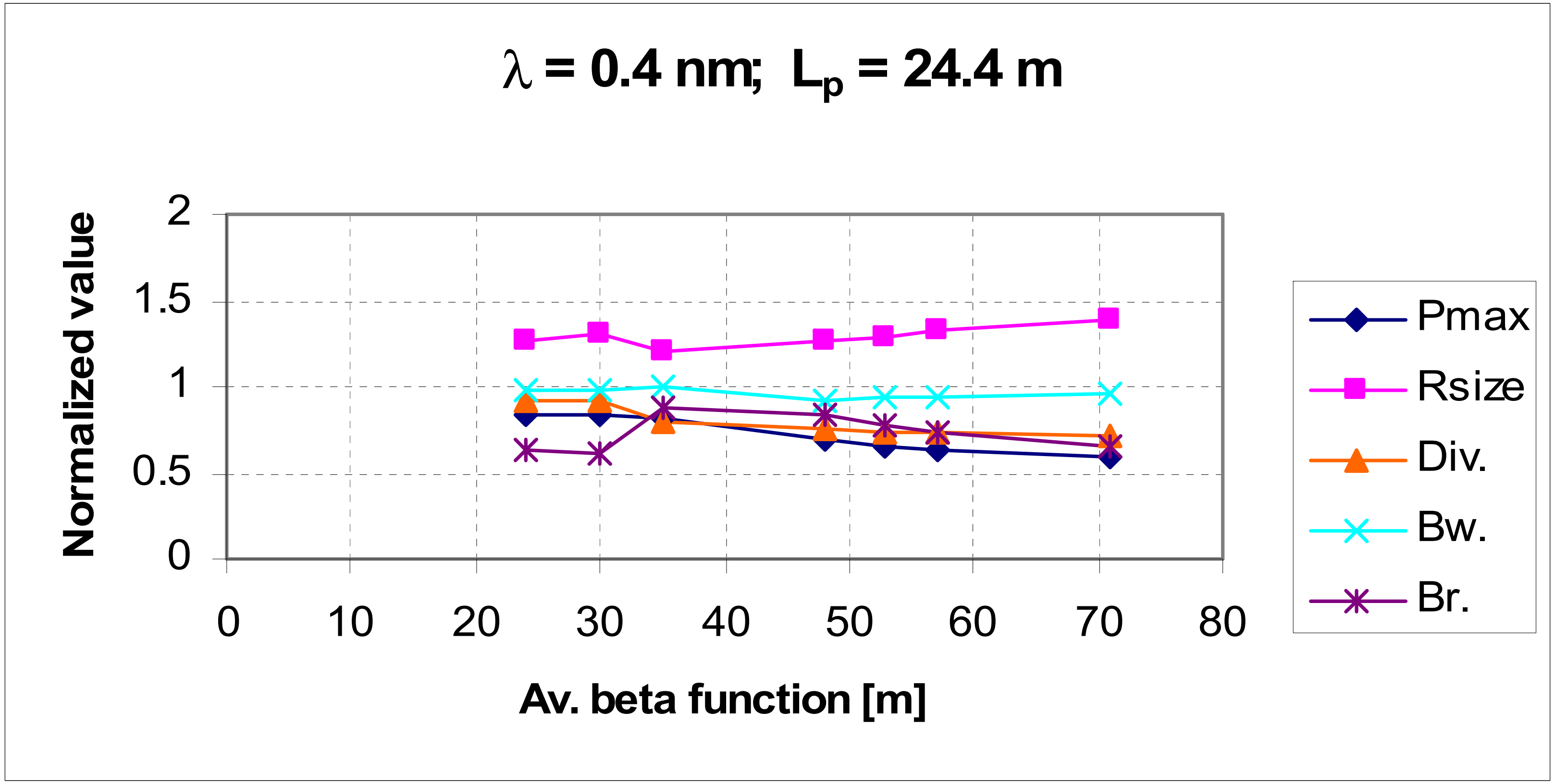
SASE2 undulator radiation parameters (maximum power, radiation size and divergence, bandwidth and brightness/brilliance) dependence on the average beta function. All parameters are normalized to those corresponding to the lattice current design parameters: 12.2m FODO period length and 15m average beta function.



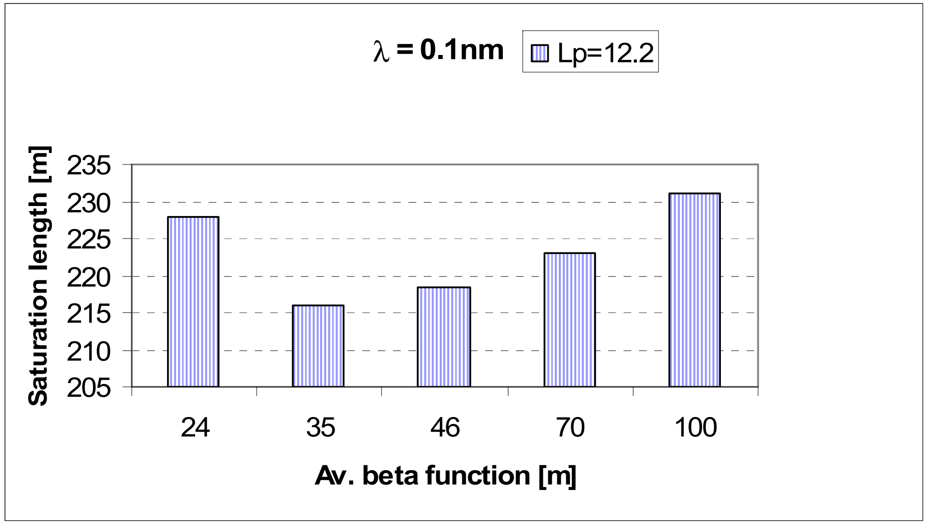
Saturation length dependence on the average beta function for the SASE2 undulator tuned to wavelength 0.4nm; FODO period length is 24.4m Current design value for the the period length is 12.2m.

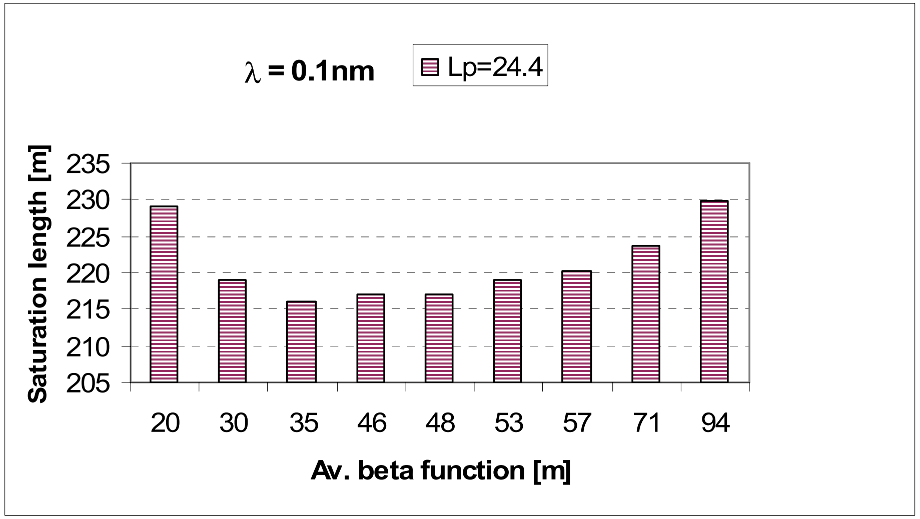
Dependence of the brilliance/brightness on the average beta function for the SASE2 undulator tuned to wavelength 0.4nm; FODO period length is 24.4m Current design value for the of the period length is 12.2m.

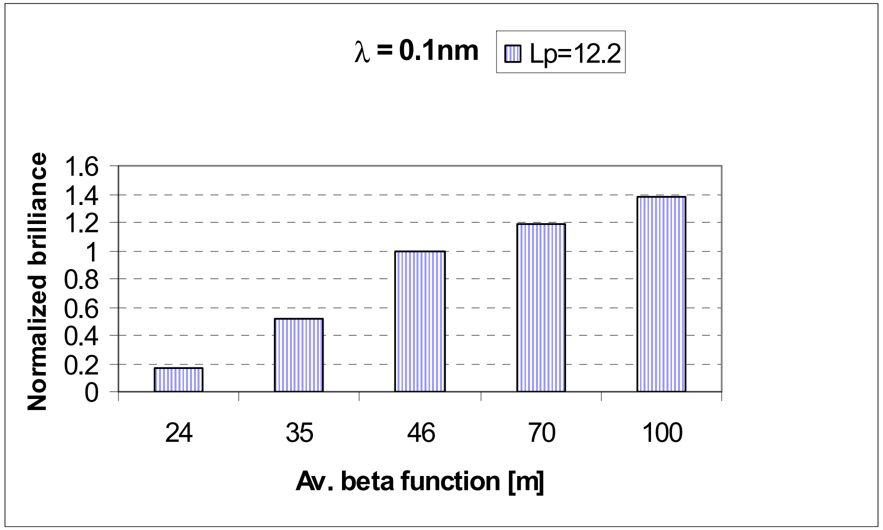


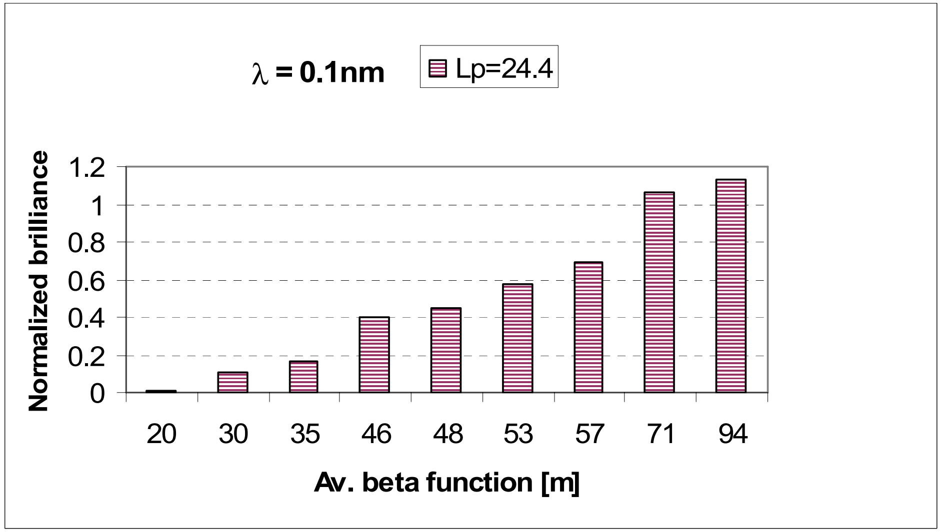


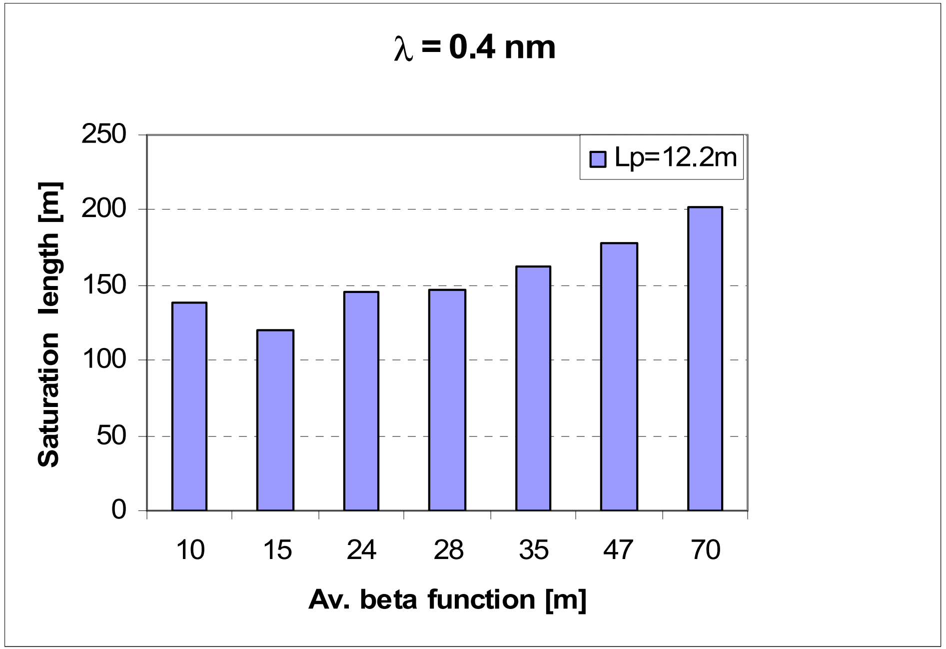
SASE2 undulator radiation parameters (maximum power, radiation size and divergence, badwidth and brightness/brilliance) dependence on the average beta function. All parameters are normalized to those corresponding to the lattice current design parameters: 12.2m FODO period length and 15m average beta function.

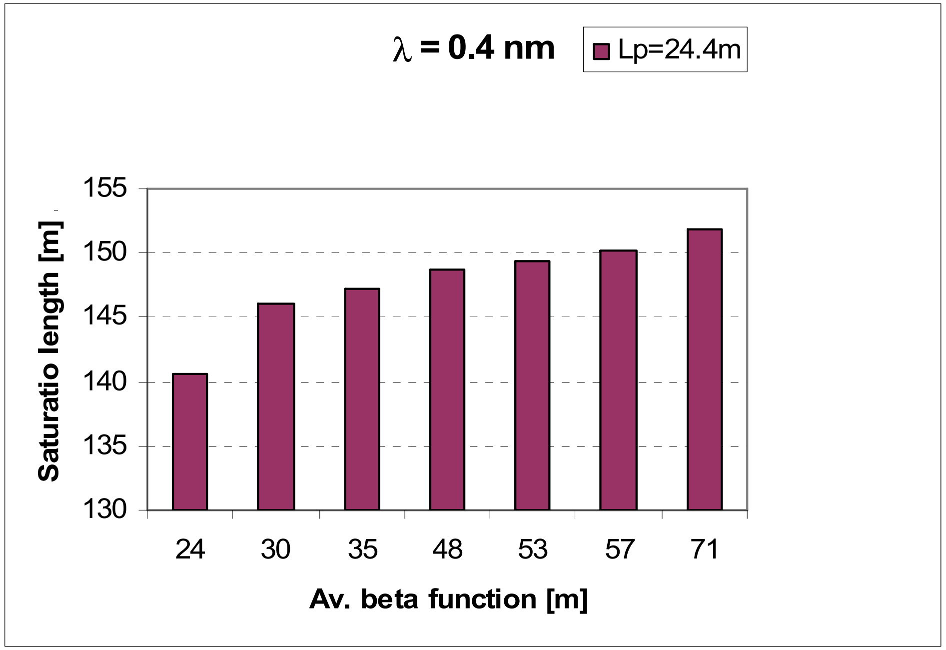

λ = 0.1nm
Lp=12.2
Saturation length [m]
235
230
225
220
215
210
205
24
35
46
70
100
Av. beta function [m]

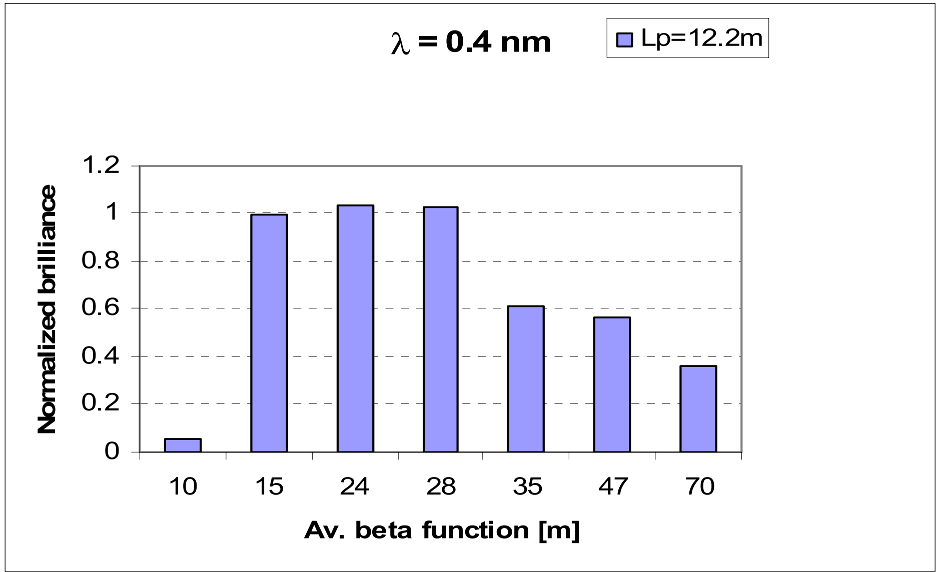

λ = 0.1nm
Lp=24.4
Saturation length [m]
235
230
225
220
215
210
205
20
30
35
46
48
53
57
71
94
Av. beta function [m]

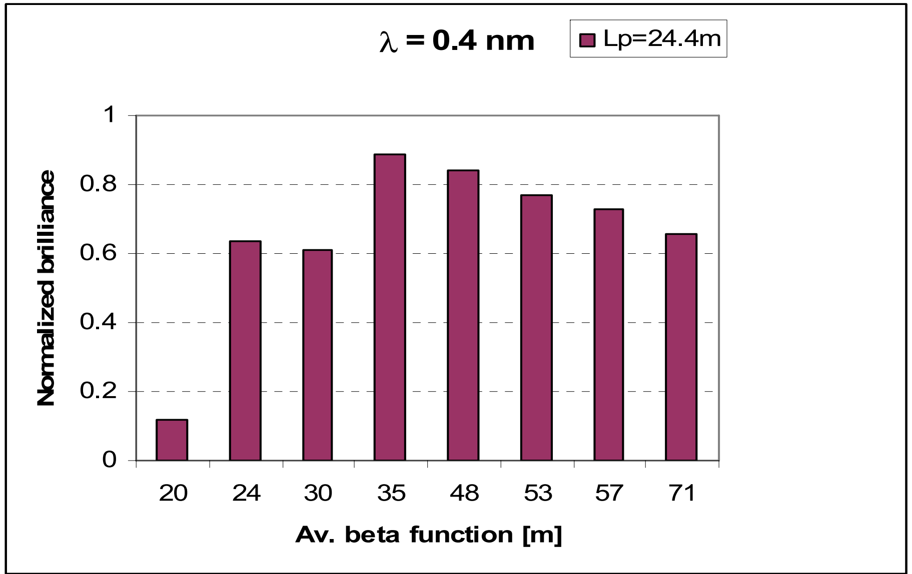

λ = 0.1nm
Lp=12.2
Normalized brilliance
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
24
35
46
70
100
Av. beta function [m]


λ = 0.1nm
Lp=24.4
Normalized brilliance
1.2
1
0.8
0.6
0.4
0.2
0
20
30
35
46
48
53
57
71
94
Av. beta function [m]


λ = 0.4 nm
Lp=12.2m
Saturation length [m]
250
200
150
100
50
0
10
15
24
28
35
47
70
Av. beta function [m]


λ = 0.4 nm
Lp=24.4m
Saturatio length [m]
155
150
145
140
135
130
24
30
35
48
53
57
71
Av. beta function [m]


λ = 0.4 nm
Lp=12.2m
Normalized brilliance
1.2
1
0.8
0.6
0.4
0.2
0
10
15
24
28
35
47
70
Av. beta function [m]


λ = 0.4 nm
Lp=24.4m
Normalized brilliance
1
0.8
0.6
0.4
0.2
0
20
24
30
35
48
53
57
71
Av. beta function [m]

Conclusions

- In terms of saturation length minimization for SASE2 undulator tuned to 0.1nm wavelength for the 12.2m FODO period 35m av. beta function is preferable over current design value of 46m.
- For the SASE2 undulator tuned to 0.1nm wavelength for the 12.2m FODO period brightness increases with the increase of av. beta function.
- For the same phase advance per cell the increase of the FODO period to 24.4m improves brightness of the SASE2 FEL tuned to 0.1nm by about factor 2.
- For the SASE2 FEL operating with 0.4nm wavelength design values and lattice period length 12.2m, the average beta function 15m is optimal.
- For the SASE2 FEL operating with 0.4nm wavelength for 24.4m of lattice period length compared with those of 12.2m period length saturation length increases and brilliance decreases(~10-15%).

A reduction of the number of quadrupole magnets brings significant benefits:

Saves the costs of eliminated magnets; Mitigates the difficulties associated with magnet misalignment and construction errors; Saves place between undulator segments, providing more room for phase shifters and diagnostic equipment; Gives possibility of shortening the gap between the segments and thus increasing the undulator “filling factor”.