The Use of Wigglers for Damping Rings

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Damping wiggler issues

- ♦ **Lattice cell optimization.**
- ♦ **Wiggler optimization.**

  (a) Damping optimization.
  (b) Emittance optimization (FODO, TME, …).
  (c) Linear effect minimization.
  (d) Non-linear effect minimization.

- ♦ **Radiation heat load.**

  ~ hundreds KW of SR has to be intercepted safely.

- ♦ **Wiggler design.**

Lattice cell and linear effect

For small transverse field roll-off wiggler mainly distorts the vertical optic.
For sin-like wiggler field approximation the vertical tune shift is

$$\Delta\nu_y = \frac{\bar{\beta}_y L_w}{8\pi\rho_w^2}$$

For FODO cell one can minimize the average beta function as

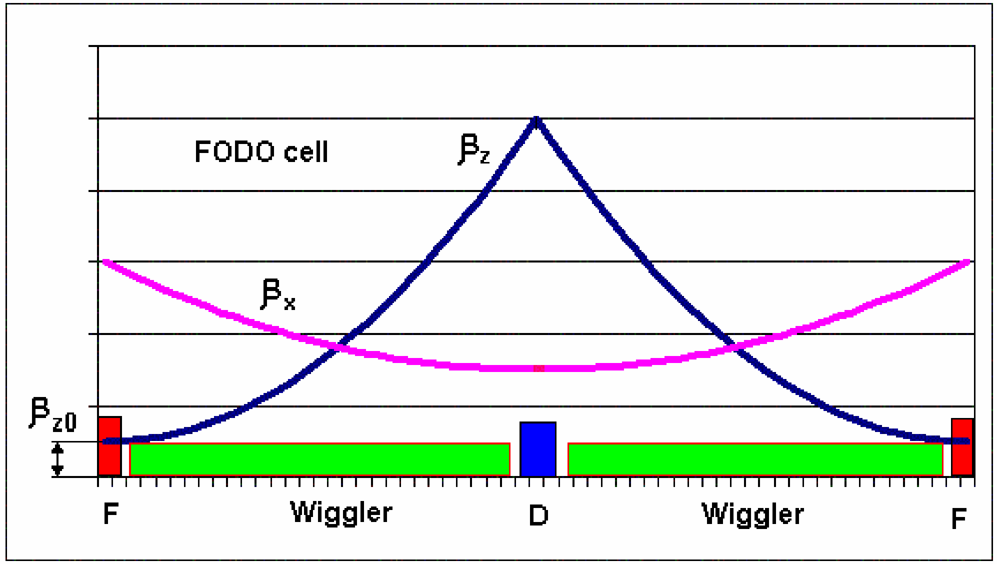
$$\bar{\beta}_{y\,\min} = \frac{2}{\sqrt{3}} l_w$$

where l_w is the wiggler length and

$$\beta_{y0} = \frac{1}{\sqrt{3}} l_w$$

The minimum tune shift is

$$\Delta\nu_{y\,\min} = \frac{1}{4\sqrt{3}\pi} n_w \frac{l_w^2}{\rho_w^2}$$



► Increasing the wiggler number n_w and small wiggler length l_w is preferable.

Radiation integrals (damping)

Damping integral:

$$I_2 = \int_M \frac{ds}{\rho^2} \quad \xrightarrow{\text{wiggler}} \quad i_2 = \frac{1}{2} h_w^2 L_w$$

where h_w is the peak curvature and L_w is the total wiggler length.

► **For higher damping increasing of the wiggler field is desirable.**

For several harmonics wiggler field $B_y(s) = \sum_k B_k \sin\left(\frac{2\pi k}{\lambda_w} \cdot s\right)$

$$i_2 \propto \sum_k B_k^2$$

Radiation integrals (energy spread and partition numbers)

- $$I_3 = \int_M \frac{ds}{|\rho^3|} \xrightarrow{\text{wiggler}} i_3 = \frac{4}{3\pi} h_w^3 L_w$$

Wigglers increase the energy spread but effect is small $\propto 1/\rho_w^3$

- $$I_4 = \int_M \frac{1-2n}{\rho^3} \eta ds \xrightarrow{\text{wiggler}} i_4 = -\frac{1}{32\pi^2} L_w \left(\frac{\lambda_w}{\rho_w^2}\right)^2$$

Effect is negligible $\propto 1/\rho_w^4$

Radiation integrals (horizontal emittance)

Wiggler dispersion
↓ derivative

$$I_5 = \int_{mag} \frac{H(s)}{\left|\rho^3(s)\right|} ds \quad \xrightarrow{\text{wiggler}} \quad i_5 = \frac{8}{15} N_w \theta_w \left[\frac{1}{\bar{\beta}_x} \left(5\frac{\eta_0^2}{\rho_w^2} + 9\theta_w^4 \right) + \bar{\beta}_x \frac{\theta_w^2}{\rho_w^2} \right] \approx \frac{8}{15} N_w \bar{\beta}_x \frac{\theta_w^3}{\rho_w^2}$$

$$H(s) = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2$$

Residue ring ↑
dispersion

↑ Wiggler
dispersion

$$\theta_m = \frac{\lambda_w}{2\pi\rho_w}$$

► Residue dispersion control: $\eta_0 << \frac{\bar{\beta}_x \cdot \theta_m}{\sqrt{5}}$

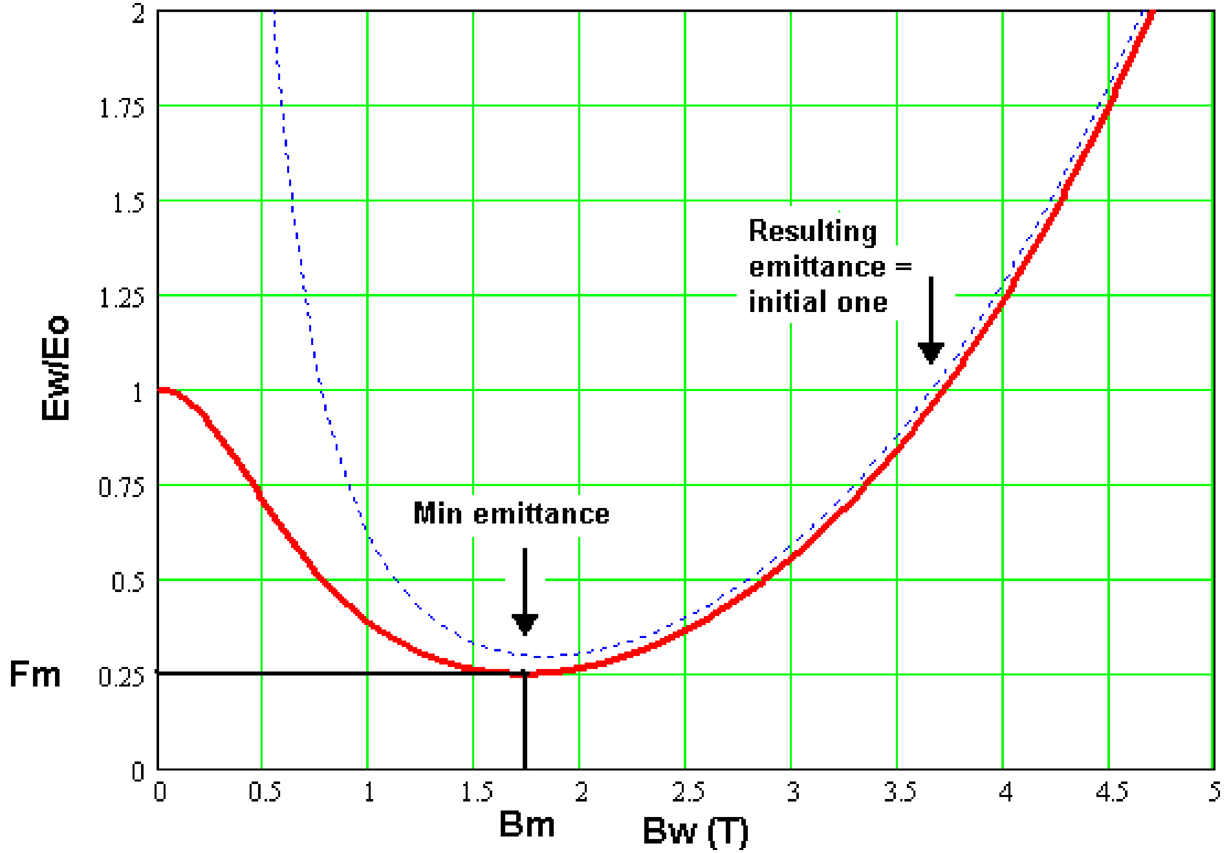
► Beta-x optimization for FODO cell $\bar{\beta}_{x\min} = l_w / \sqrt{3}$ $\quad i_{5\min} = \frac{2}{15\sqrt{3}\pi^3} \cdot L_w \cdot l_w \cdot \frac{\lambda_w^2}{\rho_w^5}$

► To reduce i_5 it is necessary (a) reduce the cell length, (b) reduce the period length, (c) increase the peak field but to some extend.

Emittance minimization

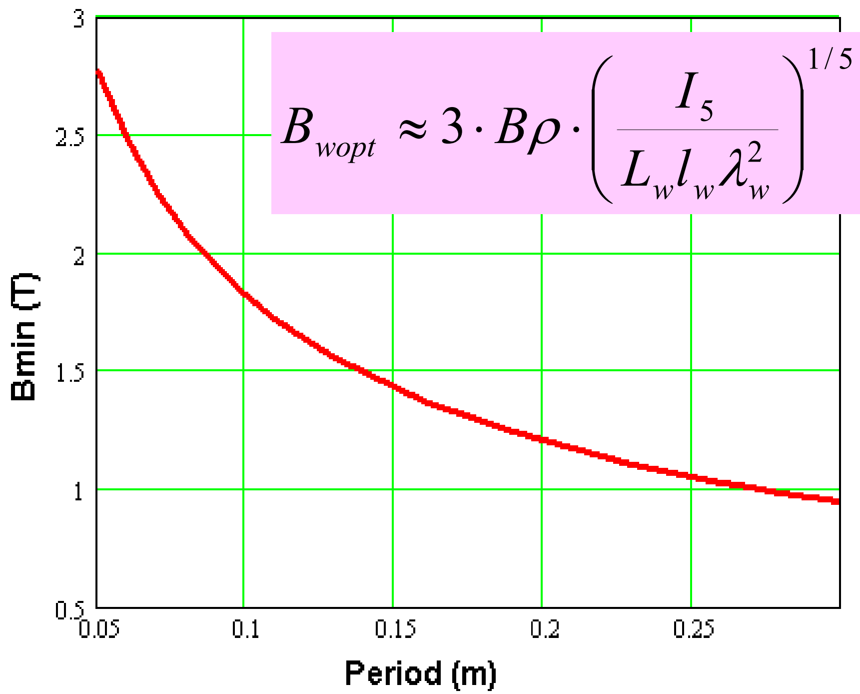
$$\frac{\varepsilon_w}{\varepsilon_0} = C_q \frac{\gamma^2}{J_x} \frac{1 + i_5 / I_5}{1 + i_2 / I_2}$$

► **Resulting emittance has minimum for particular peak field.**

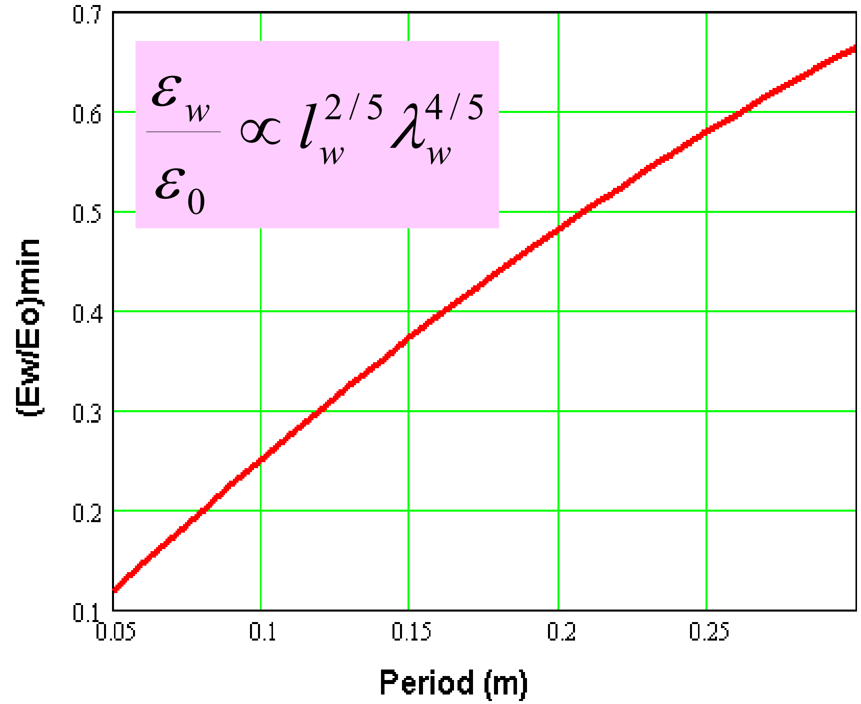


Optimum peak field and period length

- Spurious ring dispersion is zero.
- FODO cell with minimized horizontal beta.
- Wiggler dominating damping.
- Sine-like wiggler model.



$$B_{wopt} \approx 3 \cdot B\rho \cdot \left(\frac{I_5}{L_w l_w \lambda_w^2} \right)^{1/5}$$



$$\frac{\varepsilon_w}{\varepsilon_0} \propto l_w^{2/5} \lambda_w^{4/5}$$

► **To reduce the resulting emittance one have to reduce the wiggler period and increase the peak field.**

Wiggler nonlinearity

The main effect is due to the wiggler magnets edge field producing strong vertical cubic nonlinearity.

$$\Delta H = \frac{1}{24} n(s) y^3 \quad \longrightarrow \quad (n \cdot l) = \frac{B''' \cdot \lambda_w}{B\rho} = \frac{8\pi^2}{\lambda_w \rho_w^2}$$

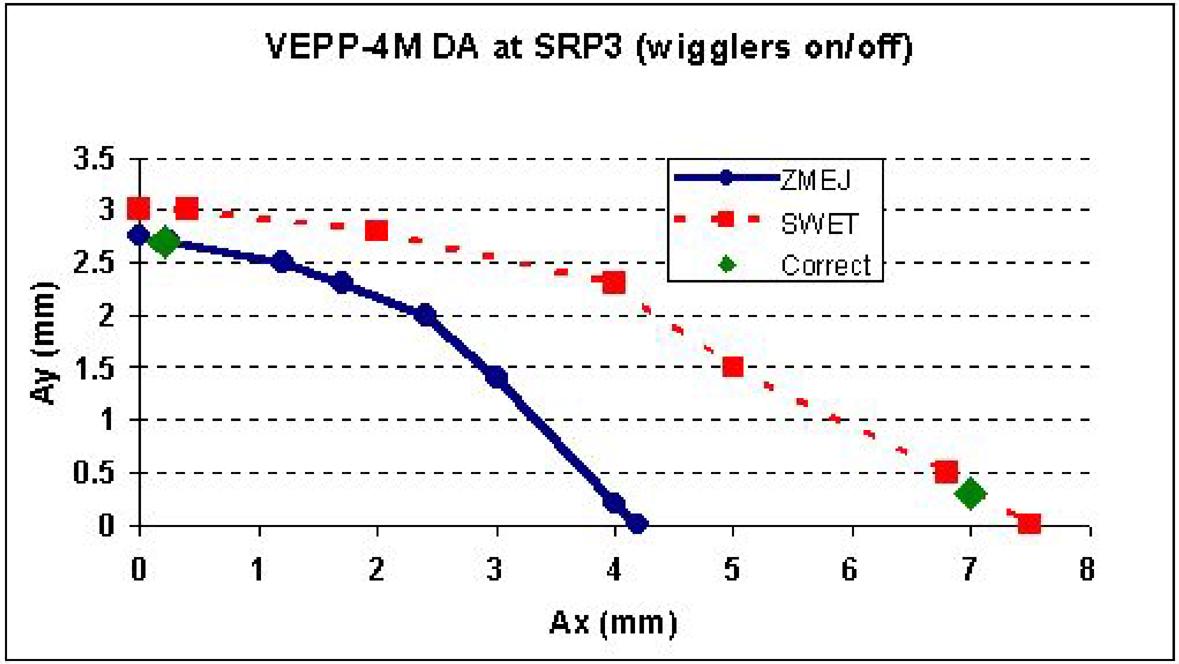
and relevant amplitude-dependent tune shift is given by

$$\Delta \nu_y (J_y) = \left(\frac{\pi \cdot L_w \bar{\beta}_y^2}{\lambda_w^2 \rho_w^2} \right) \cdot J_y$$

► Reducing of the wiggler period results in the enhancement of the vertical cubic nonlinearity.

Wiggler nonlinearity (experiment)

Octupole magnets correction of the wiggler tune-amplitude dependence may be effective.



Змейка	Октуп. корр. *SEOQ* (A)	$\times 10^4$, мм$^{-2}$			
		C_{xx}	C_{xy}	C_{yx}	C_{yy}
Off	0	3	–0.1	**1.2**	**–2**
On	–3	5	3	**10**	**8**
On	+9	5	1	**3**	**2**

Radiation heating problem

♦ Several hundreds kW or even MW of SR power from wigglers must be safely absorbed.

♦ Periodic structure of absorbers + long lumped absorber in the end of the wiggler straight section.

♦ Tight tolerance for COD in the wiggler section. COD feedback system.

♦ Fast dump of the beam in case of any failure.

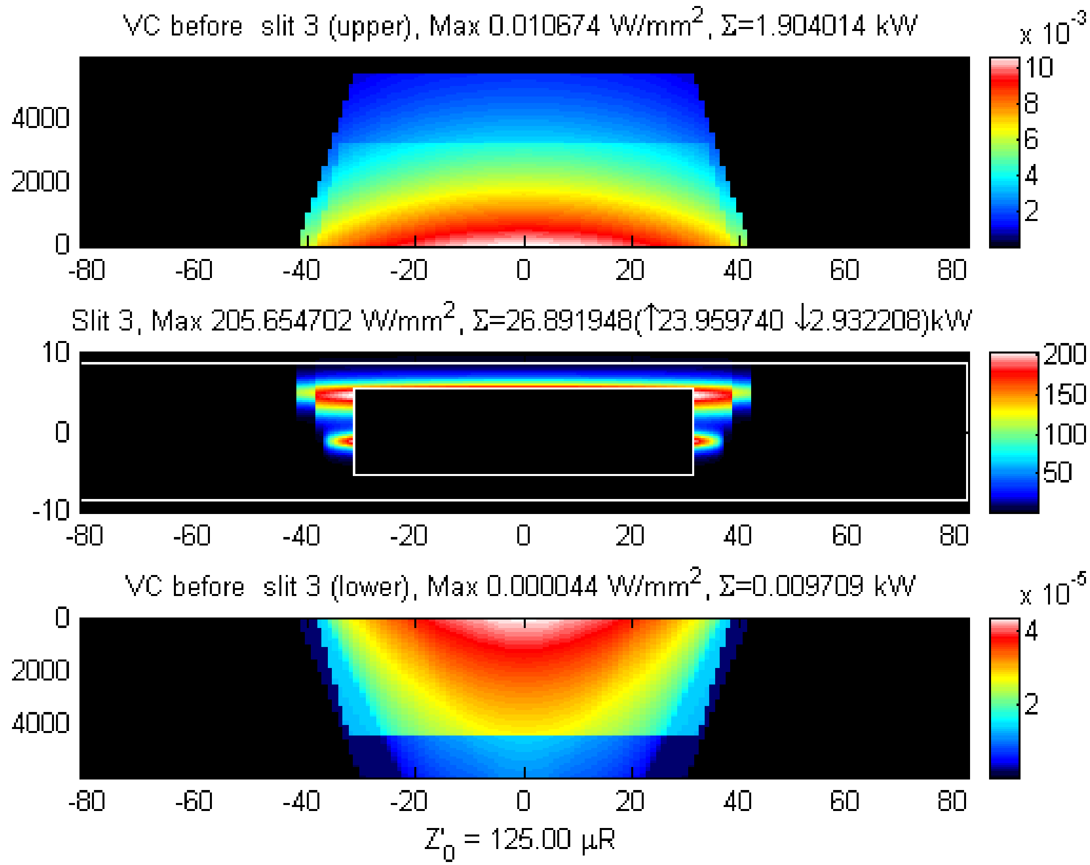
♦ Powerful SR hitting the absorber surface generates particles shower that can cause damage of magnet coils.

Radiation heating problem

10 damping wigglers of PETRA III generate 400 kW of SR.

Periodic absorbers: 200 kW

Single 10-m absorber: 200 kW



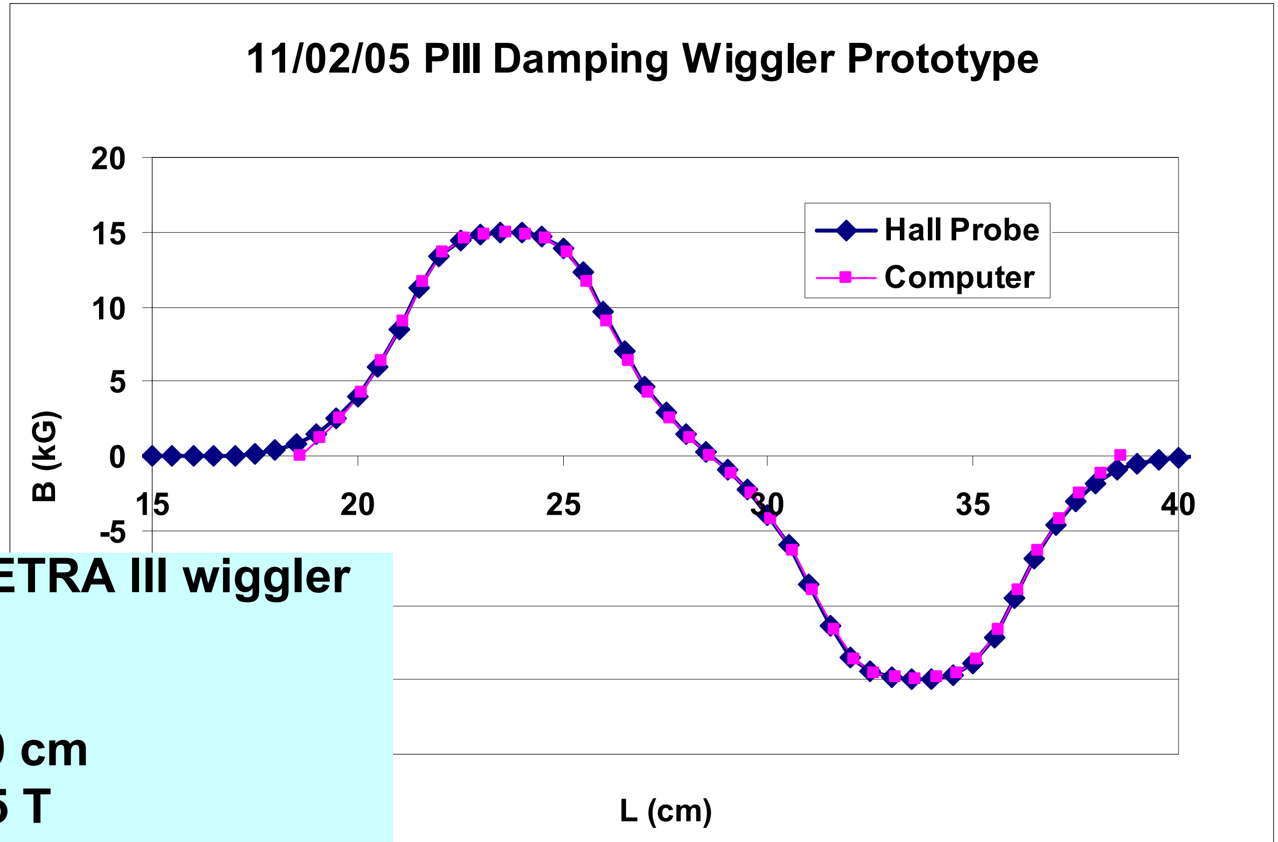
Examples of damping wiggler design

BINP experience:

- ~ 100 m of the permanent magnet wigglers at PETRA III result in 4-times emittance reduction.
- Permanent magnet and superconducting wiggler design for the CLIC damping ring.
- More than 10 superconducting wigglers developed and installed at different machines.

Permanent magnet wiggler (PETRA III)

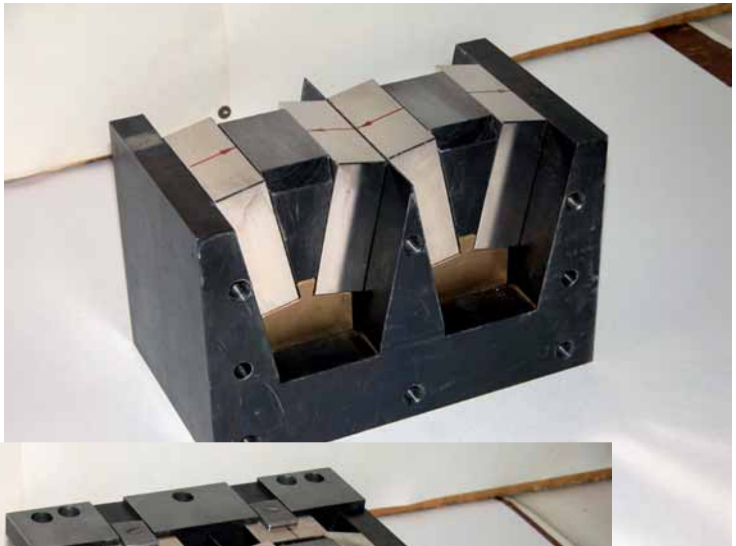
Field measured and computed →

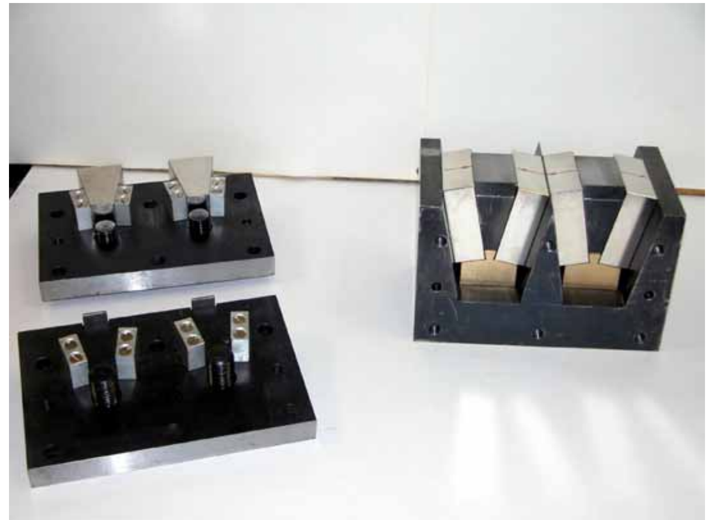


Main parameters of the PETRA III wiggler

No of wigglers:	20
Period:	20 cm
Field amplitude:	1.5 T
Field quality @ 1 cm:	10^{-3}
Total length:	80 m
Total radiation power:	887 kW

Permanent magnet wiggler





Damping wiggler for the CLIC DR (project)

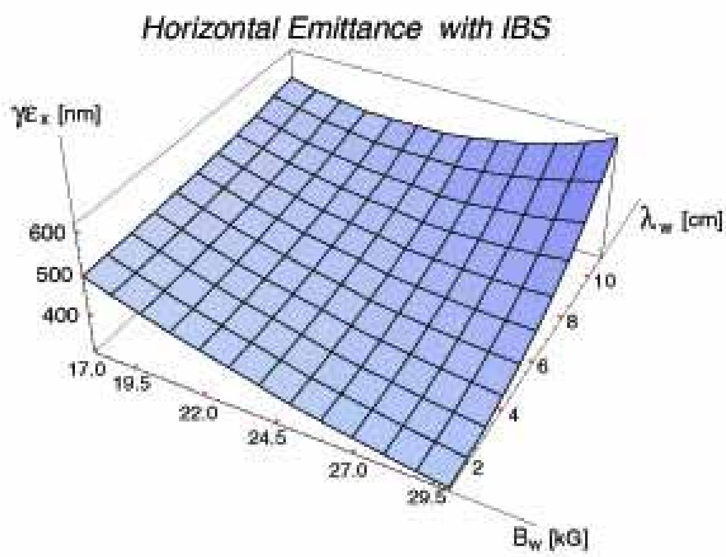
Permanent wiggler:

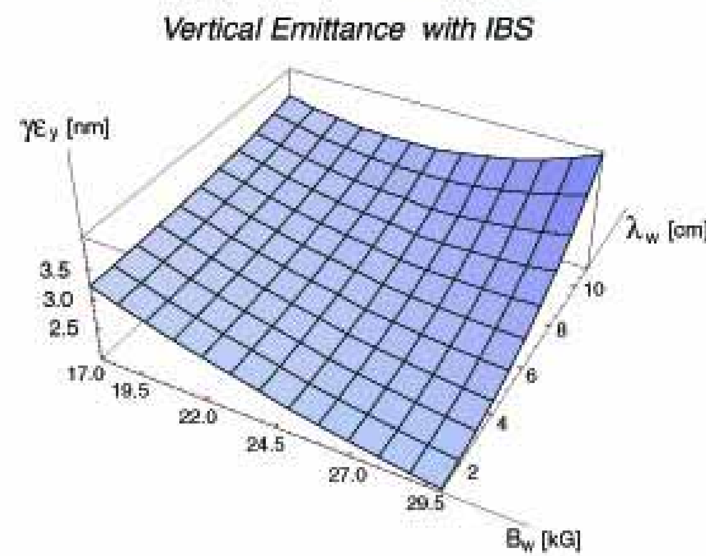
Period:	10 cm
Field amplitude:	1.7 T
Gap:	12 mm
Pole width:	50 mm
Length:	2 m
Field quality @ ±1 cm:	10^{-3}
Total length:	160 m
Total radiation power:	1.7 MV at 1 A

SC wiggler:

❖ Period length	45 mm
❖ Field amplitude	2.5 T
❖ Pole gap	20 mm
❖ Beam aperture	12 mm
❖ Superconductor	Nb_3Sn
❖ Field quality	~10^{-4} at ± 1 cm.

Normalized emittances with IBS of the CLIC DR as a function of wiggler period and wiggler peak field at betatron coupling 0.65%

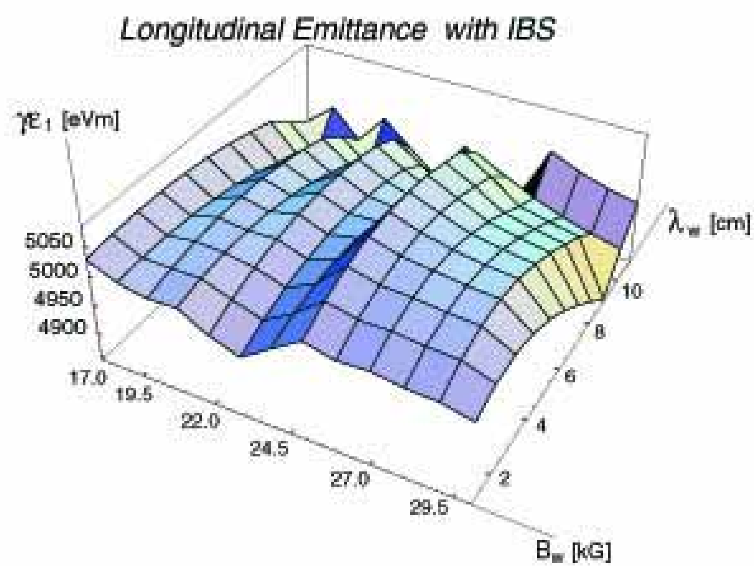




$\gamma\varepsilon_x$ = 400 nm $\gamma\varepsilon_z$ = 2 nm

at 2.4 GeV incl. IBS

	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
1.0	494	472	452	432	415	399	383	365	353	341	329	319	309
2.0	495	473	452	433	417	401	385	367	355	344	333	323	314
3.0	496	475	454	436	419	404	389	372	361	350	340	331	324
4.0	498	478	458	440	423	409	395	379	369	360	351	344	338
5.0	502	482	462	445	429	416	404	388	380	373	366	360	357
6.0	505	487	467	452	437	425	414	400	394	389	385	382	382
7.0	510	492	474	460	446	436	427	415	411	409	408	408	412
8.0	515	499	482	469	457	449	443	433	431	433	436	440	449
9.0	522	507	491	481	470	464	461	453	456	462	469	478	494
10.0	534	520	505	497	487	485	485	484	490	500	513	529	549
11.0	542	526	518	508	505	506	506	514	525	537	556	579	607



Maxim Korostelev 16.09.2005 (CLIC meeting)

Superconducting wiggler

3.5 TESLA SUPERCONDUCTING WIGGLER for ST (TRIESTE, Italy), 2002

Parameter	Units	Value
Max magnetic field	T	3.62
Operating magnetic field	T	3.5
Number of base poles		45
Number of additional poles		4
Gap	mm	16.5
Pole length (period)	mm	32 (64)
Energy content	kJ	240

Superconducting wiggler

7 TESLA 17 POLE SUPERCONDUCTING WIGGLER

for BESSY-II, HMI, (Berlin, Germany), 2002

Parameter	Units	Value
Max magnetic field	T	7.45
Operating magnetic field	T	7
Number of base poles		13
Number of additional poles		4
Gap	mm	19
Pole length (period)	mm	74 (148)
Energy content	kJ	460

Conclusions

♦ Superconducting devices seem to be most effective as damping wigglers. The field up to 2.5-4 T can be achieved for 50-70 mm period and 15-20 mm gap.
Expensive and requires cryogenic equipment.

♦ Permanent magnet devices can provide 1.5-2 T in gap 20-10 mm for period ~10…15 cm.
Cheap and reliable but not so effective as SC devices .

♦ Damping wigglers have to be design together with DR (damping optimization, minimization of the wiggler effect to the beam, …).

♦ Radiation power interception has to be considered carefully.