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EVACUATION OF SR POWER FROM THE CLIC DAMPING RING

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Abstract

Absorption of synchrotron radiation (SR) power generated by wigglers of damping rings is a difficult technical task. The CLIC damping ring operates with electron (or positron) beams with energy 2.424 GeV, average beam current is up to 150 mA. The 38 wigglers installed in one straight section of the CLIC damping ring produce radiation with a total power of about 122 kW. Power density at the end of the straight sections is about 75 W per square mm. Such a power density can destroy vacuum chambers, therefore a careful design and placement of appropriate radiation collimators and absorbers is required.

In this paper we describe an algorithm to compute SR power density as well as options for safe absorption of SR power. All the calculations were performed for the current design of the CLIC damping ring and wigglers. Some related problems for absorption of high SR power are described.

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1. Introduction

The CLIC damping ring facility is destined to reduce emittance of electron and positron bunches for the Compact Lineal Collider (CERN) [1]. A general layout of the damping ring for the currently adopted design (May, 2005) is presented in Figure 1. The damping ring is of the racetrack shape. The total circumference is about 360 m and the working energy is 2.424 GeV. Two arc sections have theoretical minimum emittance (TME) magnetic structures. Long straight sections have FODO structures and are assigned to comprise a large number of damping wigglers (38 wigglers in every section).

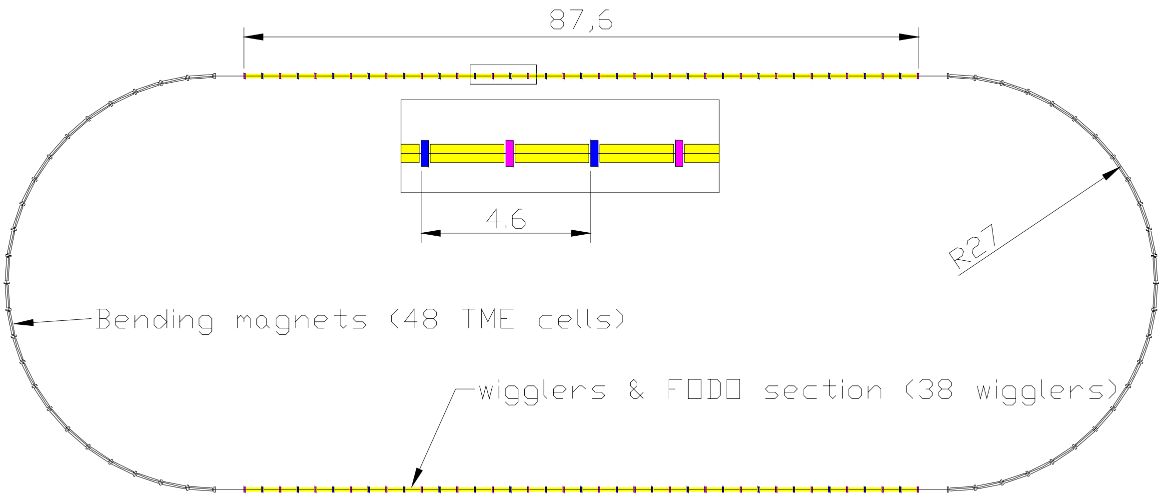

Figure 1: General layout of the CLIC damping ring.

For our calculation we use parameters of the permanent magnet wigglers listed in Table 1. Such wiggler are considered as a candidate design for the CLIC damping ring.

Table 1. Main parameter of permanent magnet damping wigglers.

Parameter	*Symbol*	*Value*
Maximal magnetic field in the wiggler	B	1.7 T
Period of the wiggler	λ	10 cm
Magnetic gap of the wiggler	d	12 mm
Number of periods	N	20
Length of the wiggler	L	2 m
Vertical beam aperture		8.5 mm
Number of wigglers in the straight section	N_W	38

Basic parameters of SR beams can be estimated by these values. Main parameters of SR beams are presented in Table 2.

Table 2. Main parameters of electron and SR beams

Parameter	*Symbol, formula*	*Value*
Beam current (maximal)	I	150 mA
Electron energy	E_e	2.424 GeV
SR critical energy	$\varepsilon_c[\text{keV}] = 0.655 \cdot E_e^2[\text{GeV}] \cdot B[\text{T}]$	6.541 keV
Deflection parameter K	$K = 0.934 \cdot B[\text{T}] \cdot \lambda\,[\text{cm}]$	15.878
Relativistic factor	$\gamma = E_e / m_e c^2$	4743
Vertical divergence angle	$\theta_v = 1/\gamma$	210.8 μrad
Horizontal divergence angle	$\theta_h = 2K/\gamma$	6.695 mrad
Tot.power from one wiggler	$P_T[\text{kW}] = 0.633 \cdot E_e^2[\text{GeV}] \cdot B^2[\text{T}] \cdot L[\text{m}] \cdot I[\text{A}]$	3.22 kW
Tot.power from 38 wigglers	$P_A[\text{kW}] = P_T \cdot N$	**122.5 kW**

It is seen that large total radiation power creates a serious problem of safe SR absorption. A dedicated system of SR absorbers is indispensable.

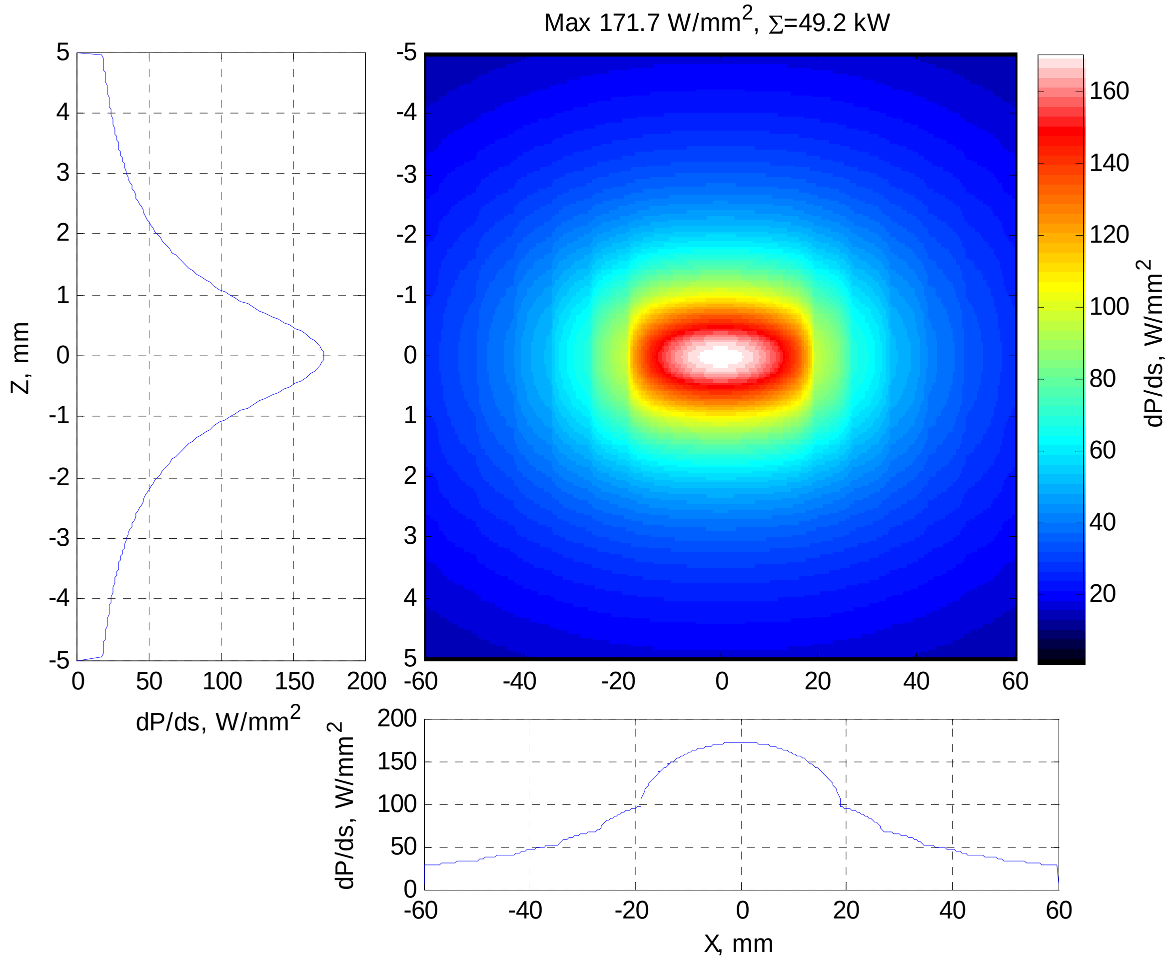

Figure 2: Power density distribution from all wigglers at the end of the straight section.

Another problem is linked with the high density of power due to narrow angular divergence of SR beams. Figure 2 shows power density distribution in the transverse plane at the end of the straight section (on axis orbit, no COD is assumed). The maximal value of power density in the center of the map is 171.7 W/mm^2.

Due to the small vertical aperture of the vacuum chamber (8.5 mm, see Table 1) and long straight section (about 88 m, see Figure 1) it is clear that protection of the vacuum chamber of the wigglers is also a problem.

One goal of this work is to find ways of SR power absorption with maximal safety and protection of the vacuum chambers even in case of inevitable orbit distortion. Another goal is to define the maximal level of closed orbit distortion (COD) and tolerances of transverse mechanical adjustment for optical elements and wigglers that permits safe absorption.

2. Method to Estimate the Absorbed Power

We use the formulae from [3] to estimate angular distribution of the power radiated by wigglers. The total power radiated by a wiggler is:

$$P_T[\mathrm{kW}] = 0.633 \cdot E_e^2[\mathrm{GeV}] \cdot B^2[\mathrm{T}] \cdot L[\mathrm{m}] \cdot I[\mathrm{A}], \tag{0.1}$$

all notations are given in Table 1 and Table 2. The angular distribution of irradiated power is given by

$$\frac{dP}{d\Omega} = \frac{d^2P}{d\theta\, d\psi} = P_T \frac{21\gamma^2}{16\pi K} G(K)\, f_K(\gamma\theta, \gamma\psi) \tag{0.2}$$

where θ is the horizontal angle (count from the wiggler axis), and ψ is the vertical one,

$$G(K) = K \frac{K^6 + \frac{24}{7}K^4 + 4K^2 + \frac{16}{7}}{\left(1+K^2\right)^{7/2}} \tag{0.3}$$

and

$$f_K(\gamma\theta, \gamma\psi) = \sqrt{1-\left(\gamma\theta/K\right)^2}\left\{\frac{1}{\left(1+(\gamma\psi)^2\right)^{5/2}} + \frac{5(\gamma\psi)^2}{7\left(1+(\gamma\psi)^2\right)^{7/2}}\right\} \tag{0.4}$$

The expressions shown above were used to estimate absorbed power density distributions on the absorber blades and on the vacuum chamber walls.

The absorbers are placed regularly along the wiggler straight section. Thus, to take into account the effects of shadows from upstream absorbers, we used a simple ray tracing procedure. In order to evaluate power density distribution over the surface of the absorber or vacuum chamber wall, this surface is approximated by a rectangular mesh. Power density in each node of the mesh is calculated. The resulting value is set to zero if the corresponding ray (from the wiggler to the node) is intercepted by the blade of an upstream absorber.

In the cases of COD, the angles θ and ψ are replaced with $\theta - \theta_w - x_w / l$ and $\psi - \psi_w - z_w / l$ respectively, where θ_w and ψ_w are the horizontal and vertical angles of electron trajectory in the wiggler; x_w, z_w are the transverse coordinates of electron orbit in the wiggler center; l is the distance between the mesh node and center of the wiggler. The procedure is repeated for each of the nodes and for every wiggler. Transverse orbit angles and coordinates at the wiggler center are calculated with the use of optical functions in the straight section for a COD with the defined maximal deviation and for different values of initial betatron phases.

3. Absorbers Arrangement

The most critical parameter is the linear power density on the absorber surface, which, in accordance with our experience for a copper water cooled wall, should not exceed ~150-200 W/cm. So, the main task for the absorption system design is to optimally split the radiation among a number of absorbers and to distribute power density over the absorber length. Three possible ways (Figure 3) can be considered:

- Regular absorber installed in every FODO cell between the wiggler and quadrupole lens (or inside the lens) so that every absorber gets a relatively small portion of outermost SR rays. But of course, the central (and most powerful) part of the SR beam is to be absorbed in the end of the straight section by a specially designed lumped absorber.
- Long absorbers installed in some of the FODO cells instead of a wiggler module.
- Chicane scheme when an achromatic (not spoiling emittance) small angle (~1°) bend is inserted downstream several wigglers whose radiation is absorbed by stand aside absorbers.

Sometimes, some combinations of method mentioned above can be applied [4].

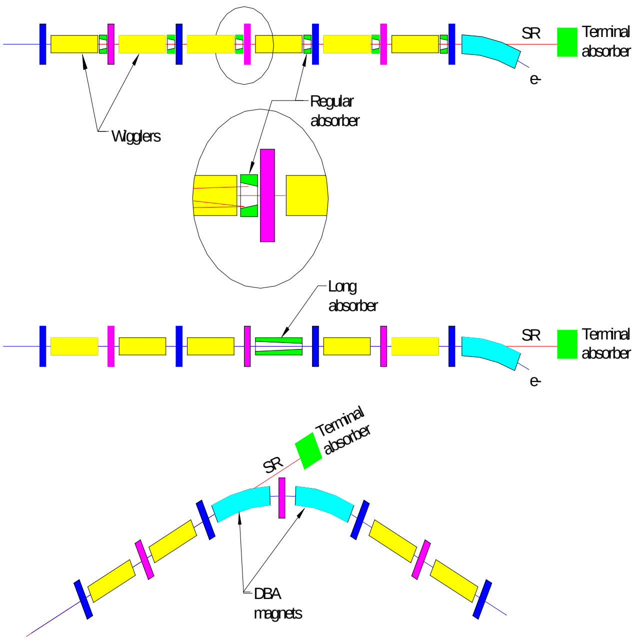

Figure 3: Different ways of absorbers arrangement.

In case of the chicane approach an optical study and optimization of the achromatic bend is required therefore we concentrate on the on-axis absorber locations only.

Long absorbers schemes are not well adapted for use with the CLIC damping rings. Because of the relatively wide vertical angular distribution of synchrotron radiation, the SR fan rays can reach a wall of vacuum chamber after few (about 5) FODO cells. Therefore the long absorber replacing wiggler modules in the FODO cells would have to be distributed along the straight section in large numbers. For example, every 5-th cell should contain a long absorber. This would considerably reduce the total length of wigglers in the ring, thus reducing significantly the damping rate. Therefore the regular absorbers seems to be most suitable for effective SR power evacuation.

4. Regular Absorbers Configuration

In the power load calculation we have assumed a rectangular shape of the vacuum chamber and absorber aperture.

The vertical absorber gap depends on the machine acceptance and amplitude betatron function at the absorber azimuth. To prevent reduction of vertical acceptance by the absorbers it is necessary to study the combined effects of beam envelop for different COD's. In our research the 6/8 mm absorbers configuration has been chosen. It means, that in focusing quadrupole lenses absorbers have a vertical 6 mm gap, and 8 mm gap in defocusing lenses. Those gaps provide 2 mm·mrad acceptance.

Figure 4 shows a schematic view of the wiggler straight section for the 6/8 absorber configuration. Absorbers blades are shown in green, the yellow bars show wigglers and the light green line indicates the vacuum chamber aperture. The dark blue line shows the distorted beam orbit with maximum deviation amplitude of 0.3 mm while 1-mm-amplitude betatron oscillations around this COD are shown in light blue.

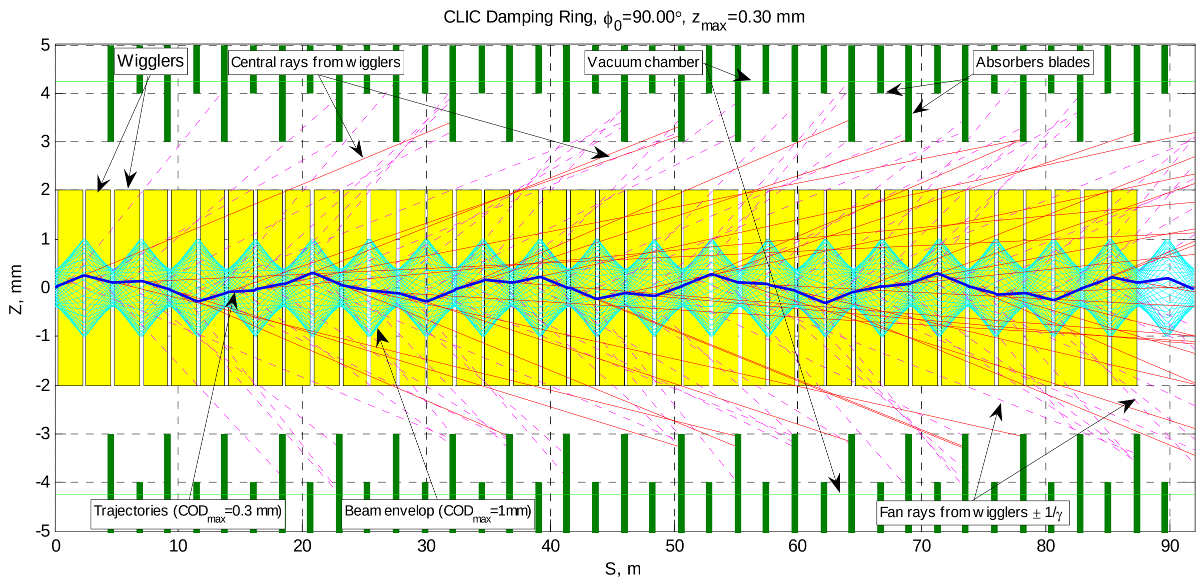

Figure 4. Schematic view of the wiggler straight section.

The red lines depict central SR rays from each wiggler, and the dashed magenta lines present SR fan distribution with an angular width of $\pm 1/\gamma$. It is worth to note that the vertical divergence of the wiggler radiation for 0.1 mm COD is determined mainly by the natural SR cone because $\theta_\gamma = 1/\gamma >> \Delta z' \approx \Delta z / \beta_z$.

Figure 5 shows the total power loads on wiggler vacuum chambers (due to the distribution tails) and absorber blades for a 0.1 mm COD. One can see that the 4/6 configuration is good enough to prevent the wiggler vacuum chamber from overheating with SR. Indeed, 20 W of the total power for every half chamber (upper or lower) can be easily removed by cooling water.

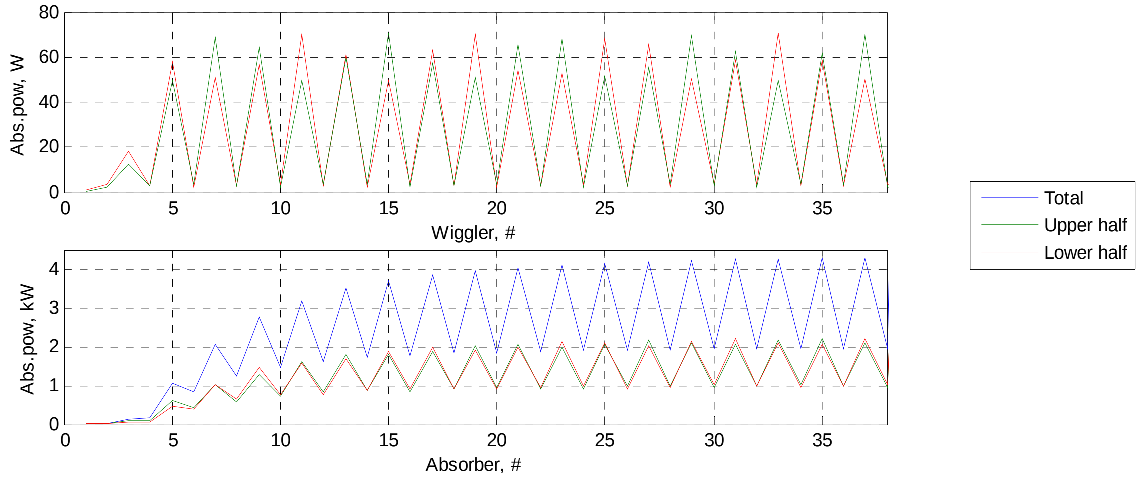

Figure 5: Total power loads for vacuum chambers (the upper plot) and absorbers (the lower plot) (COD is 0.1 mm; the 6/8 mm configuration).

As for absorber blades, 4 kW is also permissible for the copper water cooled absorber with a length of ~0.2-0.4 m. Some reduction of the blades power load can be achieved via optimization of the absorber widths. So, the total power loads for absorber blades and vacuum chambers for the 6/8 configuration satisfy the requirement of safe SR power evacuation.

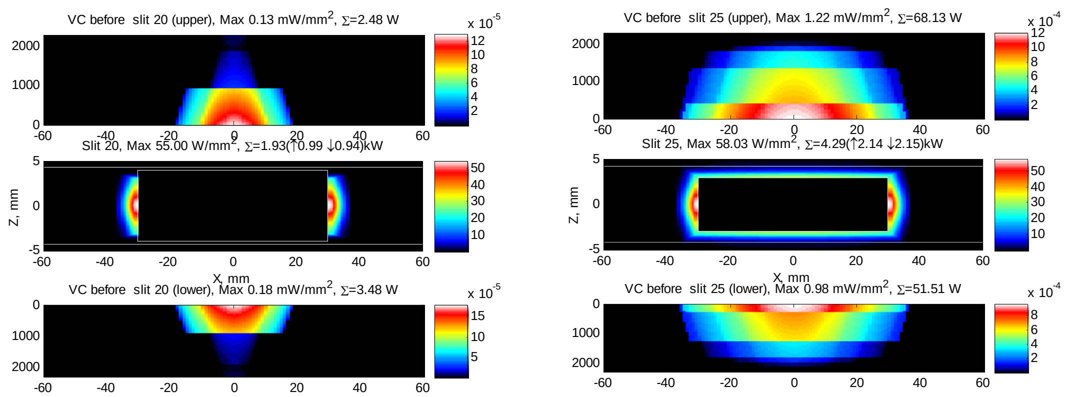

Figure 6: Power density distribution for absorbers 25 (left) and 20 (right) and for upper and lower halves of the vacuum chamber before them.

For two absorbers (No.25 and No.20) the power density distribution is shown in Figure 6. These absorbers are located in the regular part of the longitudinal power profile (see Figure 5) where the radiation power from upstream wigglers already reaches its maximum. The vertical aperture for the absorber 25 is 6 mm and for the absorber 20 is 8 mm. The plots in Figure 6 are arranged as follows. In the center one can see the power density distribution at the absorber slit (in the plane perpendicular to the beam axis). The distribution on the upper and lower walls of the vacuum chamber just before the particular absorber is shown above and below. The values of the relevant power load characteristics (typical for the regular part of the wigglers chain) are given in Table 3.

The power load asymmetry, which is seen from Table 3, is because of the COD. The total power that passes through the whole system of absorbers is equal to 30 kW (~25% of the total radiation power) and should be absorbed in the final absorber outside the straight section.

Table 3: Radiation power characteristics.

Absorber No.	25		20	
Gap (mm)	6		8	
Max. power (kW)	4.29		1.93	
Max. power density (W/mm^2)	58		55	
Vacuum chamber before	Upper	Lower	Upper	Lower
Max. power (W)	68.1	51.5	2.48	3.48
Max. power density (mW/mm^2)	1.22	0.98	0.13	0.18

In frame of this research an analysis of COD tolerance to the absorbers power loads was performed too. The result of the simulation is shown in Figure 7 where the maximum value of the radiation power hitting either the upper or the lower half of the absorber is given as a function of the COD amplitude. Figure 7 shows power loads only for the most loaded absorbers with odd number (see Figure 5). Absorbers with even number have sufficiently lower loads and they can be omitted in the present analysis.

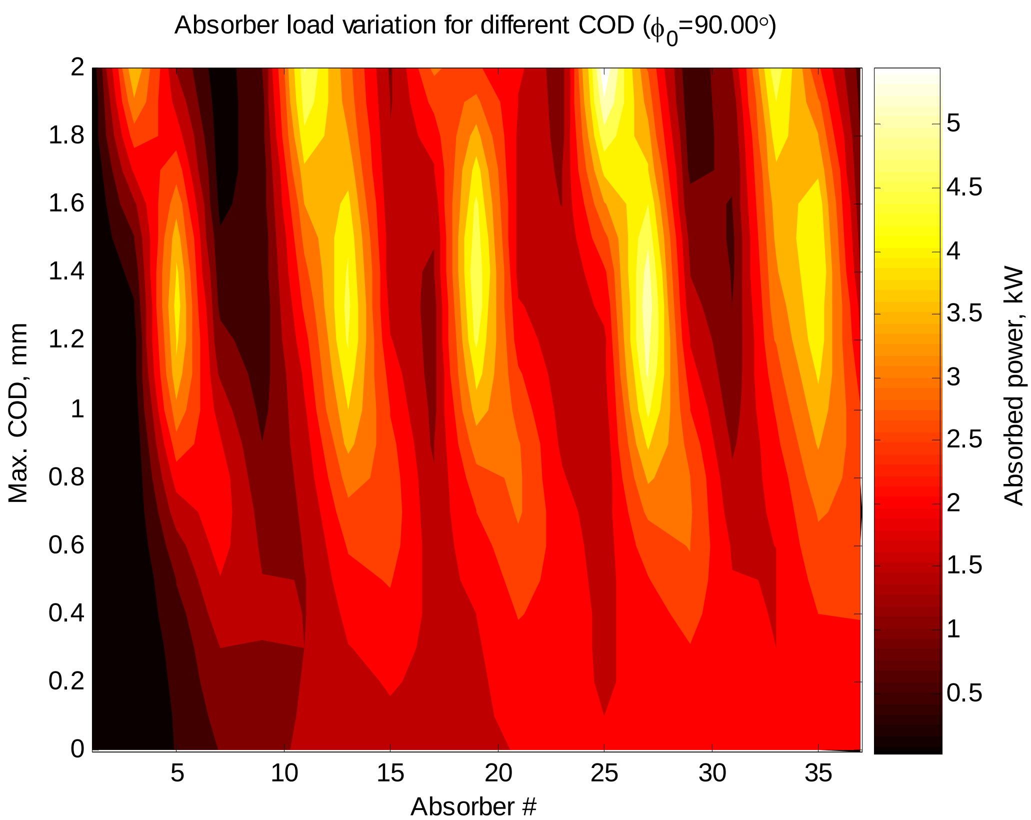

Figure 7: Power loads at odd-numbered absorber as function of COD magnitude.

One can see that the level of 2 mm of the COD amplitude can be considered as rather safe because the value of total power is acceptable for the copper cooled absorber and its variation from one absorber to another is negligible.

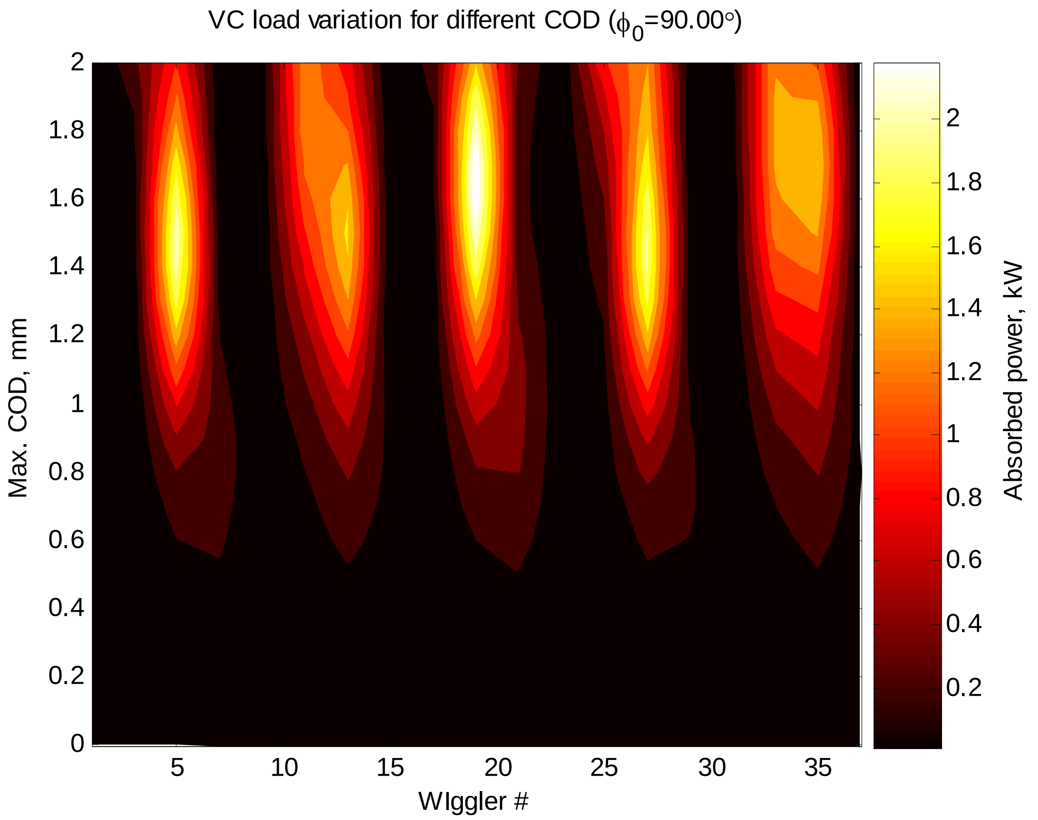

Figure 8. Power loads at vacuum chambers of odd-numbered wigglers for different COD.

The same analysis, which was performed for the absorbers, was also made for the vacuum chamber walls (see Figure 8). The data of vacuum chamber loads are presented there and indicate that 0.8 mm vertical COD amplitude is acceptable. In that case, the total power load on half of vacuum chamber of wiggler does not exceed 200 W and can be easily removed by the water cooling system.

5. Conclusions

Radiation from the damping wigglers of the CLIC DR is considered from the viewpoint of the vacuum chamber protection and effective absorption of the SR power. Analysis shows that 6/8 mm absorber configuration (which includes two type absorbers with different vertical 6 mm and 8 mm gaps, which are placed alternatingly in (or close to) focusing and defocusing quadrupoles of the FODO section, is suitable for efficient evacuation of SR power. A detailed study of the beam acceptance (including dynamic effects) is desirable for this absorbers configuration. The total maximum power at absorber (~4-5 kW) and that at the vacuum chamber walls (~50-60 W) seems to be acceptable even for standard materials (copper, aluminum) cooled by water. On the contrary, few long absorbers replacing the wigglers in some FODO straights do not provide permissible protection of the vacuum chamber walls from overheating.

Study of the COD influence to the power load tolerance provides an acceptable level of the COD amplitude of ~0.8 mm at full current (150 mA). There is no doubt that this value is feasible for modern sophisticated COD correction algorithm. For the machine tuning and adjustment, larger orbit deviation is tolerable for smaller beam intensity.

6. Acknowledgements

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7. References

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