EVALUATION OF THE POSSIBILITY OF USING DAMPING WIGGLERS IN THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source (APS) is a 7-GeV storage ring light source that has been in operation for over a decade. Over time, the performance of the APS has been increased by reduction of the emittance from 8 nm to 3.1 nm and by the use of top-up mode. We continue to explore options for improving the performance further. This paper discusses the possible improvements in emittance that could result from the use of damping wigglers. We also discuss rf and space requirements.

INTRODUCTION

The ability of suitably designed and located wiggler magnets to damp the emittance of an electron beam in a storage ring is well known. Indeed, two light sources [1, 2] that are expected to operate in the not-too-distant future are planning damping wigglers as an important part of their strategy to obtain low emittance. The possibility of using damping wigglers in the APS has been considered several times [3, 4] and was recently raised again [5]. This paper revisits these issues and reaches conclusions very similar to the earlier unpublished analyses of Emery and Borland.

The effect of damping wigglers on the horizontal emittance is given by Wiedemann [6]

$$\frac{\epsilon_w}{\epsilon_0} = \frac{1 + \frac{4C_q}{15\pi J_x} N_p \frac{\beta_x}{\epsilon_0 \rho_w} \gamma^2 \frac{\rho_0}{\rho_w} \theta_w^3}{1 + \frac{1}{2} N_p \frac{\rho_0}{\rho_w} \theta_w}, \qquad (1)$$

where $C_q = 3.81 \times 10^{-13} m$, N_p is the total number of wiggler poles, β_x is the average horizontal beta function in the wiggler, ρ_w is wiggler bending radius at the peak field, $\theta_w = \lambda_w/(2\pi\rho_w)$ is the peak trajectory angle in the wiggler, and λ_w is the wiggler period length. This equation has been cross-checked with the wiggler model in `elegant` [7] and found to agree very well. In more practical form, Wiedemann's equation gives

$$\frac{\epsilon_w}{\epsilon_0} = \frac{1 + 1.21 \times 10^{-12} \frac{\beta_x L_w \lambda_w^2 \rho_0 B_w^5}{J_x \epsilon_0 E^3}}{1 + 7.16 \times 10^{-3} \frac{L_w \rho_0 B_w^2}{E^2}}, \qquad (2)$$

where units are meters except for E, which is in GeV.

The complicated term in the numerator is related to the self-dispersion generated by the wiggler, which can result in additional quantum excitation that may limit or prevent emittance reduction, depending on the wiggler period. The longer the wiggler period, the larger the self-dispersion and the larger the wiggler-generated quantum excitation. Examination of this equation yields some interesting conclusions: 1. As the wiggler field is increased, at some point the effect of the wiggler is to increase, not decrease, the emittance. This is due to the B_w^5 term in the numerator compared to the B_w^2 term in the denominator. Hence, the surest way to lower the emittance is not to use a strong wiggler but rather long, relatively weak wigglers. 2. The self-dispersion term is worse when the wiggler period is longer, due to the λ_w^2 term in the numerator. 3. When the self-dispersion term is important, damping wigglers will work better if the energy is increased, due to the $1/(\epsilon_0 E^3) \propto 1/E^5$ term in the numerator compared to the $1/E^2$ term in the denominator. When the self-dispersion term is negligible, damping wigglers work better if the energy is decreased (as long as it is not decreased too much). 4. One can reduce self-dispersion effects by reducing the average horizontal beta function at the wiggler location.

DAMPING WIGGLER OPTIONS

The NSLS II design [1] has 50 m of wigglers and Petra III has 80 m [2]. Both of these choices were made in recognition of the self-dispersion term and limits of magnet technology, which led these projects to use weaker wigglers at the expense of giving up large amounts of real estate. This hints at a serious issue for application of damping wigglers to the APS, since we do not have real estate available to accommodate such wigglers. Hence, if anything, we will need to use rather strong, short wigglers, with due consideration of the self-dispersion term.

We looked in several sources for information on high-field and damping wigglers. One useful resource is Levichev's talk "Review of Wiggler Parameters" [8] from the Mini-Workshop on Wiggler Optimization for Emittance Control. He concludes that the following parameters are reasonable

- For superconducting wigglers: 3.5- to 4.0-T field with period of 60 to 70 mm. E.g., Levichev lists the TESLA wiggler for Trieste as having a 3.5-T field with a 64-mm period.
- For permanent magnet wigglers: 1.5- to 2.0-T field with period of 100 to 150 mm. E.g., the Petra III wigglers are 1.5 T with a 200-mm period [2]. The NSLS II [1] wigglers are 1.8 T with a 100-mm period.
- For electromagnetic wigglers: 1.7-T field and 76-mm period.

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In addition to magnet technology considerations, dynamic aperture issues worsen as the wiggler strength is increased, in part because this entails reducing the gap. This again motivates use of longer, weaker wigglers, but again it is not an option for the APS.

PREDICTED WIGGLER BENEFITS

Clearly we must place the wigglers in zero-dispersion straight sections, or else the emittance may increase, not decrease. Presently, APS operates with a distributed dispersion lattice with an effective emittance of 3.1 nm. The original high-emittance, zero-dispersion (HEZD) lattice had an emittance of 7.9 nm. We also created linear optics for a low-emittance, zero-dispersion (LEZD) lattice with an emittance of 4.7 nm. This is the best starting point for adding damping wigglers, but is perhaps too optimistic as we have not demonstrated a workable nonlinear correction.

We evaluated the two lattices with the following wiggler parameters, using `elegant`'s [7] WIGGLER element, which assumes a sinusoidal field variation.

- SC4: A superconducting (SC) wiggler with 4-T field and 60-mm period. This is the most optimistic choice we can make based on Levichev's review. That is, we've chosen the maximum field and the minimum period.
- SC5: A SC wiggler with 5-T field and 60-mm period. This is beyond what Levichev lists but perhaps possible.
- BESSY: A SC wiggler with 7-T field and 150-mm period. This is the BESSY wiggler [9] that we used in [4].
- NSLS: The NSLS wiggler, with 1.8-T field and 100-mm period.
- APS: Projected APS superconducting undulator, with 1.9-T field and 12-mm period. This should be immune to any self-dispersion effects, but is an extrapolation of present designs.
- EM: Projected electromagnet wiggler [8], with 1.7-T field and 76-mm period, listed by Levichev as a possible damping wiggler design.

In all cases, we assumed three straight sections each had a pair of 2.4-m devices. Each device began and ended with a half-strength pole to match the dispersion. We could also put one 2.4-m device in six straight sections, using a canted arrangement to allow coexistence with an undulator [4]. (It would need to be verified that the dispersion due to the canting dipole wasn't excessive, though.)

Figures 1 and 2 show the results for the two lattices. We see that only the superconducting wiggler makes a dramatic difference. For the HEZD lattice, SC4 gives 3.3 nm while SC5 gives 2.6 nm. One could improve this by 5% by reducing the horizontal beta function in the wiggler straight sections by a factor of about two. For the more speculative LEZD lattice, SC4 gives 2.1 nm while SC5 gives 1.7 nm. The best of these is a factor of factor of 1.8 below the present effective emittance.

The strongest wiggler, the 7-T BESSY device, give a poor result due to the long period. A device with such a long period can deliver good results if we use 35 devices with much weaker field, as was done in [4]. However, this obviously uses a great deal of real estate in the ring. We could also reduce β_x in the wiggler straight sections by a factor of two, which may not be easily done in the LEZD lattice, given that $\nu_x = 38.82$. This would very likely be possible in the HEZD lattice, which also has the advantage of a smaller self-dispersion effect due to the larger emittance. The predicted emittance in this case would be 1.75 nm. Unfortunately, as we'll see below, this comes at a tremendous cost in rf voltage.

For 6 GeV, looking at the SC5 device, we predict 1.6 nm for the HEZD lattice and 1.1 nm for the LEZD lattice. (The self-dispersion term increases first value by about 10%.) If we use the BESSY device with the HEZD lattice and assume we can lower the beta functions a factor of two in the wiggler straight sections, we'd again get down to 1.1 nm. For reference, if we ran the present-day low-emittance lattice at 6 GeV, we'd have an emittance of 2.3 nm. While 1.1 nm is appealing, users interested in high-energy photons will not be pleased. In addition, damping wigglers inevitably increase the energy spread, which adversely impacts the brightness for high-energy photons. It is unclear if we can readily compensate by designing a special-purpose insertion device.

We note in passing that the SC4, SC5, and BESSY devices have such a strong vertical focusing that they significantly impact the linear optics, even at 7 GeV. We didn't attempt to compensate for this, but assume that it would be possible. This hints at a real concern about the beam dynamics effects of such long, strong wigglers.

RF CONSIDERATIONS

The figures show two additional important values: the rf voltage and the energy spread. The rf voltage requirement for the SC5 case at 7 GeV is 21 MV. This value is sufficient to ensure a bucket half-height of 2.2%, which is the approximate value we use in operations today.

Presently four sectors of normal conducting NC cavities are required to supply 9-11 MV (690 kV/cavity). This is probably the most voltage we can get out of normal-conducting technology. As Milton suggests [5], to get more than 12 MV in the same space (5 m is available per straight section), we may have to install superconducting cavities, which have higher gradients. However, the additional space required for the beam pipes and cryostats may offset that advantage.

A Daresbury internal report on the length of straight sections [10] summarized the physical lengths of the three choices of SC cavity designs for storage rings. These val-

Table 1: Space required for SC cavities at different frequencies f, broken down into cryomodule length L_{cm}, connection length L_{cnt}, end-section length L_{end}, all summing into the total length L_{2c} for two cavities. End sections include vacuum valves, pumps, and tapers to regular arc vacuum chamber.

Design	f MHz	L_{cm} m	L_{cnt} m	L_{end} m	L_{2c} m
Cornell	500	1.509	0.858	1.440	5.316
KEKB	500	1.740	0.636	1.770	5.886
Soleil	352	3.553	n/a	2.440	6.103

ues are listed in Table .

In all cases two cavities require 5-6 m of straight section. We can use any of these cavity designs as a reference. Typically the accelerating gap for a single cell ranges from 1.1 MV to 1.8 MV. Thus we could expect 2.2 MV to 3.6 MV for a single straight section at APS. Presently the APS NC system can produce 2.5 to 2.75 MV accelerating gap in a straight section. Thus SC cavities produce perhaps 30% more gap voltage per straight section than our present system. The advantage of the SC system appears to be not so much space efficiency but rather fewer cavities and other components, and reduction of number and strength of higher-order modes.

In any case, a gap-voltage requirement of 31 MV would require using at least nine straight sections using the high-end value of 1.8 MV/cavity. For 21 MV, seven straight sections are needed. In the future cavities will support higher gradients, but it may be unreasonable to expect a breakthrough that will allow 21 MV or more in four straight sections. Even using a simple long straight section scheme may not be much help as it is hard to get an additional 5 m (the cyrostat length) in a straight. More ambitious long straights, beyond 10 m, are possible, but would add considerably to the cost and complexity of the project.

CONCLUSION

We investigated the feasibility of using damping wigglers to lower the emittance of the APS. Because of space limits, we must use nonoptimal high-field wigglers. We found that with a 5-T, 60-mm-period wiggler design (a more than 25% extrapolation of existing technology), an emittance of 1.7 nm at 7 GeV is possible. The impact on the linear optics is considerable and hints at concerns about the nonlinear beam dynamics, which are common in any damping wiggler scheme. These were not investigated.

We also estimated the space requirements for the 21 MV of rf required for this wiggler system. We found that using the most optimistic values from the literature for superconducting storage ring rf systems, seven APS straight sections would have to be devoted to rf cavities. Hence, given that three straight sections would be occupied by wigglers, we'd have to withhold a total of six additional straight sections from users. Given the rather modest improvement in the emittance, this appears a poor choice for the APS.

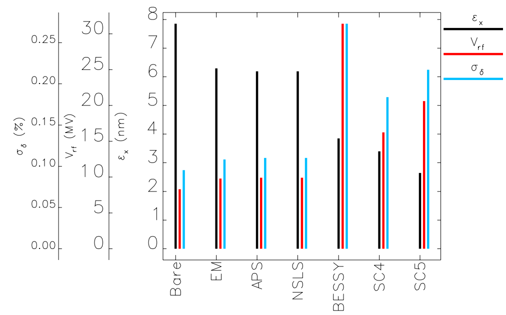

Figure 1: Results for 14.4 m of various wigglers for the APS high-emittance zero-dispersion lattice.

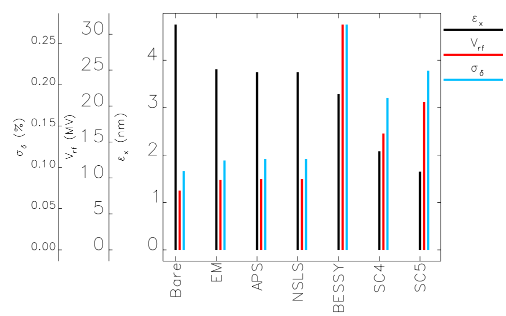

Figure 2: Results for 14.4 m of various wigglers for the APS low-emittance zero-dispersion lattice.

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