Title
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Author
Zisman, M.S.

Publication Date
1987-06-01

LBL-23484

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the ICFA Workshop on Low Emittance Beams,
Upton, NY, March 20–25, 1987

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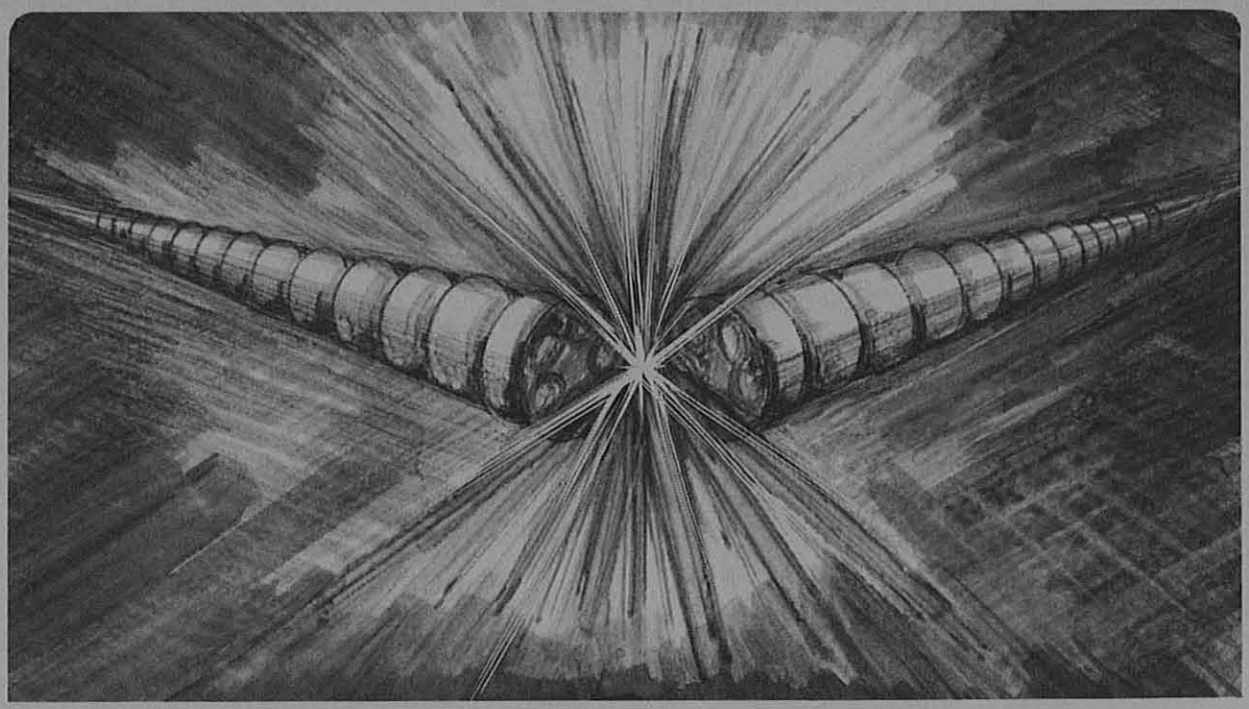

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-23484
ESG-31

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Michael S. Zisman

Lawrence Berkeley Laboratory
University of California

Berkeley, CA 94720

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*This was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

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Summary of Working Group on Storage Ring Collective Effects

Michael S. Zisman
Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
Berkeley, California 94720
U.S.A.

(June, 1987)

M. Barton, BNL
S. Chattopadhyay, LBL
J.-P. Delahaye, CERN
E. Keil, CERN
R. Palmer, BNL/SLAC
L. Rivkin, SLAC
A. Chao, URA/SSC
B. Craft, BNL
Y. Kamiya, KEK
S.Y. Lee, BNL
C. Pellegrini, BNL
R. Ruth, SLAC

Introduction

The purposes of this Workshop were to investigate the techniques available for the production of very low emittance electron beams, to explore the limitations of these techniques, and to consider new possibilities that might improve the present situation. Two uses for these low emittance beams are of interest here: *(i)* to serve for a high energy linear collider, which requires very small beam sizes to achieve a suitable value for the luminosity; and *(ii)* to serve for a free-electron laser (FEL) in the short wavelength—say 40 Å—regime, which requires both small transverse beam dimensions and a very low longitudinal emittance.

This paper contains a brief summary of the main topics discussed by the Working Group on Storage Ring Collective Effects. In the case of the linear collider application, we envision the use of a damping ring (DR) to reduce, by radiation damping, the emittance of an intermediate energy linac beam prior to its subsequent injection into the remaining high energy linac. For FEL use, we imagine a high-gain device with a storage ring to damp

the beam periodically between passages through a bypass section containing the long FEL undulator. Such designs—at a longer wavelength of 400 Å—are already available,[1] but the shorter wavelength of interest here is much more of a challenge.

The importance of collective effects in the production of low emittance electron beams is clear. Collective effects arise from interactions of the beam bunches with themselves and with their environment. If we require the lowest possible values for transverse and longitudinal emittance, while simultaneously demanding high beam currents, we must ultimately be limited by such effects. In the cases discussed here, we consider rings having a beam intensity of at least 1×10^{10} electrons per bunch, with a normalized rms transverse emittance of about $1 \times 10^{-6}\ \pi$ m-rad, and a normalized longitudinal emittance, $\varepsilon_{n,\ell} = \gamma\sigma_\ell(\sigma_p/p)$, of about 0.01 m.[2,3] As we will see below, even at relatively high beam energies these parameters are very difficult to realize because of limitations from such effects as intrabeam scattering, which increases the transverse emittance, and the longitudinal microwave instability, which increases the longitudinal emittance. Given the rather fundamental nature of these limitations, it was of interest to explore other, less traditional, storage ring designs to see whether they hold any promise for avoiding some of the known pitfalls in the production of low emittance beams.

To this end, we separated our efforts into three main areas. One subgroup investigated what we refer to here as "exotic" lattices. These lattices contain a combination of both positive and negative bending magnets (with strengths chosen to provide a net positive bend, of course) and thus permit a low emittance with an acceptably short damping time. It is possible in such "wiggler" lattices to achieve an isochronous condition, where the momentum compaction factor, α, and hence the phase-slip factor, η, are essentially zero. Because the properties of such isochronous lattices are not well characterized, a second subgroup concentrated primarily on issues of relevance to the $\alpha = 0$ case.

Finally, the third subgroup investigated the performance expected from the various lattices, including the standard lattice types provided[4] by the Lattice Working Group and also an example of the wiggler lattice type mentioned above. Papers detailing the work of each of the subgroups are found[5-7] elsewhere in these proceedings. Here we will simply summarize the main conclusions of each and comment on areas where more effort is needed.

Results

Exotic Lattices

To achieve a low equilibrium emittance in an electron damping ring, we are driven toward a solution with strong focusing, and thus a high betatron tune. Unfortunately, such lattices tend to become large and to consist of relatively low field magnets. A side effect of such a design is a reduced damping rate, which is particularly undesirable for a damping ring application and a disadvantage for an FEL ring also. To avoid this situation, the solution explored in Ref. 5 is to consider a lattice with alternating positive and negative bends, which we refer to here as a wiggler lattice. With this approach, we can make use of high bending fields to achieve a rapid damping rate and also provide the strong focusing necessary for a low emittance beam.

One potential drawback of the wiggler lattice concept is that the momentum compaction factor tends to become very small, or even zero, leading to problems with longitudinal stability. We were led, then, to consider what happens in the case where α, or more precisely η, becomes exactly zero. In this case the growth time of the longitudinal instability becomes infinitely long, and it may be controllable via radiation damping. [As we will see below, however, our estimates indicate that this assumption corresponds to an extremely stringent limit on the momentum compaction

factor.] Such an isochronous storage ring is analogous to a relativistic linac, and the effect of the ring impedance is to produce wake fields that give an energy spread (see the estimate below) across the bunch. As discussed in Ref. 5, however, it should be possible to correct for this by proper adjustment of the RF phase.

A comparison of the wiggler lattices (both isochronous and normal) with a more conventional design, summarized in Table I, shows that the wiggler lattice produces a better normalized emittance than the conventional design and a faster damping time. The isochronous lattice, which is considerably larger, is able to improve on both the normalized emittance and the damping time even further. In all comparisons, the ring broadband impedance was taken as 0.2 Ω, which was felt by our Working Group to be achievable with suitable care in the design of the ring (but by no means trivial to accomplish). For details on the optimization procedure followed, see Ref. 5.

α = 0 Issues

The philosophy adopted here (see Ref. 6) was to accept that the design of a low emittance damping ring leads inevitably to a very small value for the momentum compaction. If we cannot "beat" this limitation, perhaps we can exploit it in some way. In Ref. 5 it was demonstrated that such an $\alpha = 0$ lattice offers the possibility of improved normalized emittance compared with a standard lattice, so we are encouraged to explore the ramifications of such a design from the viewpoint of collective effects.

There are a number of peculiarities associated with a lattice having $\eta = 0$:[6]

- The beam is frozen in its longitudinal shape.
- Radiation damping of the relative energy spread is twice as fast as for $\eta \neq 0$.

- The centroid of the energy distribution depends on the azimuthal position, so the beam must be injected with the correct RF phase.

Other effects must also be considered in the $\eta = 0$ case. One example is the tolerance on second-order path length coefficients due to phase slippage in the ring. In one damping time, τ_D, the runaway phase-slip is given approximately by:[6]

$$\Delta z \cong \alpha'_2 \delta^2 \tau_D$$

where $\delta = (\Delta E/E)$ is the relative energy spread. We will estimate a limit for α_2 itself below.

Another consideration is whether the introduction of wigglers (to produce an $\alpha = 0$ lattice) could affect the damping partition numbers sufficiently to lead to anti-damping. Fortunately, it is estimated[6] that the wigglers will only modify the $\mathcal{D}$ value by about 50%, corresponding to an insignificant effect on the damping partition numbers for realistic lattice parameters.

As mentioned earlier, for the $\alpha = 0$ lattice, where the beam is frozen longitudinally, there is a beam-loading voltage induced across the bunch:

$$\Delta V \approx I_p Z_{\|} = I_p \, |Z_{\|}/n| \, n$$

$$\approx 10 \text{ keV/turn},$$

giving

$$\Delta E/E = \pm \Delta V/(2U_o) \quad .$$

For typical parameters,[6] this voltage leads to an energy spread, $\Delta E/E$, of about ±1.25%, which should be possible to compensate by proper RF phasing.

As a means of estimating the Landau stability criterion for

the transverse microwave instability, which depends—in the $\alpha = 0$ case—upon the betatron tune spread, we can scale the results of the SLC damping rings, which are known to be stable. Even for an impedance as high as the SLC damping ring, it should be possible to stabilize the beam with a betatron tune spread of $\Delta\nu_\beta \approx 0.01$. Thus, the transverse microwave limit is <u>not</u> expected to be a serious problem in the $\alpha = 0$ case.[6]

One issue that we must address somewhat more quantitatively is that of limits to the momentum compaction factor, i.e., how nearly must $\alpha = 0$. To second-order in relative energy spread, we may write the circumferential path length change as:

$$\Delta C/C = \alpha_1\delta + \alpha_2\delta^2 + \alpha_\varepsilon\varepsilon + \ldots$$

where α_1 is the usual first-order momentum compaction factor and ε is the emittance at injection. If we require that the slippage remain well within the bunch length during a number of turns corresponding to three damping times, the limits from Ref. 6 become:

$$|\alpha_1| \leq 3 \times 10^{-7} ,$$

$$|\alpha_2| \leq 3 \times 10^{-4} ,$$

and

$$|\alpha_\varepsilon| \leq 0.25 \text{ m}^{-1} .$$

Since α_2 goes roughly as ν^{-2}, a tune value of about 50 is implied by this limit. We emphasize that the above limits are imposed <u>only by the path length requirement</u>. Limits from instability growth rates are considerably tighter!

To assess the limit due to the growth rate, we must estimate the value of α that would give a growth rate smaller than the radiation damping rate. This has been done for several lattices

in Ref. 6. Typical values turn out to be on the order of 10^{-9} to 10^{-10}, i.e., about three orders of magnitude smaller than the limit from path length considerations discussed above.

Performance Comparisons

To assess the performance of a number of lattices provided during the course of this Workshop, we have analyzed[7] them with the LBL accelerator physics code ZAP.[8] Considerations of relevance here are the longitudinal and transverse emittance values for each candidate lattice based on the influence of the longitudinal microwave instability and the effects of intrabeam scattering. Relevant parameters of the four lattices studied are collected in Table II.

In the longitudinal case, we used[7] as a figure of merit the longitudinal brilliance, $\mathcal{B}_\ell = I_p/(\gamma\sigma_p/p)$, where I_p is the peak current determined from the microwave instability, and σ_p/p is the rms momentum spread. We also evaluated the normalized longitudinal emittance, defined earlier in this paper. For the DR case, we require $\varepsilon_{\ell,n} \leq 0.025$ m;[2] for the FEL case (at an energy of about 1 GeV), we require $\varepsilon_{\ell,n} \leq 0.001$ m,[3] which is very stringent indeed. As mentioned above, we have adopted the (optimistic) value of 0.2 Ω for the ring broadband impedance. Irrespective of this choice, however, we note that—in the very short bunch regime of interest here—the free-space impedance, which results from the interaction of the beam with its own synchrotron radiation, is comparable in magnitude to this and is taken here as a practical lower limit to the impedance that can be achieved. As can be seen in Table III, the DR longitudinal emittance requirements can be met without difficulty.

The FEL requirements, in contrast, are far from being achieved. In this case, we need to minimize both the bunch length (to keep the proper phase relationship in the undulator) *and* the momentum spread (to avoid substantial gain reduction from Landau damping). Even with a 1 GHz RF system, it is not practical to

obtain a normalized longitudinal emittance as low as 0.001 m with any of the lattices studied. It *is* possible to achieve the required longitudinal beam properties by reducing the operating energy of Lattice 4 from 4 GeV to 1 GeV. The penalty we pay for this is a substantial reduction in peak current and a damping time of nearly 1 second. It is unlikely that this option would be received favorably by the FEL community.

To ensure that the required dense beam bunches do not show excessive transverse growth, we estimated the equilibrium emittance of our sample lattices including the effects of intrabeam scattering. The figure of merit in this case is the 6-dimensional brightness, $\mathcal{B}_6 = \mathcal{B}_\ell / (\varepsilon_{n,h}\, \varepsilon_{n,v})$. As can be seen in Table IV, none of the lattices show appreciable transverse emittance growth. When the energy of Lattice 4 is reduced to 1 GeV, there *is* substantial emittance growth (about a factor of 50 beyond the natural emittance value). Even so, the normalized equilibrium emittance value is consistent with our specification of below $1 \times 10^{-6}\ \pi$ m-rad.

For completeness, there is one other topic that should be mentioned here. During the workshop, it was pointed out that, beyond a certain bunch density, there should be Debye screening, which would reduce or eliminate any emittance growth from intrabeam scattering; this issue was explored in Ref. 6. For the parameter regime of interest here, it was concluded that the Debye length exceeds the average interparticle spacing by about a factor of 100. Thus, screening effects are expected to be negligible for the cases under consideration.

From these results,[7] we conclude that it is feasible to achieve the DR specifications of Palmer,[2] but the FEL specifications proposed by Pellegrini[3] cannot be achieved without significantly compromising the intensity and damping time requirements.

Summary

In this paper we have presented the results of our investigations of the influence of collective effects upon the performance of storage ring lattices designed to produce very low emittance beams. We have explored somewhat unconventional lattice types and find[5] that:

- For fixed ring size, wiggler lattices provide lower emittance than conventional designs.
- The impedance requirement is more severe for a wiggler lattice with $\alpha \neq 0$ than for a conventional lattice.

We also pursued the issues relevant to the $\alpha = 0$ case. The main ones appear to be:[6]

- Energy spread in the bunch due to the longitudinal impedance.
- Phase slippage due to the second-order path length coefficients.
- Tolerance on α_1 from growth rate limitations.
- Instability issues related to the non-zero values of α_2 and α_ε when $\alpha_1 = 0$ (not studied here).

With the possible exception of the last two items above, these effects are likely to be acceptable. Nonetheless, a good deal more work than described here would be required to confirm the viability of the $\alpha = 0$ design.

Finally, based upon standard collective effects, we have looked[7] at the performance of various conventional lattices. We conclude from these studies that the damping ring specifications may be achievable, but that the FEL specifications cannot be met without severely compromising the damping time and intensity requirements. There are several areas relevant to this analysis

where more work is needed. First of all, it will be important to explore the issue of limits to the achievable longitudinal impedance at existing machines and how these limits can be improved. In addition, we must better understand how the free-space impedance manifests itself in terms of the longitudinal microwave instability. Finally, it will be worthwhile to better understand the limits to the achievable emittance coupling in very low emittance storage rings.

Acknowledgments

We would like to thank the various members of the Lattice Working Group, and especially A. Ruggiero and J. Murphy for many informative discussions. In addition, we wish to thank Brookhaven National Laboratory, and particularly C. Pellegrini and J. Murphy, for hosting such a pleasant and productive Workshop.

This work is partially supported by the U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

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Table I.

Lattice Comparisons

Lattice		1	C	A
Type[a]		W	W[b]	FODO
E	[GeV]	1.1	1.5	1.9
C	[m]	125	440	125
ε_n	[10^{-6} π m-rad]	5.0	2.4	10.0
σ_p	[10^{-4}]	6.0	7.3	5.5
σ_ℓ	[mm]	18.0	11.0	8.5
τ_E	[ms]	3.7	2.7	13.0
U_o	[MeV/turn]	0.2	1.3	0.1

[a] W denotes a wiggler (alternating positive and negative bend) lattice; CF is a combined-function lattice.

[b] with $\alpha = 0$.

Table II.

Major Lattice Parameters

Lattice		1	2	3	4
Type[a)]		W	CF	FODO	FODO
E	[GeV]	1.1	2	3	4
C	[m]	125	120	135	341
α	[10^{-3}]	1.7	1	1	0.2
τ_E	[ms]	3.7	2.6	3.8	10.8
f_{RF}	[MHz]	25	500	1000	1000
V_{RF}	[MV]	0.5	2	2	2

a) W denotes a wiggler (alternating positive and negative bend) lattice; CF is a combined-function lattice.

Table III.

ZAP Results for Longitudinal Parameters

Lattice		1	2	3	4
σ_ℓ	[mm]	19.1	3.7	3.3	2.8
σ_p/p	[10^{-3}]	0.6	1.0	1.0	1.0
$\varepsilon_{n,\ell}$	[m]	0.025	0.014	0.019	0.022
I_p	[A]	21	74	114	77
N_b	[10^{10}]	2.1	1.4	2.0	1.1
$\mathcal{B}_\ell$	[A]	16.3	19.0	19.4	9.8

Table IV.

ZAP Results for Transverse Parameters

Lattice		1	2	3	4
$\varepsilon_{0,n}$	[10^{-6} π m-rad]	3.0	6.8	6.2	1.2
ε_n	[10^{-6} π m-rad]	3.0	7.7	6.7	2.1
$\mathbf{B}_6$	[10^{14} A/m^2]	1.80	0.32	0.43	2.20