LBL-21760

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

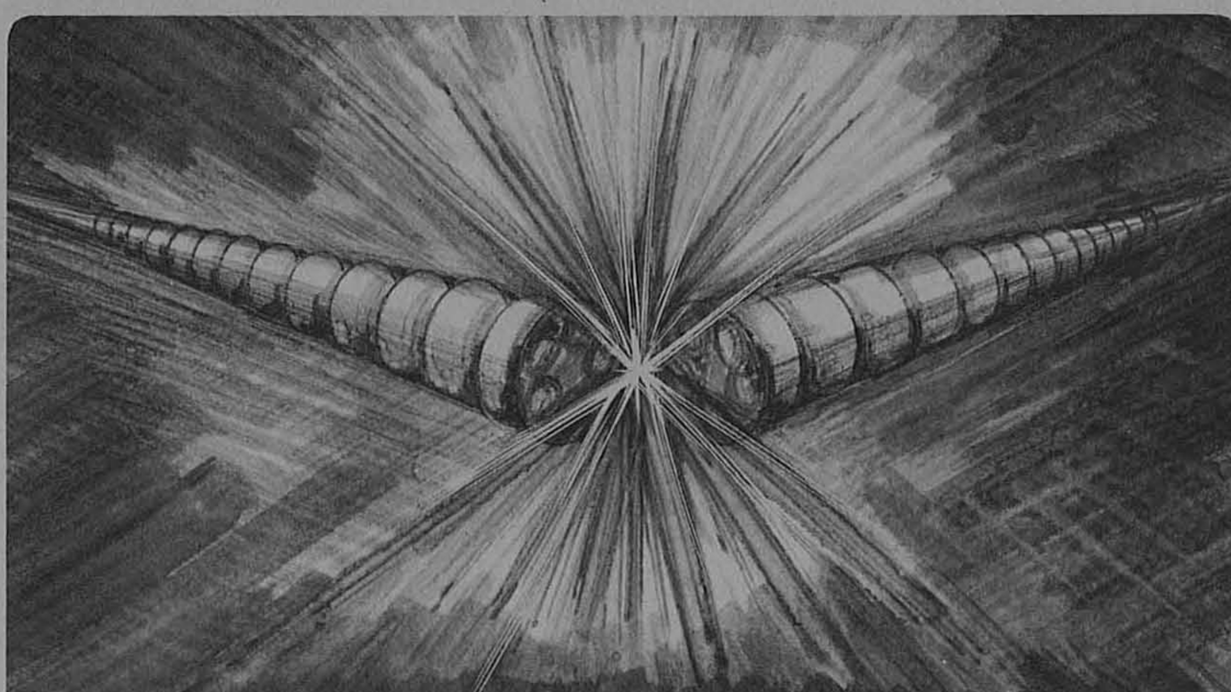
Accelerator & Fusion Research Division

Presented at the Institute of Nuclear Physics
Workshop, Frascati, Italy, April 6-11, 1986

PARAMETER STUDIES OF CANDIDATE LATTICES FOR THE 1-2 GeV SYNCHROTRON RADIATION SOURCE

M.S. Zisman

January 1986



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

ESG-NOTE-14
LBL-21760

Parameter Studies of Candidate Lattices for the 1-2 GeV Synchrotron Radiation Source

Michael S. Zisman

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

January 13, 1986

*This work was supported by the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Parameter Studies of Candidate Lattices for the 1-2 GeV Synchrotron Radiation Source

Michael S. Zisman
January 13, 1986

Abstract

This document discusses the implications of various collective phenomena on the required performance of candidate lattices for the LBL 1-2 GeV Synchrotron Radiation Source. The performance issues considered include bunch length, emittance growth, and beam lifetime. In addition, the possible use of the 1-2 GeV Synchrotron Radiation Source as a high-gain FEL is explored briefly. Generally, the differences between lattices are minor. It appears that the most significant feature distinguishing the various alternatives will be the beam lifetime.

I. Introduction

At a recent meeting of the potential users of an advanced 1-2 GeV synchrotron light source [1], the specifications for a desirable machine were agreed upon. These user requirements, which will provide the basis for an LBL proposal to build such a machine, are summarized in Table I. Compared with our original Advanced Light Source (ALS) proposal [2], the most significant change has been to increase the nominal operating energy of the proposed machine from 1.3 to 1.5 GeV. (The energy range of the machine, from 1.0 to 1.9 GeV, remains unchanged from the earlier specifications.)

In the time between the original proposal [2] and now, there has been a considerable increase in our understanding of the characteristics of low-emittance 1-2 GeV storage rings. For this reason, we have explored various alternative designs for the 1-2 GeV Synchrotron Radiation Source lattice and have also carefully examined the original design in light of more recent insights into lattice behavior.

In this document, we examine each of the candidate lattices in terms of collective effects that can influence machine performance. Section II will deal with the issue of bunch length. The expected bunch length obtainable from the various lattices is calculated under several assumptions, and the degradation in bunch length that would result from the absence of SPEAR scaling is estimated. An estimate of possible growth in beam emittance due to intrabeam scattering is made in Section III. Although this phenomenon is generally not expected to be important at high energies, the dense beam bunches specified for the 1-2 GeV Synchrotron Radiation Source make it necessary to confirm this for the particular lattices under consideration. Section IV deals with beam lifetime, due to the combined effects of Touschek and gas scattering. The performance of each lattice at 750 MeV is used, in Section V, to assess the Free Electron Laser (FEL) gain parameter, ρ. Finally, a summary of our findings is presented in Section VI.

Candidate lattices have been provided for this study by several members of the LBL Exploratory Studies Group. Details of their work will be documented separately [3]. Altogether, five different lattices were investigated, representing different approaches to the design of a low-emittance synchrotron radiation source. These include: the "original" Chasman-Green ALS lattice [2], designated "CG"; an expanded Chasman-Green structure in which the central quadrupole of the achromat is replaced with two empty FODO cells, designated "ECG"; a triple-bend achromat structure, designated "TBA"; and two FODO structures, one with two and one with three cells per achromat, denoted "FODO2" and "FODO3," respectively.

All of the calculations reported herein have been performed with the LBL accelerator physics code ZAP [4].

II. Bunch Length

The bunch length requirement for the 1-2 GeV Synchrotron Radiation Source is for very short bunches, $2\sigma_\tau \approx$ 20-50 psec. In practice, the attainable bunch length is determined by two things: the RF parameters and the constraints of the longitudinal microwave instability.

With regard to the RF parameters, we will take as our nominal case a 500 MHz system operated at 3 MV. Insofar as these parameters have already been selected to provide very short bunches, we will see that further improvements to the bunch length will not be easy to come by.

The influence of the longitudinal microwave instability is determined by the effective impedance assumed for the ring. In particular, the magnitude of the turbulent bunch lengthening is very sensitive to whether or not we assume the validity of SPEAR scaling [5] in obtaining the effective impedance. The microwave threshold is given by:

$$I_{thresh} = \frac{\sqrt{2\pi}\ |\eta|\ (E/e)\ \sigma_p^2\ \sigma_\ell}{R\ |Z/n|_{eff}} \tag{1}$$

The broadband impedance is made up of contributions from the vacuum chamber and the RF cavities:

$$(Z/n) = (Z/n)_o + n_c (Z/n)_{RF} \tag{2}$$

where we take the number of RF cells, n_c, from the RF voltage (assuming 500 kV per cell). If SPEAR scaling is applied, then

$$\begin{aligned} (Z/n)_{eff} &= (Z/n)\ (\sigma_\ell/b)^{1.68} && (\sigma_\ell < b) \\ &= (Z/n) && (\sigma_\ell \geq b) \end{aligned}$$

where σ_ℓ is the rms bunch length and b is the vacuum chamber radius. Thus, the SPEAR scaling assumption (denoted "S.S." in this document) has the effect of markedly reducing $(Z/n)_{eff}$ for short bunches, which considerably reduces bunch lengthening in this regime. Although S.S. can lead to very low impedance values, we will follow our past practice [6] of not allowing the effective impedance to become smaller than the free-space value of

$$(Z/n)_{fs} = 300\ (b/R)\ \text{ohms},$$

where R is the machine radius. For the lattices considered here, this limit is on the order of a few tenths of an ohm.

In the absence of a detailed impedance inventory, we have taken a value of 2 ohms for the vacuum chamber broadband impedance. The RF cavity is assumed to have an impedance (per cell) of 0. 25 ohms, as obtained from the higher order modes of our reference RF design (taken from the KEK cavity [7]). Thus, prior to applying S.S., the effective impedance is 3. 5 ohms at a voltage of 3 MV. As mentioned, applying S.S. reduces this value to roughly a few tenths of an ohm.

In Figs. 1 and 2 we compare the bunch lengths of the five candidate lattices as a function of average current. As can be seen, the S.S. assumption leads to very short bunch lengths in the 250-bunch case (Fig. 1) and to slightly longer bunches in the single-bunch scenario (Fig. 2). No attempt has been made to distinguish the various lattices in Figs. 1 and 2; the message here is that all of the candidate lattices show essentially identical behavior. With this in mind, in what follows we will generally look at the behavior of only selected "representative" lattice examples rather than studying each case individually.

The effects of S.S. are demonstrated in Figs. 3 and 4 for the CG lattice in the multi- and single-bunch mode, respectively. At the higher currents, the effect of S.S. is to reduce the bunch length by about a factor of 2 to 3. The problem of achieving a bunch length of 20 psec (with a reasonable single-bunch current) if S.S. does not apply is clearly evident in Fig. 4.

To investigate the effects of RF parameters, we consider the most difficult scenario (in terms of bunch length), the single-bunch mode without S.S. The change in bunch length with RF voltage is shown in Fig. 5. Not much help is available, even at an RF voltage of 5 MV. In Fig. 6 we investigate the effect of going to a higher-frequency RF system. Again, the potential gain is small compared with the changes corresponding to applying S.S.

Based on the above results, we can draw several conclusions. If the S.S. assumption is applicable to the 1-2 GeV Synchrotron Radiation Source, there should be no problem reaching bunch lengths on the order of 20 psec for any of the candidate lattices. If not, we expect to lose about a factor of 2-3 in bunch length. In the latter case, it does not appear practical to regain the lost bunch length via reasonable variation of RF parameters.

III. Emittance Growth

In this section, we will estimate the equilibrium emittance values of the various 1-2 GeV Synchrotron Radiation Source lattices, based on the theory of intrabeam scattering (IBS) of Bjorken and Mtingwa [8]. From previous comparisons between the predictions of ZAP and experimental results at low energies from Aladdin [9] and MAX-lab [10], we are confident that the results of the code are in reasonable agreement with "reality."

In general, the severe effects of IBS diminish rapidly as the beam energy increases. However, in the case of the 1-2 GeV Synchrotron Radiation Source lattices, the natural emittance and natural bunch length values (see Table II) are very small, i.e., we have very high bunch density. Thus, even at rather high energies we might expect to see some beam emittance blowup from IBS. Because the IBS phenomenon is a single-bunch effect, the most severe problems will occur in the (high current) single-bunch scenario.

In Fig. 7 we show the emittance growth for the representative case of the TBA lattice at an emittance ratio ($\varepsilon_x/\varepsilon_y$) of 10:1. A beam current of 7.6 mA in a single bunch has been assumed. As is obvious, the emittance growth is negligible at high energies and is only about a factor of 2 beyond the natural emittance at 1000 MeV. Due to the higher beam density, the S.S. case leads to more growth than the case of no S.S. at the same average beam current. The standard multi-bunch scenario for the 1-2 GeV Synchrotron Radiation Source, i.e., 400 mA in 250 bunches, leads to an even smaller growth, as expected. Indeed, the behavior shown in Fig. 7 is essentially the same for all of the five lattices under investigation here. If we take a case with a larger emittance ratio of 100:1, the beam density, and hence the emittance growth, is larger; this is shown in Fig. 8. Nonetheless, the expected emittance growth at the lower energies does not at all compromise the operating specifications outlined in Table I.

To summarize, we conclude that there is a noticeable emittance growth at the lower end of the energy range (near 1000 MeV) but it is not severe enough to limit the performance of any of the lattices studied.

IV. Beam Lifetime

The beam lifetime will be limited by a combination of two effects: Touschek scattering and gas scattering. In this section we will first discuss the former phenomenon and then briefly report on the results of our gas scattering lifetime estimates.

<u>Touschek Scattering</u>

Touschek scattering, which involves large-angle intrabeam scattering, is most severe for bunches that have high current, short bunch length, low emittance, and large emittance ratio. These properties are (unfortunately from this viewpoint) just those we are striving for in the 1-2 GeV Synchrotron Radiation Source. In addition, the Touschek lifetime is strongly influenced by the momentum acceptance of the lattice.

The momentum acceptance limit of the lattice can be either longitudinal, i.e., the RF bucket height, or transverse, i. e., the physical or dynamic aperture. For the lattices studied here, the limiting acceptance at low energies is always transverse. One reason for this is that the RF voltage was already chosen to be quite high in order to maintain short bunches in the ring (see Section II).

In the code ZAP, the transverse limits can be used in several ways. The code can be given information on the physical aperture at each lattice point, and/or it can be given a list of the maximum value of the dynamic aperture (in the dispersive region) as a function of $\Delta p/p$. Finally, the code can use a pair of values that give the maximum momentum acceptance values (e. g., from tracking or well-honed intuition) in the dispersive and non-dispersive regions of the lattice. (The distinction between dispersive and non-dispersive regions is due to the fact that, in the dispersive region, the scattering event gives rise to a betatron oscillation amplitude, whereas a scatter in the non-dispersive region does not. The available aperture is thus lower in the dispersive region due to the need to accommodate both the closed-orbit deviation and the betatron oscillation.) In the present study, different lattices were handled differently; the various values used are summarized in Table III.

Touschek lifetimes have been calculated for all lattices for the cases of 400 mA in 250 bunches and 7. 6 mA in 1 bunch, both with and without the S.S. assumption. Figure 9 shows a comparison among the lattices for the 250-bunch case with S.S. The single-bunch results (again with S.S.) are given in Fig. 10. For both the single- and multi-bunch cases, the calculated pattern is about the same. On the average, the single-bunch lifetimes are about half those for the multi-bunch case. Because of their lower momentum acceptance, the CG and ECG lattices tend to look unfavorable at the lower energies compared with the FODO and TBA designs. At higher energies, where the limiting acceptance is longitudinal, the various lattices look more comparable. Not using the S.S. assumption (Fig. 11) leads to longer bunches (by about a factor of 2) and to longer lifetimes (by a similar factor).

The Touschek lifetime can also be affected by the RF parameters, as shown in Fig. 12. For the most severe situation (the CG lattice in the single-bunch mode) we find that, at low energies, it is helpful to reduce the RF voltage. This works because the bunch density can be somewhat reduced without decreasing the momentum acceptance, which is limited transversely at low energies. Indeed, in this regime, increasing the RF voltage actually decreases the Touschek lifetime. As can be seen in Fig. 12, the "crossover" for this effect is at about 1500 MeV, so reducing the RF voltage only helps the lifetime (at the expense of the bunch length, of course) at low energies.

Changing the emittance ratio from 10:1 to 100:1 reduces the Touschek lifetimes by about a factor of three; this is demonstrated for the TBA lattice in Fig. 13. Although the higher emittance ratio might be acceptable for those lattices having a large momentum acceptance (such as the TBA lattice in Fig. 13), it is not obvious that it would be suitable for the CG lattices.

<u>Gas Scattering</u>

Gas scattering lifetimes have been calculated for each lattice based on the formulae given by Le Duff [11]. The calculations assume a pressure of 1 nTorr of nitrogen gas, and a ring acceptance limited by an undulator (full) gap of 1 cm. The resultant lifetimes (Fig. 14), which include contributions from both elastic and inelastic (bremsstrahlung) scattering, lie in the range of about 5-20 hours; all lattices exhibit fairly similar behavior.

<u>Overall Lifetime</u>

Overall beam lifetimes (at 1500 MeV) for the five lattices studied are collected in Table IV. Lifetimes in excess of 6 hours should be achievable except for the CG and ECG lattices in the single-bunch mode. It is important to remember, of course, that the lifetimes tend to decrease at lower beam energies.

V. FEL Performance

Although it is only a curiosity at this point, it was mentioned at the users meeting [1] that the 1-2 GeV Synchrotron Radiation Source might someday be utilized to drive a high-gain Free Electron Laser (FEL). It was of interest, therefore, to evaluate the performance of the candidate lattices for this purpose. As a useful benchmark, we will compare the predicted FEL performance of the present lattices with that of a ring designed by our group [6] specifically for this purpose. See Ref. [6] for an explanation of the FEL parameters calculated.

To allow direct comparison with our CXF design [6], we will evaluate the performance of each lattice at 750 MeV, for a radiation wavelength of 400 angstroms. Values for the FEL gain parameter, ρ, and the predicted peak output power are summarized in Table V. Included in Table V are the values for the lattice designated CF144 from Ref. [6]. Although not as good as the CXF case, the performance predicted for the various lattices is fairly encouraging. The 1-2 GeV Synchrotron Radiation Source lattices show a peak power of about 5-10 MW, compared with 30 MW for a more optimized design. It appears, however, that the predicted FEL performance depends heavily on the validity of the S.S. assumption. In the absence of S.S., the gain and the e-folding length for the FEL radiation are predicted to be much poorer, and may well be unsuitable for experiments; this is demonstrated in Table VI.

VI. Summary

In this section we will try to briefly summarize our conclusions regarding performance of the various candidate lattices.

With regard to bunch length, we find that the SPEAR scaling assumption is required in order to achieve, with a reasonable beam intensity, the very short bunches (about 20 psec) that have been requested. If the SPEAR scaling assumption is not valid, it should still be possible to achieve the beam intensity and emittance goals of the 1-2 GeV Synchrotron Radiation Source, but with longer bunches (about a factor of 2-3). This conclusion is independent of the details of the particular lattice being considered.

We find, not surprisingly, that emittance growth is not a serious issue for the 1-2 GeV Synchrotron Radiation Source. The growth can be a factor of 3-4 at very low energies (about 750 MeV), but is never enough to compromise lattice performance. Without the S.S. assumption, the growth is even smaller. Here too, these conclusions are basically lattice independent.

At low energies, single-bunch lifetimes for the various lattices can drop to only a few hours in some cases. The FODO and TBA lattices, with their larger momentum acceptance, are better than the CG lattices in this regard. If short bunches are not needed at the lower energies, some gain in lifetime can be made by varying the RF parameters. Should it be necessary or desirable to run with a larger emittance ratio (e.g., 100:1 rather than 10:1), the lifetimes will drop significantly. It may well be impractical to consider such a scenario for the CG lattices due to their shorter lifetime at low energies.

A brief investigation of FEL performance indicates that the 1-2 GeV Synchrotron Radiation Source lattices should give acceptable results, producing about 1/3 of the peak power of an optimized lattice design.

Finally, the study presented here suggests that the key issue in distinguishing the various lattices is the beam lifetime.

Acknowledgments

The help of the lattice designers (A. Garren, A. Jackson, and A. Wrulich) has been invaluable in the preparation of this report. This work was supported by the Office of Basic Energy Sciences of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

[1] Report of the Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source: Applications to Science and Technology, Berkeley, CA, Nov. 13-15, 1985, Lawrence Berkeley Laboratory Report PUB-5154.

[2] The Advanced Light Source: Technical Design, May, 1984, Lawrence Berkeley Laboratory Report PUB-5111, Appendix A.

[3] Lattices from the following sources: CG, A. Garren and A. Jackson; ECG, A. Garren and A. Wrulich; FODO2, A. Wrulich (LBL-21215, May 1986); FODO3, A. Garren; TBA, A. Jackson (LBL-21279, March 1986).

[4] ZAP User's Manual, M.S. Zisman, S. Chattopadhyay, and J. Bisognano, Lawerence Berkeley Laboratory Report LBL-21270, 1986.

[5] Scaling Law for Bunch Lengthening in SPEAR II, A. Chao and J. Gareyte, PEP-224, December, 1976.

[6] Feasibility Study of a Storage Ring for a High Power XUV Free Electron Laser, J. Bisognano et al., Particle Accelerators, 18, 223 (1986).

[7] Damping Test of the Higher-Order Modes of the Re-entrant Accelerating Cavity, Y. Yamazaki, K. Takata, and S. Tokumoto, IEEE Trans. Nucl. Sci. NS-28, 2915 (1981).

[8] J. D. Bjorken and S. Mtingwa, Particle Accel. 13, 115 (1983).

[9] Accelerator Physics Experiments at Aladdin, S. Chattopadhyay et al., Lawrence Berkeley Laboratory Report LBL-19905, July, 1985, (unpublished).

[10] M. Eriksson, (private communication).

[11] Current and Density Limitations in Existing Electron Storage Rings, J. Le Duff, Nucl. Instr. and Meth. A239, 83 (1985).

Table I.

1-2 GeV Synchrotron Radiation Source User Requirements*

Nominal Energy	:	1500 MeV
Energy Range	:	750 - 1900 MeV
Average Current	:	400 mA
Horiz. Emittance	:	$< 1 \times 10^{-8}$ π m-rad
Pulse Width ($2\sigma_\tau$)	:	20 - 50 psec
Beam Lifetime	:	> 6 hrs

* From Ref. [1].