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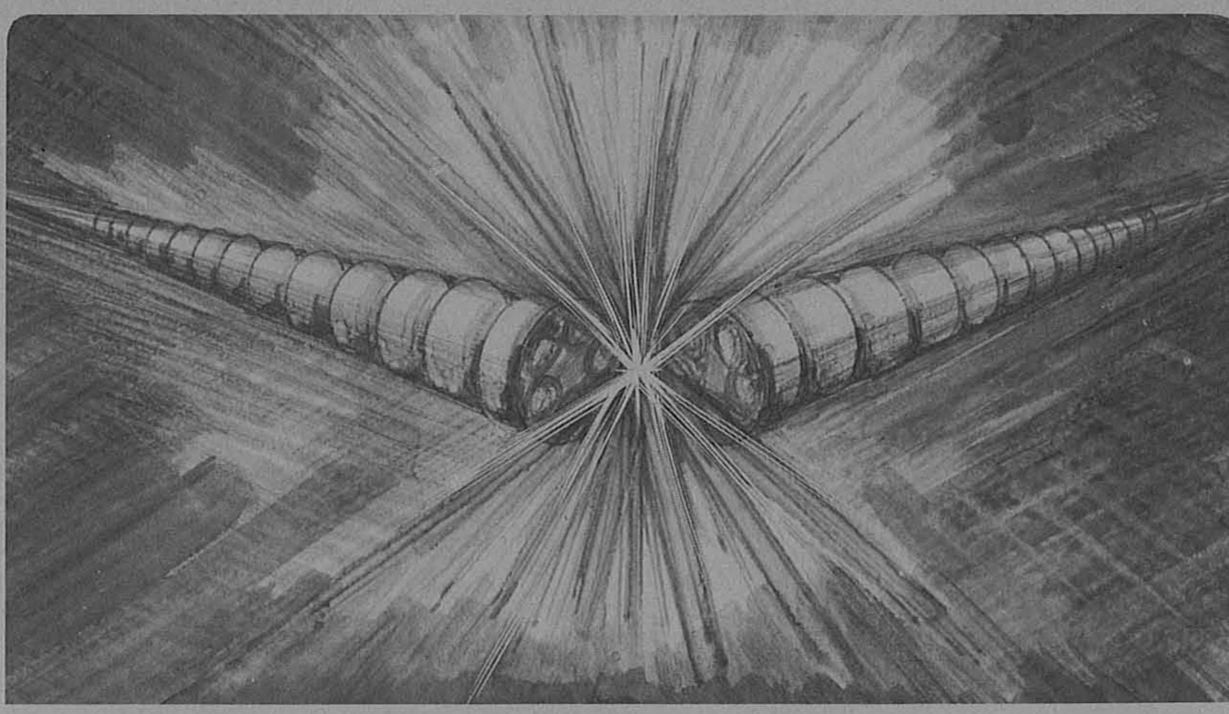

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Abstract

A new computer code, ZAP, has been written to study the influence of various collective effects on the performance of electron storage rings. In particular, the code can evaluate the equilibrium emittance of a ring including the effects of intrabeam scattering. Examples are presented of utilizing the code to optimize the design of storage rings for the purposes of a third-generation synchrotron radiation source and a high-gain free-electron laser. In addition, the importance of the intrabeam scattering emittance blowup to the issue of low energy injection is discussed. Such considerations will be necessary to optimize the design of compact synchrotrons now being studied for use in x-ray lithography. To verify predictions of the code, comparisons are made with experimental measurements of low energy beam emittance taken from the Aladdin storage ring; reasonable agreement is obtained.

I. INTRODUCTION

There has been worldwide interest recently in the design of high-brightness synchrotron light sources, both for the VUV and X-ray regimes. Most of these facilities are intended to meet the characteristic (but conflicting) requirements of low emittance, short bunches, high beam intensity, and long lifetime. As beam dimensions decrease and beam intensities increase, of course, the influence of various collective phenomena on beam properties becomes more pronounced. To investigate the influence of these effects, a new computer code, called ZAP,[1] has been written at LBL. The code is designed to facilitate parameter studies of storage rings. Such studies permit the design team to make optimum parameter choices for their particular circumstances.

In this paper, we will first briefly describe the code itself, and then illustrate, via selected examples, how the collective effects contained in ZAP manifest themselves in the new generation of synchrotron light sources. To verify predictions of the code, we include in Section IV a comparison with experimental measurements of the emittance growth at low energies made at the Aladdin storage ring; reasonably good agreement is obtained.

Although the thrust of the code is mainly toward electron storage rings, it is worth pointing out that ZAP can also be used (for most options) for calculations of proton or heavy ion storage rings.

II. DESCRIPTION OF THE CODE

Before giving examples that illustrate the usage of ZAP, it is important to understand the "philosophy" of the code. ZAP is intended mainly for systematic accelerator parameter studies that will lead to a better understanding of the (often complicated) relationships among parameters. The code is best thought of as an assemblage of "tools" rather than a monolithic program. With this approach, it tends to be straightforward to optimize a storage ring design for a particular set of physics goals, e.g., use as a high-gain Free-Electron Laser (FEL).

ZAP is an interactive Fortran code designed to run on a VAX computer. However, it was written in a manner that should not preclude its being used on other machines. In particular, the code has already been successfully run on an IBM mainframe, an IBM PC/AT, a Ridge workstation (under UNIX), and (albeit slowly) an Apple Macintosh. A ZAP User's Manual[1] has been prepared, and is available upon request from its authors.

In general, the various ZAP routines are rather loosely coupled, that is, there is no constraint in the code that the results of one routine must be used as inputs to a subsequent routine. The user is free to provide his own input values whether or not they form a consistent parameter set. This feature greatly facilitates parameter studies, but it does place the burden on the *user* to interpret the results of his calculations properly. A summary of the various types of calculations that can presently be performed with the code is provided in the Appendix.

III. EXAMPLES OF PARAMETER OPTIMIZATION

To illustrate how the code is best utilized, we select several representative cases. First, we examine the influence of collective effects on the predicted performance of the lattice that was adopted for the LBL 1-2 GeV Synchrotron Radiation Source (SRS).[2] This sort of parameter study is typical of that employed to evaluate the suitability of a particular lattice design for a synchrotron light source. Next, we consider the design of a storage ring optimized for use as a high-gain FEL.[3] Because of a need for high peak current and low emittance, such designs are especially challenging. Finally, we explore the issue of low energy injection into a storage ring. This topic has particular relevance at present because of its importance to the design of compact synchrotron radiation sources for use in x-ray lithography.[4]

1-2 GeV Light Source Design

Here we discuss the implications of various collective phenomena on the required performance of the LBL 1-2 GeV Synchrotron Radiation Source lattice.[2] The lattice itself has a so-called Triple-Bend Achromat (TBA) structure. Its layout and lattice functions, taken from Ref. 2, are shown in Fig. 1. For our purposes, the performance issues to be considered are bunch lengthening, emittance growth from intrabeam scattering, and beam lifetime. We take as a starting point a set of requirements specified[5] by the potential users of such a facility; these are summarized in Table I.

Bunch length. The bunch length requirement for the LBL 1-2 GeV SRS is for very short bunches, $2\sigma_\tau \approx 20\text{-}50$ ps. In practice, the attainable bunch length is determined by the RF parameters and the constraints of the longitudinal microwave instability ("turbulent bunch lengthening"). For RF parameters, we assume a 500-MHz system operated at 1.5 MV; these parameters were selected[2] to provide very short bunches.

The influence of the longitudinal microwave instability depends upon the effective impedance assumed for the ring. This dependence is shown in Eq. (1), which gives the threshold peak current for the microwave instability in terms of the ring broadband impedance and other lattice parameters.

$$I_p = \frac{2\pi|\eta|(E/e)(\beta\sigma_p/p)^2}{|Z/n|_{eff}} \qquad (1)$$

where η is the phase-slip factor and $|Z/n|_{eff}$ is the longitudinal impedance seen by the beam bunch.

In the absence of a detailed impedance inventory, a value of 2 Ω was taken for the vacuum chamber broadband impedance. The RF cavity is assumed to have an impedance (per cell) of 0.25 Ω, as obtained from the higher-order modes of a reference RF design.[6] In Fig. 2 we show the bunch length as a function of average current, based upon the relationship given in Eq. (1).

The magnitude of the turbulent bunch lengthening is very sensitive to whether or not we assume an impedance roll-off in obtaining the effective impedance for these very short beam bunches. In ZAP, we use the phenomenological "SPEAR scaling" rule[7] for estimating the effective impedance. For short bunches, $\sigma_\ell \leq b$, where b is the beam pipe radius, we take the effective impedance to be given by:[1]

$$(Z/n)_{eff} = (Z/n)_o (\sigma_\ell/b)^{1.68} . \qquad (2)$$

The influence of SPEAR scaling on the predicted bunch length is indicated in Fig. 2. At higher currents, the effect of the impedance roll-off is to reduce the bunch length by a factor of 2-3. In the absence of SPEAR scaling, achieving a bunch length of 20 ps with a reasonable single-bunch current is clearly difficult. On the other hand, if the SPEAR scaling assumption were not valid, it would still be possible to achieve the beam intensity and emittance goals in Table I, albeit with longer bunches.

Emittance growth. Equilibrium emittance values of the LBL 1-2 GeV SRS lattice can be estimated with ZAP based on the IBS theory of Bjorken and Mtingwa.[8] That is, the code iterates to obtain the emittance value that is a solution to

$$[g_{IBS}(\varepsilon) - g_{sr}]\varepsilon + g_{sr}\varepsilon_o = 0 , \qquad (3)$$

where g_{sr} is the radiation damping rate (either horizontal or longitudinal), defined as

$$g = \frac{1}{\varepsilon}\frac{d\varepsilon}{dt} \quad ,$$

g_{IBS} is the corresponding IBS rate (which is itself a function of the emittance) averaged over the lattice, and ε_o is the natural emittance of the lattice, i.e., the emittance that results solely from the emission of synchrotron radiation.

In general, the severe effects of IBS diminish rapidly as the beam energy increases. However, in the case of the LBL 1-2 GeV SRS lattice (and other so-called third generation designs), the natural emittance and natural bunch length values are very small, i.e., we have very high bunch density. Thus, even at rather high energies we might expect to see some emittance blowup. Because the IBS phenomenon is a single-bunch effect, the most severe problems will occur in the (high current) single-bunch operating mode and for the smallest coupling.

In Fig. 3 we show the emittance growth for the 1-2 GeV SRS lattice at 10% emittance coupling and a single-bunch beam current of 7.6 mA. Predicted emittance growth is negligible at high energies, and is only about a factor of two beyond the natural emittance at 1 GeV. Due to the resultant higher beam density, the SPEAR scaling case leads to more growth than that without this assumption (at the same average beam current). The multibunch operating mode for the LBL 1-2 GeV SRS, which requires 400 mA in

250 bunches (i.e., 1.6 mA per bunch), gives rise to even smaller growth. It is clear that the expected emittance growth, even at the lower energies, will not compromise the requirements in Table I.

Beam lifetime. Beam lifetime will be limited by a combination of two effects: Touschek scattering and gas scattering. Touschek scattering is most severe for bunches that have high current, short bunch length, low emittance, and small coupling ratio. These properties are (unfortunately from this viewpoint) just those for which we are striving. In addition, the Touschek lifetime is strongly influenced by the momentum acceptance of the lattice, which can be either longitudinal, i.e., the RF bucket height, or transverse, i.e., the physical or dynamic aperture. For the lattice considered here, ZAP shows that the limiting acceptance at low energies is transverse. Touschek lifetimes, based upon the formulation of Bruck,[9] have been calculated for the cases of 400 mA in 250 bunches and 7.6 mA in 1 bunch; results are given in Fig. 4. For both single-bunch and multibunch cases the calculated pattern is about the same but, on the average, the single-bunch lifetimes are about half those for the multibunch case. Not using the SPEAR scaling assumption would result in longer bunches (by about a factor of 2) and longer lifetimes (by a similar factor).

Gas scattering lifetimes are calculated for each lattice based on the formulae given by LeDuff.[10] The calculations assume a pressure of 1 nTorr of nitrogen gas, and a ring acceptance limited by an undulator (full) gap of either 1 or 2 cm. Resultant lifetimes (see Fig. 5), which include contributions from both elastic scattering and bremsstrahlung, lie in the range of about 20-35 hours for the 2 cm gap or 8-18 hours for the 1 cm gap. Overall beam lifetimes for the case of a 1 cm gap are shown in Fig. 6. Lifetimes in excess of 6 hours should be achievable in most cases.

High-Gain Free-Electron Laser Design

One of the promising approaches to the production of coherent radiation in the XUV region is the so-called high-gain FEL.[3,11] In this device, the interaction of the electron beam with the undulator occurs in a single pass, and no mirrors are required. For efficient interaction between the beam and its radiation, the undulator must be long and must have a small gap. Because of the disruptive effect on the beam (in terms of energy loss, energy spread, and gas scattering lifetime), the FEL undulator is envisioned[3] to be located in a special bypass section (see Fig. 7), through which the stored beam passes periodically. As shown in Ref. 3, the beam requirements for this purpose include a high peak current, a low emittance, and a small energy spread; these requirements place severe demands upon the storage ring design.

In order to study the trade-offs inherent in such an application, a series of FEL lattices—designed to produce 400 Å undulator radiation—was investigated in Ref. 3. Both separated function (SF) and combined function (CF) rings were considered, with circumferences ranging from 130 to 180 m. Several of the lattices included damping wigglers (W) to improve the natural emittance value and damping time. Properties of the various lattices, designated according to the preceding notation, are summarized in Table II; ZAP results for each are given in Table III.

Peak current. For the desired low momentum spread, the peak current limitation arises from the longitudinal microwave instability. The requirement for high peak current also favors short bunches (due to the expected impedance roll-off). To gain in peak current, the obvious solution is to allow the momentum spread of the beam to increase. This possibility is illustrated in Fig. 8 for a fixed rms bunch length of 1.25 cm and a desired wavelength of 400 Å. Unfortunately, the gain of the FEL itself degrades with increasing momentum spread quite rapidly,[3] so the actual effect of the increase in momentum spread is to decrease the gain parameter and increase the e-folding length. Thus, the optimum situation actually favors a smaller momentum spread, despite the penalty in peak current.

Lifetime. For the bypass scenario, the beam lifetime will be determined by Touschek scattering. The required high bunch density makes this issue a potentially serious concern, especially for relatively low beam energies of about 750 MeV. Because the Touschek lifetime is a strong function of the momentum acceptance of the ring, ZAP was used to investigate the momentum acceptance necessary to achieve a Touschek lifetime in excess of one hour. For all the FEL lattices studied, this value turns out to be about

3%, corresponding in most cases (see Table III) to an RF voltage of about 1.5 MV. In one case (SF180W) in which the lattice was designed to achieve a very high momentum compaction factor, the required RF voltage increased to nearly 5 MV. Although the overall performance of lattice SF180W was somewhat better than alternative designs, this lattice was deemed an unattractive choice for this reason.

Emittance growth. As might be expected (see, e.g., Fig. 3), there is significant emittance growth for the high peak current, low energy regime of interest for FEL purposes. In most of the cases studied (see Table III), this growth was about a factor of two beyond the natural emittance value at 750 MeV. Thus, the equilibrium emittance values for the various candidate lattices all tend to be similar, and the best performance in terms of current density depends mainly on the attainable peak current.

Optimum beam energy. The final topic of concern is the choice of optimum beam energy. Issues that must be considered (simultaneously) include the threshold current for bunch lengthening, emittance growth from IBS, and Touschek lifetime. Using ZAP to sort out the rather complicated interplay among these phenomena, we obtain the results shown in Fig. 9. In this example, the best energy appears to be somewhere between 750 and about 1000 MeV.

Low Energy Injection

The topic of low energy injection is an important one for the design of electron storage rings, especially the so-called "compact" devices being designed to serve as photon sources for x-ray lithography.[4,12,13] The issue, of course, is not *whether* a low energy injection scheme can work—it can and does—but to assess the consequences of such a technique on the required beam aperture and beam lifetime. The problem to be faced is that there can be substantial growth in the beam size at low energies under the influence of IBS. In Ref. 8, it is shown that the rate of IBS growth depends strongly on the phase-space density of the electron bunch. Because of the quadratic dependence of the beam emittance values (horizontal, vertical, and longitudinal) on beam energy, the relative rates of IBS at the "natural" emittance values for a ring (i.e., the emittance values obtained solely from the influence of synchrotron radiation emission) scale as roughly E^{-9}. Clearly, the rates associated with an injection energy of, say, 1/10 of the full energy of a ring can be very large, even if the IBS effects at full energy are essentially negligible.

The mechanism that "controls" the growth rate, of course, is radiation damping. The damping rate is also strongly energy dependent, increasing as E^3. Thus, at low energies, where little synchrotron radiation is emitted, damping times of seconds—in contrast to the millisecond damping times typical at full energy—are the rule. As a result, the situation during low energy injection is likely to be one in which the IBS growth rates are large and the radiation damping rates small, leading to equilibrium emittance values that are very much larger than the natural values. Because ZAP has the ability to solve for the equilibrium emittance in the presence of both synchrotron radiation and IBS, we can use the code to estimate the magnitude of this growth. As an example, we discuss a ring, Aladdin, that utilizes low-energy injection and calculate the resultant effects on beam size and lifetime.

Aladdin is a 1-GeV electron storage ring operated by the University of Wisconsin. Its injection system is a nominally 100-MeV microtron. Because of problems during the commissioning phase of the machine, a study was carried out to investigate its behavior. At low energies, the predicted[14] effects of IBS on the beam emittance (both longitudinal and transverse) are quite large, as shown in Figs. 10 and 11. Thus, the beam size and energy spread at injection are much larger than those given by the natural emittance values of the storage ring. The beam size blowup is even more evident in Fig. 12, which shows the predicted energy dependence of the effect. We see from this calculation that low-energy injection can lead to substantial growth, which must be taken into account in the design of the injection system.

It is worth noting, however, that the Touschek lifetime—which would otherwise be expected to be very short at 100 MeV—is considerably increased by this emittance blowup because of the concomitant lowering of the bunch density.

Compact synchrotrons. It is clear from the above results that the growth in beam size at low energies is an important issue. For the design of compact synchrotrons, fortunately, things tend to be somewhat improved. The reason is that the bending radius will generally be much smaller, which—for a given injection energy—enhances the radiation damping process. Although the qualitative features of emittance growth are similar to those in Fig. 12, the growth tends to be smaller. In cases examined up to now, a typical result is that the emittance at 100 MeV is comparable to that at an operating energy of about 600 MeV. Thus, the increase in beam size at injection energy is unlikely to complicate the filling process greatly. On the other hand, of course, the smaller beam size implies that the Touschek lifetime may be more of a problem.

As can be seen from the shape of the curves in Figs. 3 or 12, we expect a minimum value for the equilibrium emittance at a particular energy that we denote E_{min}. Although detailed calculations are required to pin down the exact energy corresponding to this minimum emittance, we can estimate the value of E_{min} by following the approach of Ref. 3. We write the equilibrium emittance value as

$$\varepsilon \approx \frac{\varepsilon_o + [\varepsilon_o^2 + 4 \, (K_{IBS}/g_{SR})]^{1/2}}{2} \qquad (4)$$

where $K_{IBS} = g_{IBS}\,\varepsilon^2$ is approximately constant at a fixed energy. [Note that the numerical factor of 4 in the square root term in Eq. (4) was inadvertently omitted in Ref. 3.] To obtain E_{min}, we must make Eq. (4) explicitly energy dependent. We do this by defining

$$\varepsilon_o = K_\varepsilon E^2 \qquad (5)$$

$$g_{SR} = K_{SR}E^3 \tag{6}$$

and

$$g_{IBS}(\varepsilon) = K_{IBS}/\varepsilon^2 \tag{7a}$$

$$= K'_{IBS}/(\varepsilon^2 E^m) \tag{7b}$$

and then differentiating Eq. (4). The resultant estimate for E_{min} is given by

$$E_{min} = \left[\frac{(m+3)^2}{(2m+10)} \; \frac{K'_{IBS}}{K_{SR}} \; \frac{1}{K_\varepsilon^2} \right]^{1/(m+7)} \tag{8}$$

Although Eqs. (5) and (6) are exact, the exponent m in Eq. (7b) depends to some extent on the energy regime of interest and on whether the selected beam current is above or below the threshold for the longitudinal microwave instability. Fortunately, the m-dependence of Eq. (8) is quite weak, provided that K'_{IBS} is suitably extracted from Eq. (7b). (As an example, for the data in Fig. 3 we obtain E_{min} = 1.34 GeV for m = 5, or 1.15 GeV for m = 2.5.) Thus, despite the approximate nature of Eq. (8), it does give some feeling for the energy below which the emittance blowup from IBS will be important (or above which it will not be).

IV. EXPERIMENTAL VERIFICATION

To use ZAP predictions in the design of new accelerators, it is important to verify experimentally—where possible—the reliability of the code. For the cases considered in this paper, the most noteworthy prediction of the code is that of very large emittance growth at low beam energies (see Section III). Fortunately, the Aladdin facility provided an opportunity to perform such measurements at beam energies of 100 and 200 MeV. To avoid any uncertainties due to coupled-bunch effects, the experiments[15] were performed using a first-harmonic RF cavity so that only a single bunch was stored in the ring. Of course, this choice leads to relatively long bunches, thereby decreasing the bunch density and reducing the magnitude of IBS emittance growth. Nonetheless, the predicted growth was substantial.

That these predictions were realistic was verified experimentally,[15] with the results shown in Table IV. We see that the observed emittance is very large—more than a factor of 100 larger than the natural emittance at injection energy. Indeed, the beam size at injection is larger than that at an operating energy of 800 MeV. There is some indication in Table IV that the ZAP results (especially at 100 MeV) systematically underpredict the emittance growth. This may be due to the omission of any effects on the emittance from ion trapping, which is known to have been a serious problem at Aladdin.

To interpret the bunch length results in Table IV, we must consider the effects of both IBS and the longitudinal microwave instability. In assessing the latter effect, we take a value for the Q=1 broadband resonator of 13 Ω. This value was obtained from independent measurements[15] at Aladdin via two complementary techniques. First, the real part of the impedance was determined by observing the change in synchronous phase (due to parasitic mode loss) as a function of beam intensity. In a second investigation, the beam transfer function was measured by modulating the RF phase and observing the corresponding changes on the beam itself; this gives a measure of the reactive part of the impedance. The two measurements yielded consistent results.

Despite the relatively long bunches associated with the use of a first-harmonic RF system, we see evidence (see Table IV and Fig. 13) for IBS growth even in the longitudinal dimension. Based on the longitudinal microwave instability alone, we would expect the bunch length to decrease by about a factor of 2.5 over the range of beam currents studied. Experimentally (Fig. 13) we find a much smaller decrease in bunch length, a trend in good agreement with the ZAP predictions that include intrabeam scattering.

V. SUMMARY

A new accelerator physics code, ZAP, has been written at LBL. The code is designed for systematic studies that can elucidate the often complicated trade-offs implicit in various parameter choices. The examples contained here give some indication of how the code can be used to good advantage in the design of various electron storage rings. In particular, the ability of the code to calculate the equilibrium emittance including the effects of IBS is very beneficial in making realistic performance evaluations. Development efforts on ZAP are expected to continue, and an updated version will be released at some future time.

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APPENDIX A: DETAILS OF ZAP

In this Appendix, we briefly describe each of the options available in ZAP. Further details, along with annotated sample calculations, can be found in the ZAP User's Manual.[1] *For ease of comparison with the manual, the numbering of references used in this Appendix is based on that in Ref. 1, i.e., the first reference in the ZAP User's Manual is denoted in this Appendix as 1-1, etc.*

Inputs to the code—generally provided from a terminal—fall into three categories. The first of these involves machine parameters, e.g., circumference, momentum compaction factor, natural emittance, damping times, lattice functions. Second, there are beam parameters, e.g., energy, intensity, bunch length, momentum spread. Third, there are radio-frequency (RF) system parameters, e.g., frequency, voltage, and higher-order cavity modes.

ZAP calculations are performed by selecting from any of nine "Main Menu" options. The user is free to use any—or all—of these options as he sees fit. There is, however, one distinction among the options that should be noted: options 1-6 are stand-alone options, in the sense that their inputs can all be provided interactively from the terminal; options 7-9, however, require a table of lattice functions that has previously been written to a disk file. The individual Main Menu options are described below; details can be found in Ref. 1.

Main Menu Options

Single-bunch thresholds. A table of single-bunch parameters is calculated as a function of RF voltage, based on the longitudinal microwave[1-1,1-20,1-21] and transverse fast-blowup[1-22–1-24] (or, if lower, transverse mode-coupling[1-23–1-25]) thresholds. Included are bunch lengths, synchronous phase angle, synchrotron tunes, (combined) resistive-wall[1-3,1-26] and parasitic-mode[1-3,1-27] energy loss estimates, RF bucket momentum half-height, threshold currents for both longitudinal and transverse instabilities, and the bunch current corresponding to the more severe of these. Thresholds can optionally be based on the phenomenological "SPEAR Scaling" law[1-11] for short bunches. An estimate of the RF cavity contribution to the broadband impedance can be obtained from data on higher-order cavity modes.

Single-bunch longitudinal parameters and energy scaling tables. This option comprises three different "utility" routines. The first produces a table, as a function of beam current, of longitudinal bunch parameters, based on the longi- tudinal microwave instability[1-1,1-20,1-21] ("turbulent bunch lengthening"), the effect of potential-well distortion,[1-29,1-30] or the combined effect of both phenomena.[1-31–1-32] Either a Gaussian or parabolic bunch shape can be selected. The code calculates the number of particles per bunch, rms bunch length, rms momentum spread and peak current; these values can optionally be based on the SPEAR Scaling law.[1-11] Bunch length and momentum spread values from this routine should typically be used as starting values for intrabeam or Touschek scattering calculations, which then include bunch lengthening in a consistent fashion.

The second routine produces a table of parameters needed for calculations of electron storage rings, as a function of energy. Values of the synchrotron radiation energy loss, natural emittance, radiation damping rates (transverse and longitudinal), and natural momentum spread are provided.[1-33] All values are scaled from a set of input values at a specified energy.

The third utility routine provides, as a function of energy, values of the unnormalized emittance (for protons or ions) based on an input normalized emittance value.

Longitudinal coupled-bunch instabilities. This option performs longitudinal coupled-bunch calculations[1-9,1-10,1-31] for equally spaced Gaussian or parabolic bunches. The code lists the modes having the fastest growth rates and those having the largest frequency shifts. For Gaussian bunches, calculations can be performed using the formalism of Wang[1-36] or that of Zotter;[1-34,1-35] for parabolic bunches, the Zotter formalism is always used. Landau damping is also considered, and the selected modes are marked as stable, unstable, or Landau damped, as appropriate. This routine requires data on the higher-order modes of the RF cavity.

Transverse coupled-bunch instabilities. This option provides the same information as that dealing with longitudinal instabilities (see previous paragraph), but for the transverse case.[1-2,1-9,1-10] Landau damping calculations for the higher-order, non-rigid transverse modes (a>0) are based solely on the average synchrotron tune spread of the bunch. Landau damping of the rigid dipole transverse mode (a=0) is absent if there is only a synchrotron tune spread, but can still be calculated[1-37,1-38] by entering a finite betatron tune spread value.

Gas scattering lifetime. This option calculates e-folding electron beam lifetimes for gas scattering.[1-39] Both elastic and bremsstrahlung processes are considered.

Free electron laser formulae. This option evaluates the FEL performance[1-42–1-48] of a ring. For a specified wavelength and undulator gap, the parameters[1-54] for the required undulator are calculated, as are values for the FEL gain parameter and e-folding length. The degradation in performance due to the finite beam momentum spread is also evaluated by solving a suitable dispersion integral.[1-53]

Intrabeam scattering. This option calculates beam growth rates (in all three dimensions) due to the effects of intrabeam scattering (IBS).[1-56] If non-zero synchrotron radiation damping rates are provided (for electrons), ZAP iterates to obtain the equilibrium emittance based on the balance among quantum fluctuations, intrabeam scattering, and radiation damping. Otherwise, the rates at the specified beam emittance are evaluated. This option requires a table of lattice betatron functions. Overall rates are weighted averages of those calculated point-by-point throughout the lattice.

Touschek scattering. This option evaluates the Touschek scattering half-life[1-58] for the ring as a weighted average over the lifetimes calculated point-by-point throughout the lattice. The momentum acceptance at any given lattice point is based on the minimum value of the RF acceptance, the physical or the dynamic aperture. Alternatively, the momentum limits can be specified explicitly if they are already known (e.g., from a tracking calculation) or can be estimated.

If the ring aperture has been given a nonzero value in the lattice file, or if dynamic aperture data are provided, the code estimates the transverse momentum limitations of the lattice due to the effects of dispersion. The limiting momentum change in the dispersive region is tabulated, along with the lattice location where the scattered particle was predicted to be lost. If the equilibrium emittance has been calculated (for electrons), this value is automatically utilized in the Touschek calculation. Thus, beam blowup from IBS is taken into account in a consistent manner.

Ion trapping formulae. This option evaluates parameters relevant to the effects of ion trapping (for electrons).[1-59,1-60] Critical masses for trapping are calculated, along with the limiting ion density, the neutralization factor, the equivalent ion "pressure," and the ion-induced tune shifts (all assuming full neutralization).

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15. S. Chattopadhyay *et al.*, Lawrence Berkeley Laboratory Report No. LBL-19905, July, 1985.

Table I

1-2 GeV Synchrotron Radiation Source User Requirements[a)]

Nominal energy	[GeV]	:	1.5
Energy range	[GeV]	:	0.75 - 1.9
Average current	[mA]	:	400
Horiz. emittance	[π m-rad]	:	$<1 \times 10^{-8}$
Pulse length, $2\sigma_\tau$	[ps]	:	20 - 50
Beam lifetime	[hr]	:	> 6

a) From Ref. 5.

Table II

Summary of FEL Lattice Parameters[a)]

Parameter		SF180W	SF130W	SF130	CF155	CF144
		Lattice				
ν_x		6.61	6.65	6.37	7.35	7.85
ν_y		6.64	4.64	2.12	4.35	4.35
α	$[10^{-3}]$	14.4	5.77	5.90	5.62	4.92
D_{max}	[m]	2.67	1.43	1.43	0.80	0.70
U_o	[keV/turn]	39.6	46.3	10.3	7.0	8.0
τ_E	[ms]	11.4	7.0	31.9	68.6	52.3
β_x, max	[m]	36.4	24.3	26.2	16.6	16.7
β_y, max	[m]	31.9	24.2	33.5	28.8	29.3
V_{RF}	[MV]	4.7	1.4	1.4	1.6	1.3
ε_{ox}	$[10^{-9}\ \pi$ m-rad]	3.25	6.85	21.5	5.0	4.6

[a)] Taken from Ref. 3.

Table III

FEL Parameters Predicted by ZAP[a)]

(E = 750 MeV)

Parameter		Lattice SF180W	SF130W	SF130	CF155	CF144
ε_x	$[10^{-9}\ \pi$ m-rad]	10.2	7.4	24.8	12.9	10.1
I_p	[A]	376	123	230	214	199
$I_p/\sqrt{\varepsilon_x \varepsilon_y}$	$[10^{10}$ A/m]	11.6	5.3	2.9	5.2	6.2
ρ	$[10^{-3}]$	1.6	1.3	1.0	1.3	1.3
τ_T	[hr]	1.0	2.4	3.7	2.0	1.4

a) Taken from Ref. 3. All values correspond to s_ℓ = 1.25 cm and 10% emittance coupling.

Table IV
Aladdin Emittance Measurements[a,b)]

I (mA)	$\varepsilon_x^{meas.}$ (10^{-8} π m-rad)	ε_x^{ZAP} (10^{-8} π m-rad)	$\sigma_\ell^{meas.}$ (m)	σ_ℓ^{ZAP} (m)	$\sigma_\ell^{\mu wave}$ (m)
		100 MeV			
7.6	23.7 ± 7.3	11.2	1.0	1.5	1.0
4.9	23.7 ± 7.3	12.1	1.0	1.4	0.84
1.1	10.6 ± 3.9	6.9	0.84	1.1	0.51
0.5	6.6 ± 2.8	4.5	0.75	0.93	0.40
		200 MeV			
4.0	4.4 ± 2.5	2.9	1.1	0.96	0.79
2.0	4.6 ± 2.4	2.5	1.1	0.88	0.63
1.0	4.3 ± 1.9	2.0	0.9	0.80	0.50
0.5	4.4 ± 1.6	1.8	0.78	0.73	0.41

a) assumed errors are: $\sigma_{x,y}$, 10%; $\beta_{x,y}$, 10%; D, 10%; σ_ℓ, σ_p, 20%.

b) based on broadband impedance of 13 Ω.

Figure Captions

1) Unit cell of LBL 1-2 GeV Synchrotron Radiation Source lattice. Top: layout of elements; bottom: lattice functions.

2) Bunch length vs. current for the lattice in Fig. 1 at 1.5 GeV, for the single-bunch case.

3) Predicted emittance growth from IBS for the lattice shown in Fig. 1 with 7.6 mA in a single bunch; the emittance coupling is 10%.

4) Touschek lifetimes for the lattice shown in Fig. 1, assuming SPEAR scaling, for the cases of 400 mA in 250 bunches and 7.6 mA in a single bunch. Below 1200 MeV, the aperture limit is transverse (T); above this energy it is longitudinal (L).

5) Gas scattering half-lives for the lattice shown in Fig. 1 with two different assumptions regarding the limiting vertical aperture. Calculations assume 1 nTorr of nitrogen gas.

6) Overall beam lifetimes for the lattice shown in Fig. 1, assuming a limiting gap of 1 cm, for the cases of 400 mA in 250 bunches and 7.6 mA in a single bunch.

7) Schematic drawing of a storage ring with a bypass section containing a high-gain FEL.

8) Dependence of peak current I, equilibrium emittance, ε_x, and some FEL parameters (ρ, ℓ_e) on the momentum spread, σ_p. Degradation of performance (ρ_{eff}, ℓ_{eff}) with increasing momentum spread is apparent. Results taken from Ref. 3.

9) Energy dependence of the following parameters: Touschek lifetime for 3% bucket height, $\tau_T{}^{3\%}$; IBS lifetime, $\tau_{x,IBS}$; equilibrium emittance, ε_x; bunch volume density, $I/\gamma^2\sqrt{\varepsilon_x\varepsilon_y}$; FEL gain parameter, ρ. Results taken from Ref. 3.

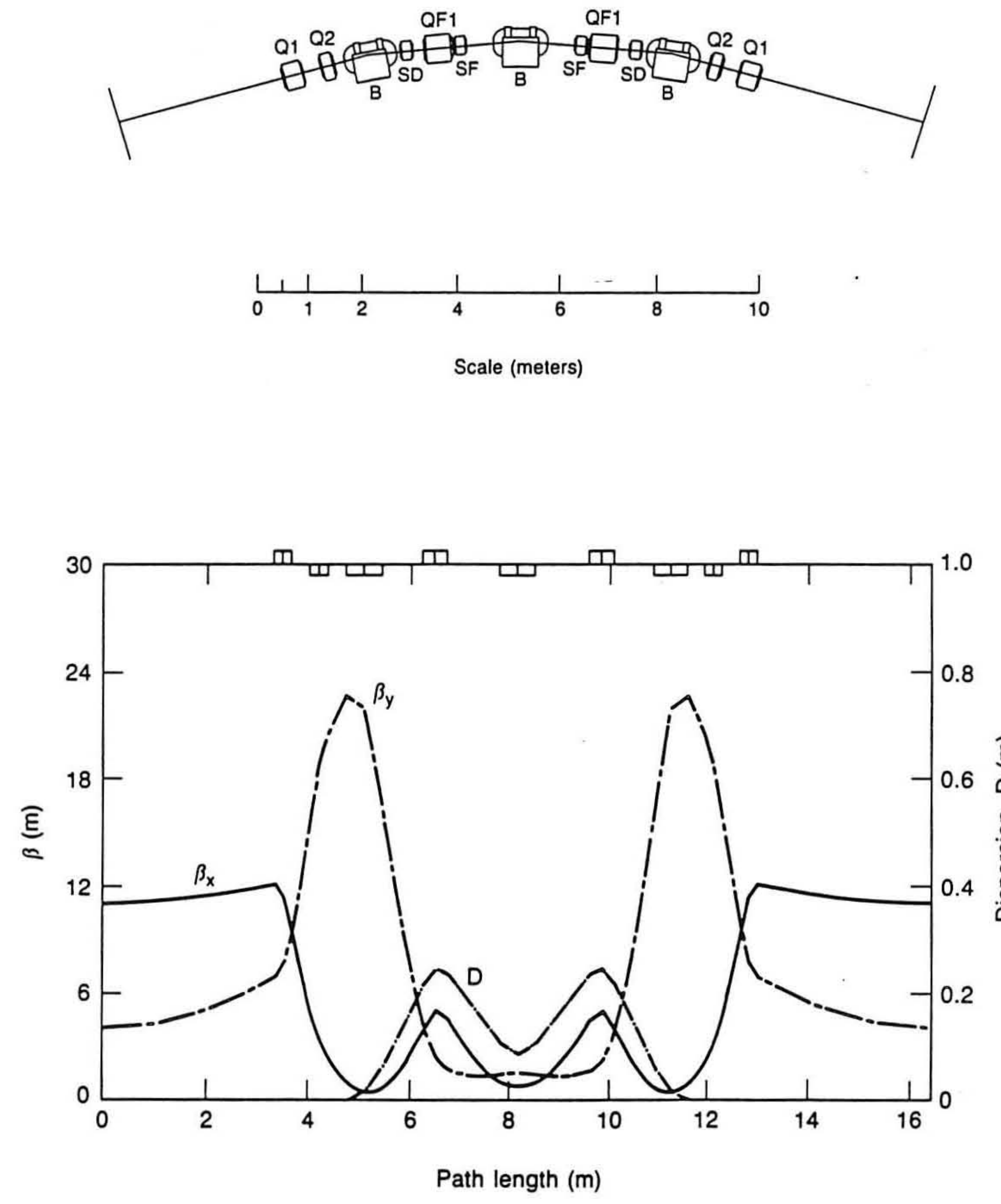
10) Equilibrium bunch length and momentum spread for Aladdin as a function of beam intensity. Calculations based only on the longitudinal microwave instability are shown for comparison.

11) Equilibrium horizontal emittance values for Aladdin as a function of beam intensity. Three different values for the horizontal-to-vertical emittance ratio are shown.

12) Energy dependence of equilibrium transverse emittance for Aladdin at two beam current values and 10% emittance coupling.

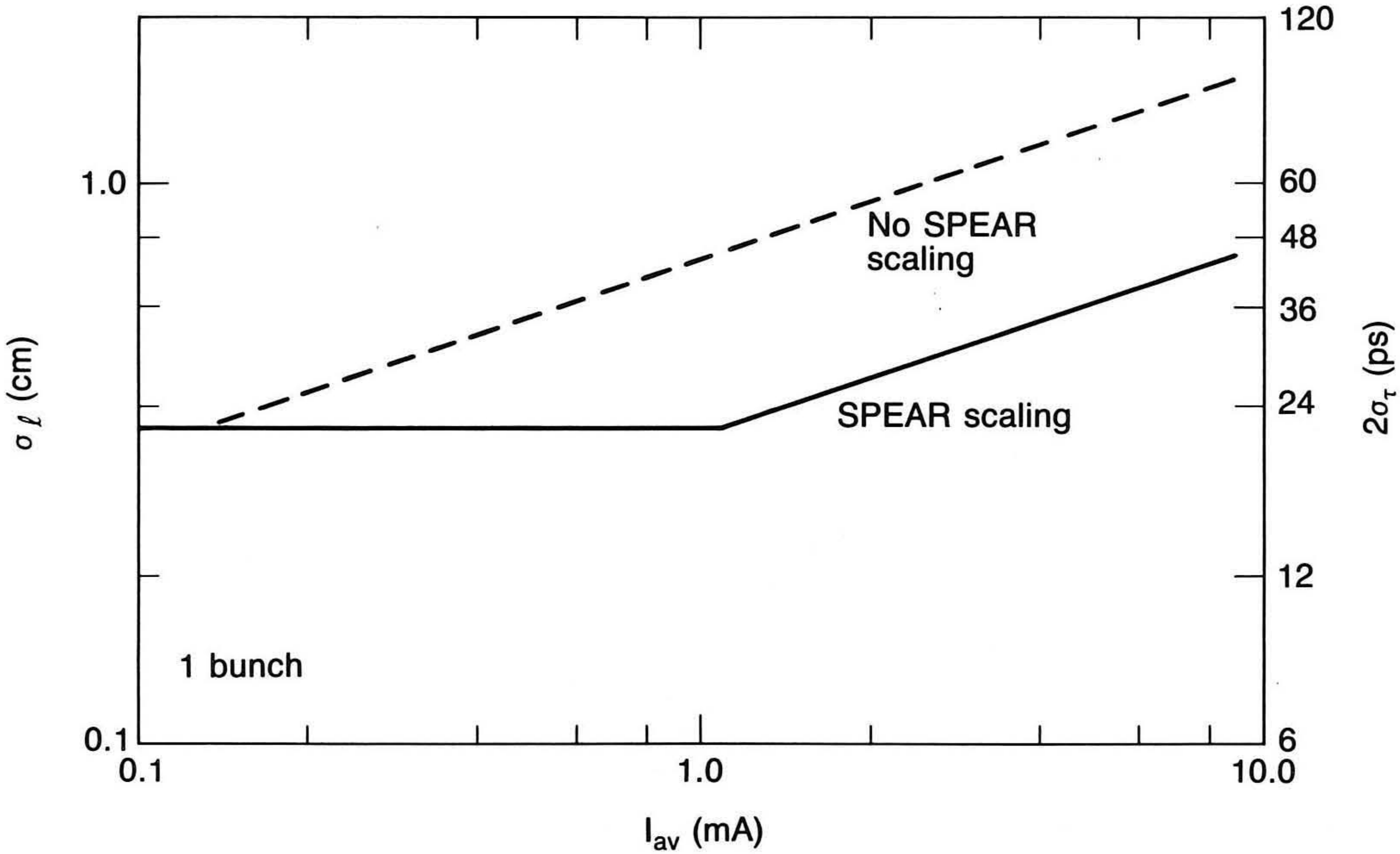
13) Bunch length measurements at the Aladdin storage ring. The

curve labeled microwave is based upon an impedance of 13 Ω. The curve labeled ZAP includes the effects of IBS growth. Experimental errors of 20% are indicated for each data point.



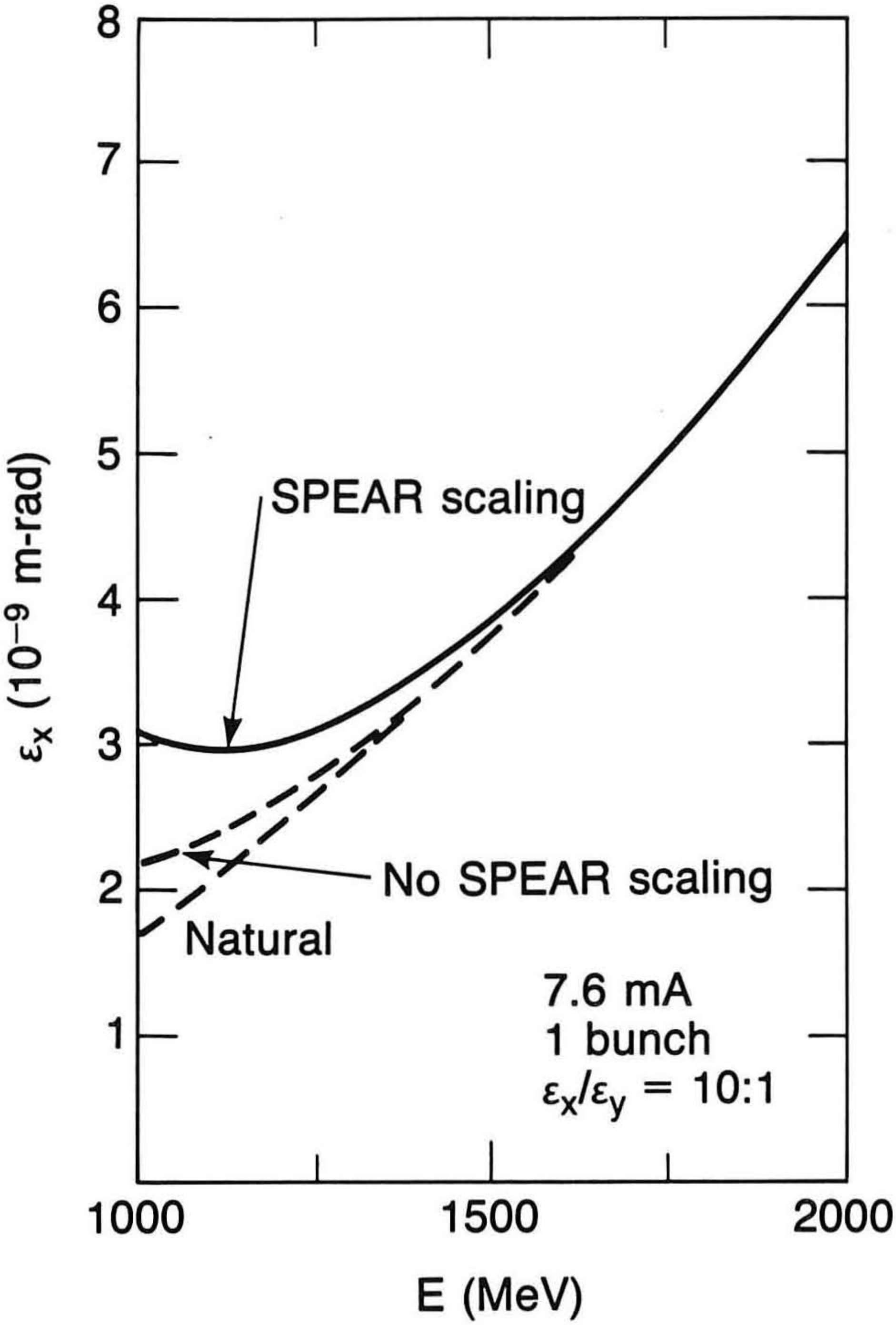
XBL 8710-4189

Fig. 1



XBL 865-6235

Fig. 2



XBL 865-6233

Fig. 3

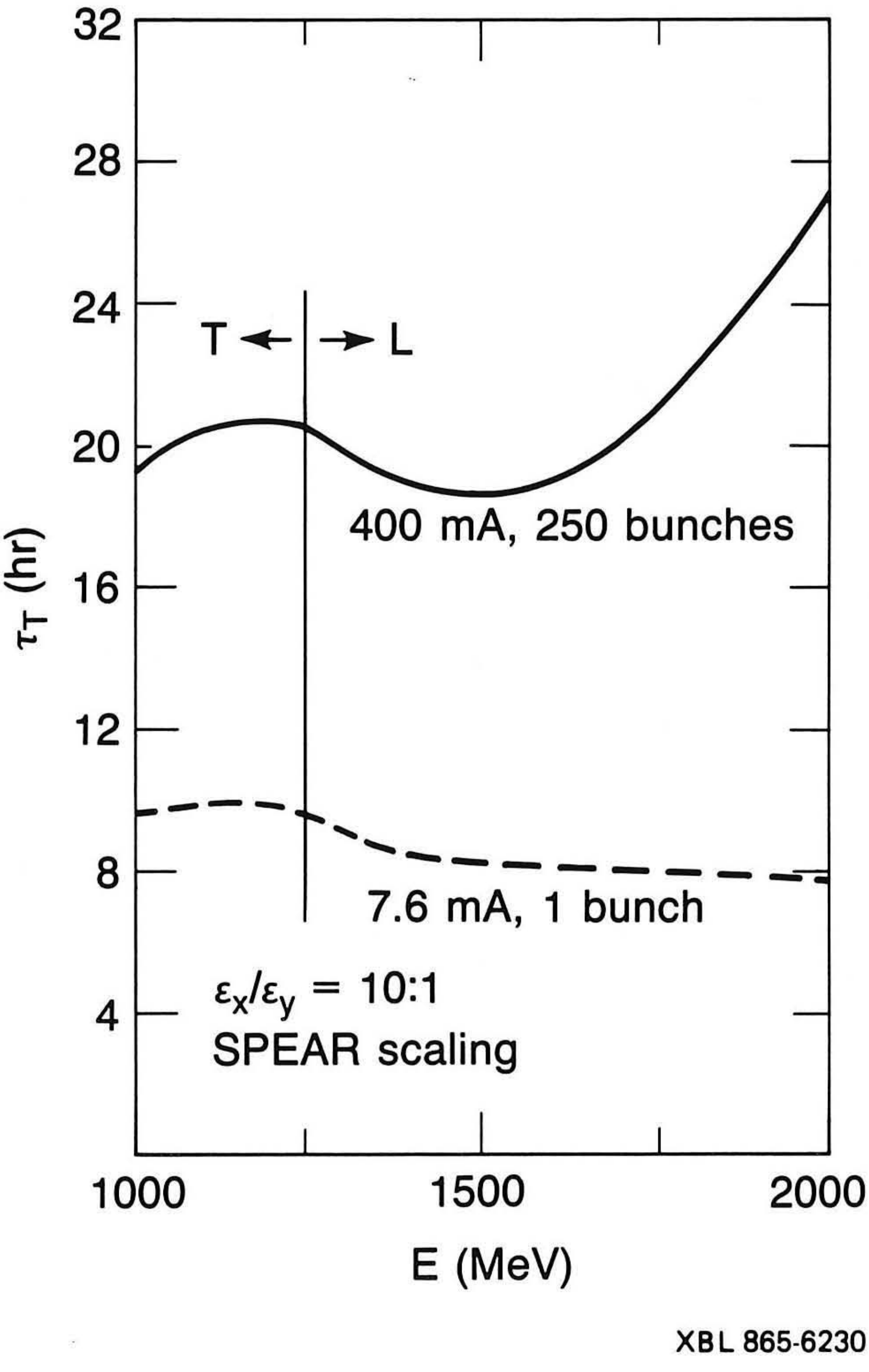

32
28
24
20
16
12
8
4
τ_T (hr)
T
L
400 mA, 250 bunches
7.6 mA, 1 bunch
$\varepsilon_x/\varepsilon_y$ = 10:1
SPEAR scaling
1000
1500
2000
E (MeV)
XBL 865-6230

Fig. 4

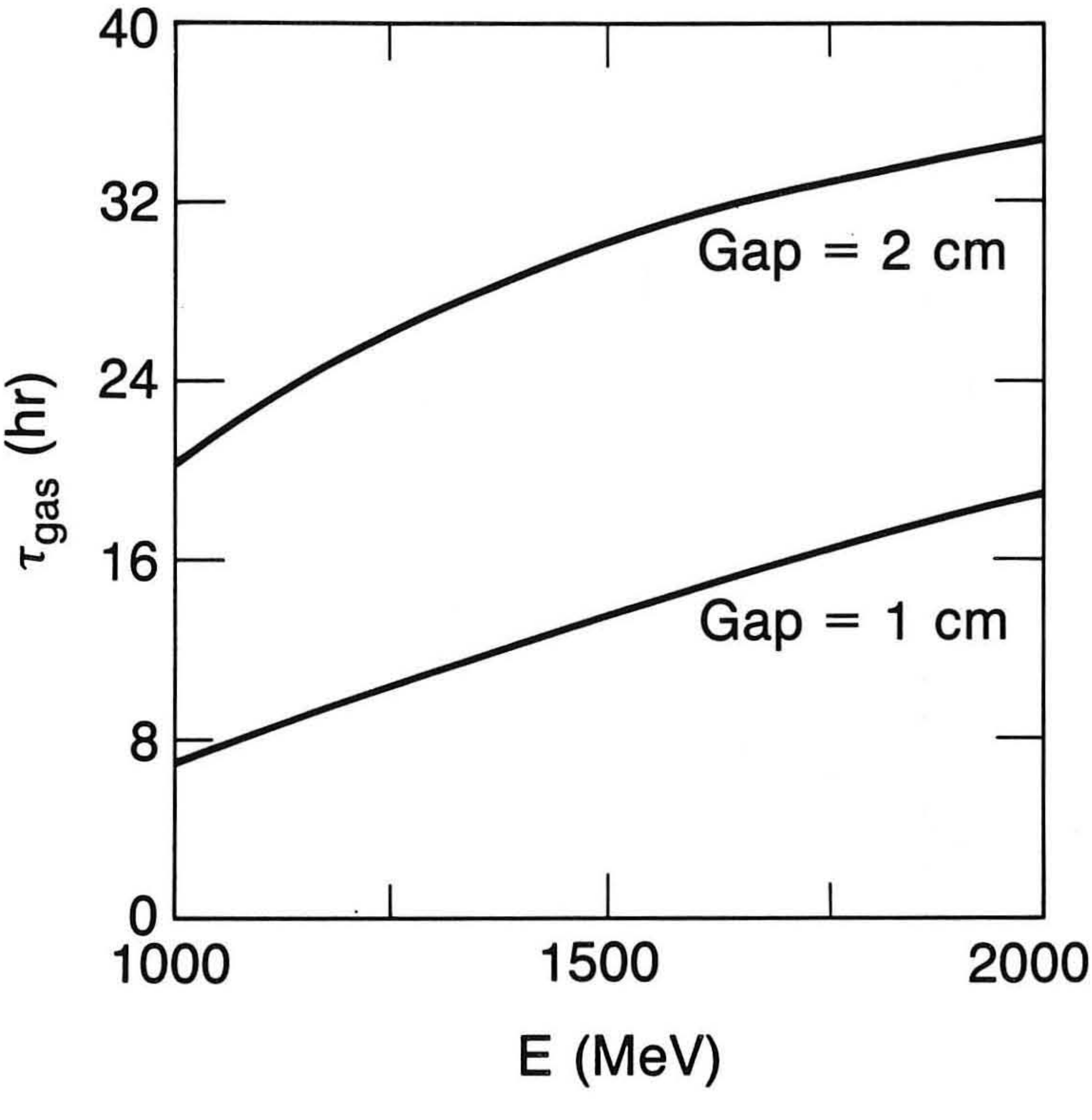
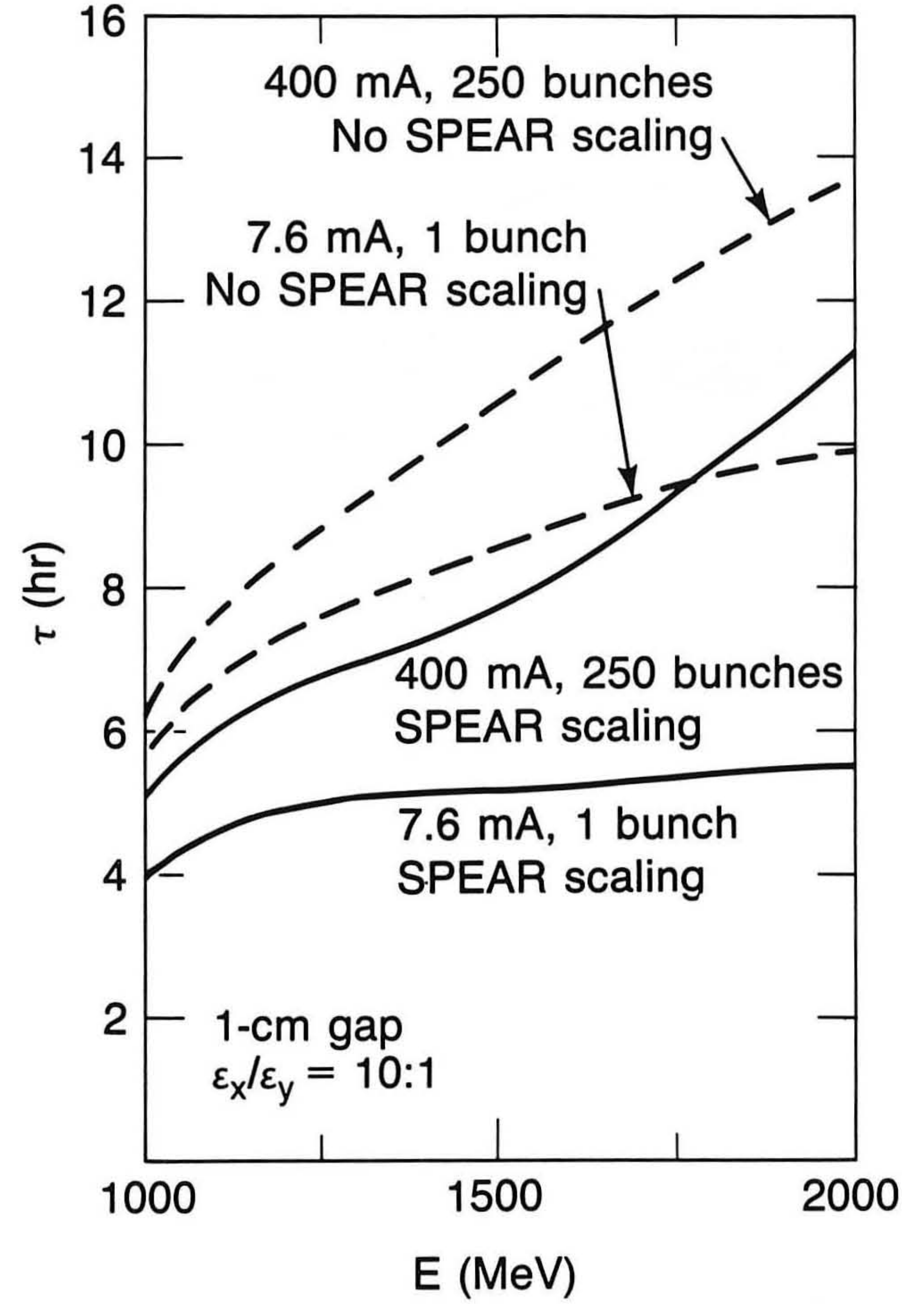
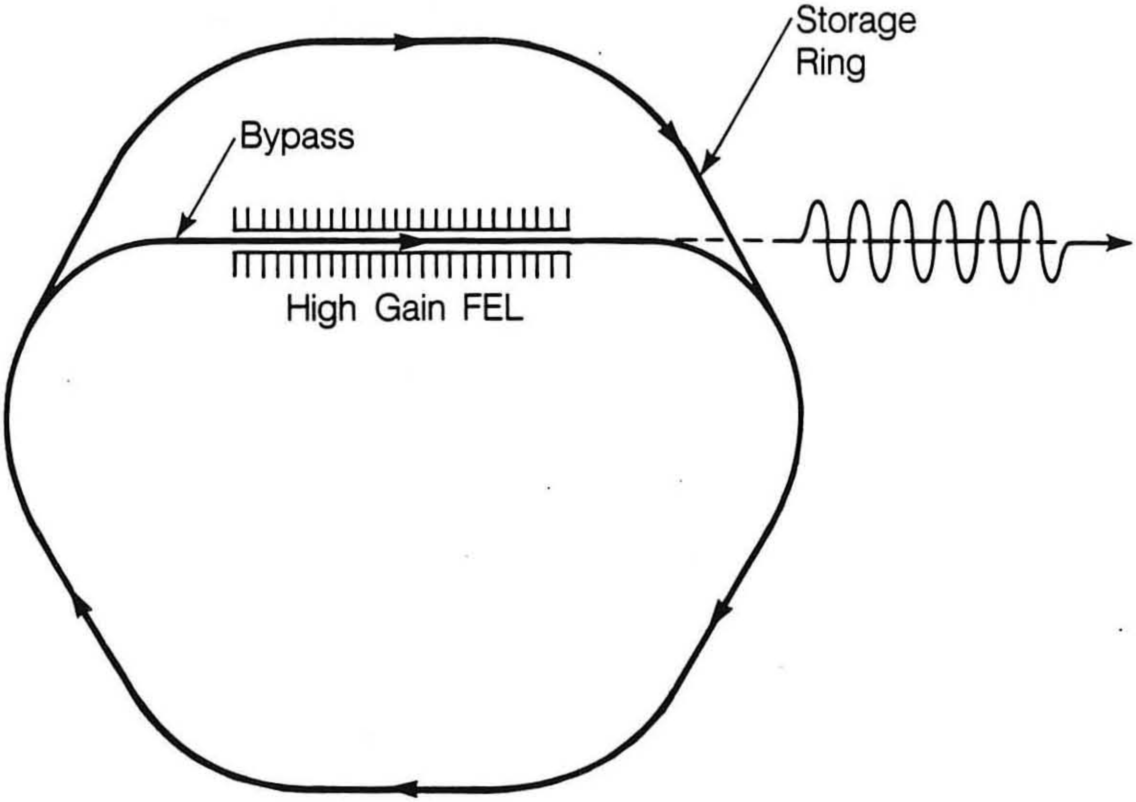

40
32
24
16
8
0
1000
1500
2000
E (MeV)
τ_{gas} (hr)
Gap = 2 cm
Gap = 1 cm
XBL 865-6226

Fig. 5



XBL 865-6224

Fig. 6



XBL 854-10171

Fig. 7

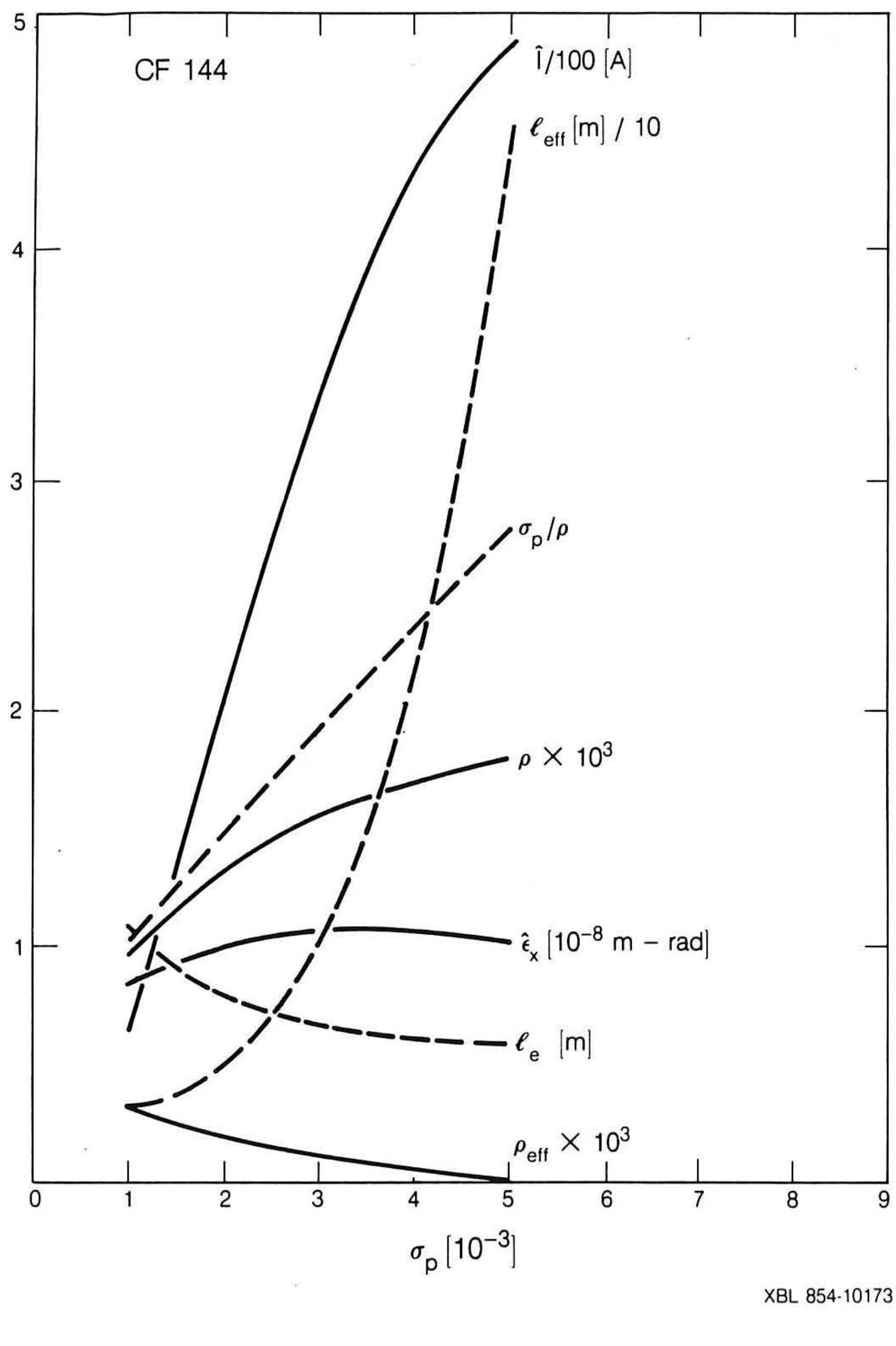
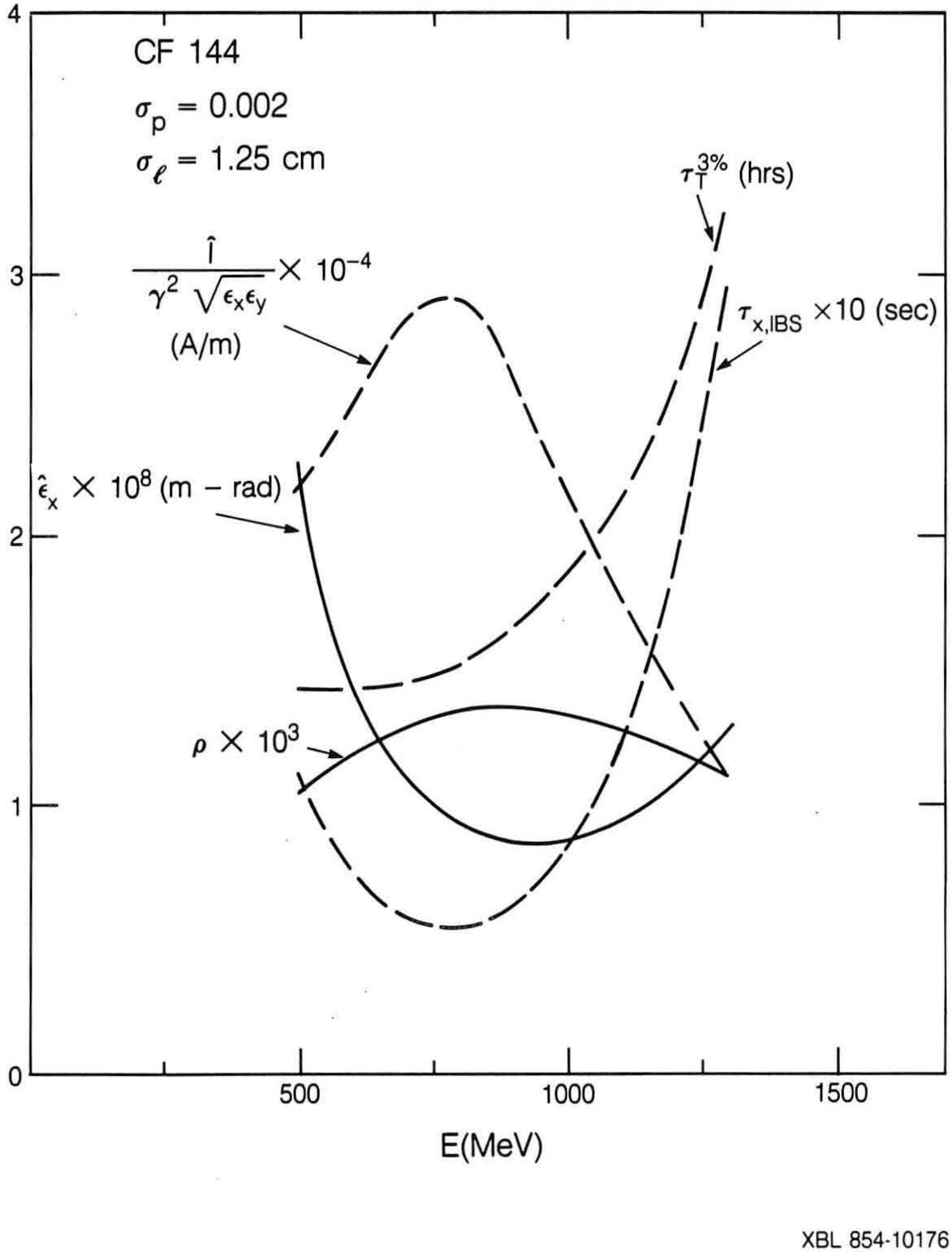
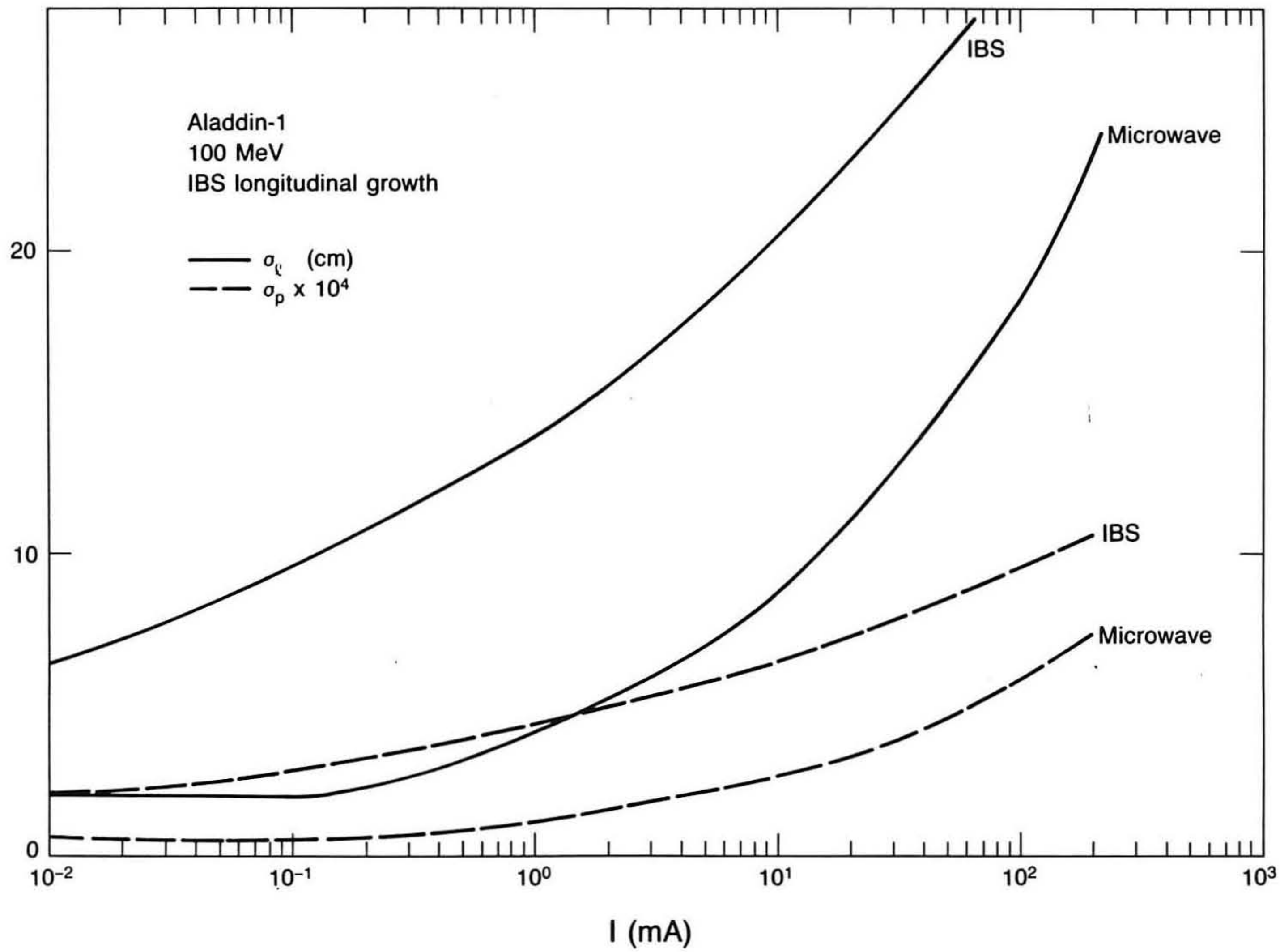

CF 144
Î/100 [A]
ℓ_{eff} [m] / 10
σ_p/ρ
$\rho \times 10^3$
$\hat{\epsilon}_x$ [10^{-8} m – rad]
ℓ_e [m]
$\rho_{eff} \times 10^3$
σ_p [10^{-3}]
0
1
2
3
4
5
6
7
8
9
XBL 854-10173

Fig. 8



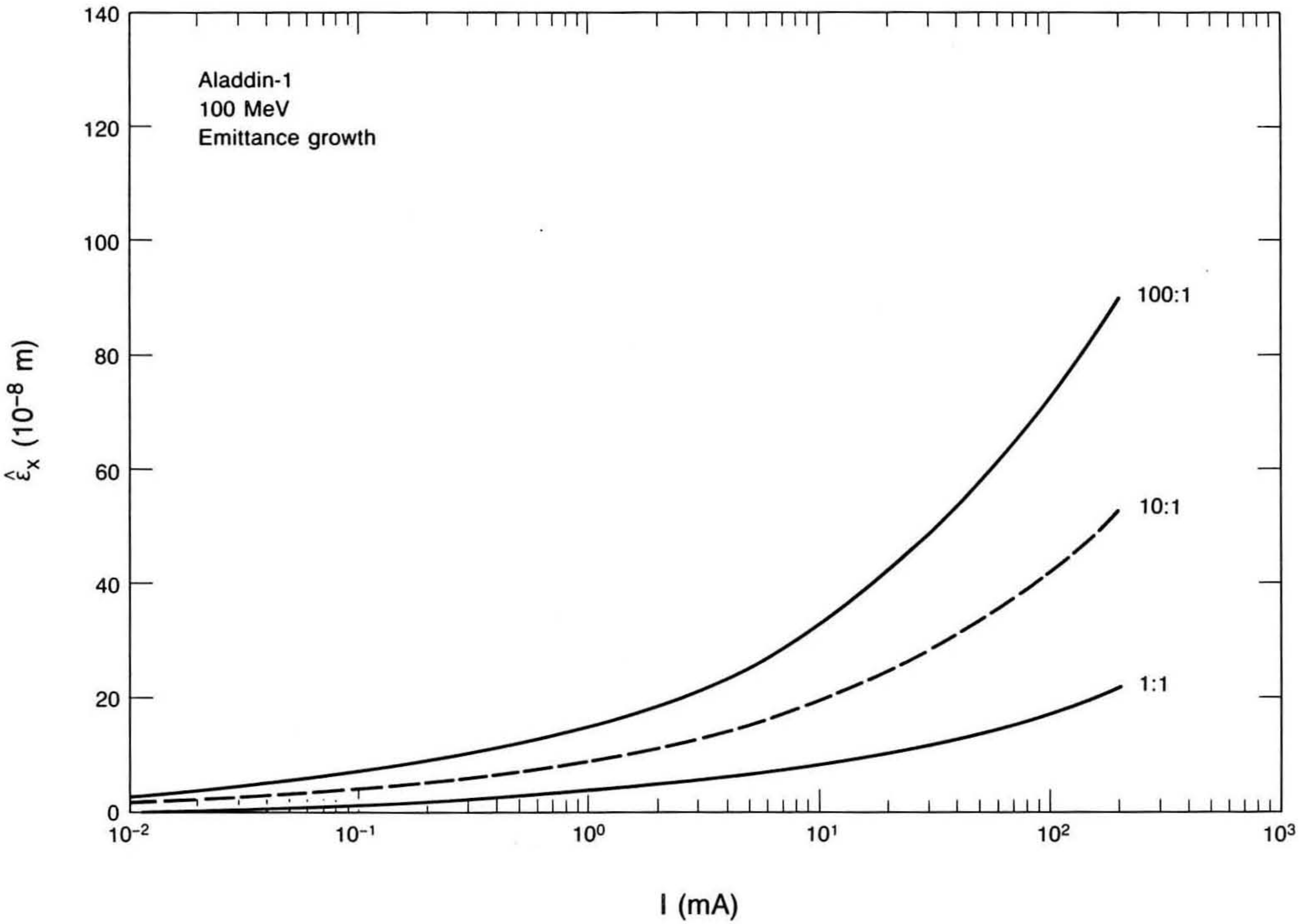
CF 144
$\sigma_p = 0.002$
$\sigma_\ell = 1.25$ cm
$\tau_T^{3\%}$ (hrs)
$\frac{\hat{I}}{\gamma^2 \sqrt{\epsilon_x \epsilon_y}} \times 10^{-4}$
(A/m)
$\tau_{x,IBS} \times 10$ (sec)
$\hat{\epsilon}_x \times 10^8$ (m − rad)
$\rho \times 10^3$
4
3
2
1
0
500
1000
1500
E(MeV)
XBL 854-10176

Fig. 9



XBL 853-8002A

Fig. 10



XBL 853-7095

Fig. 11

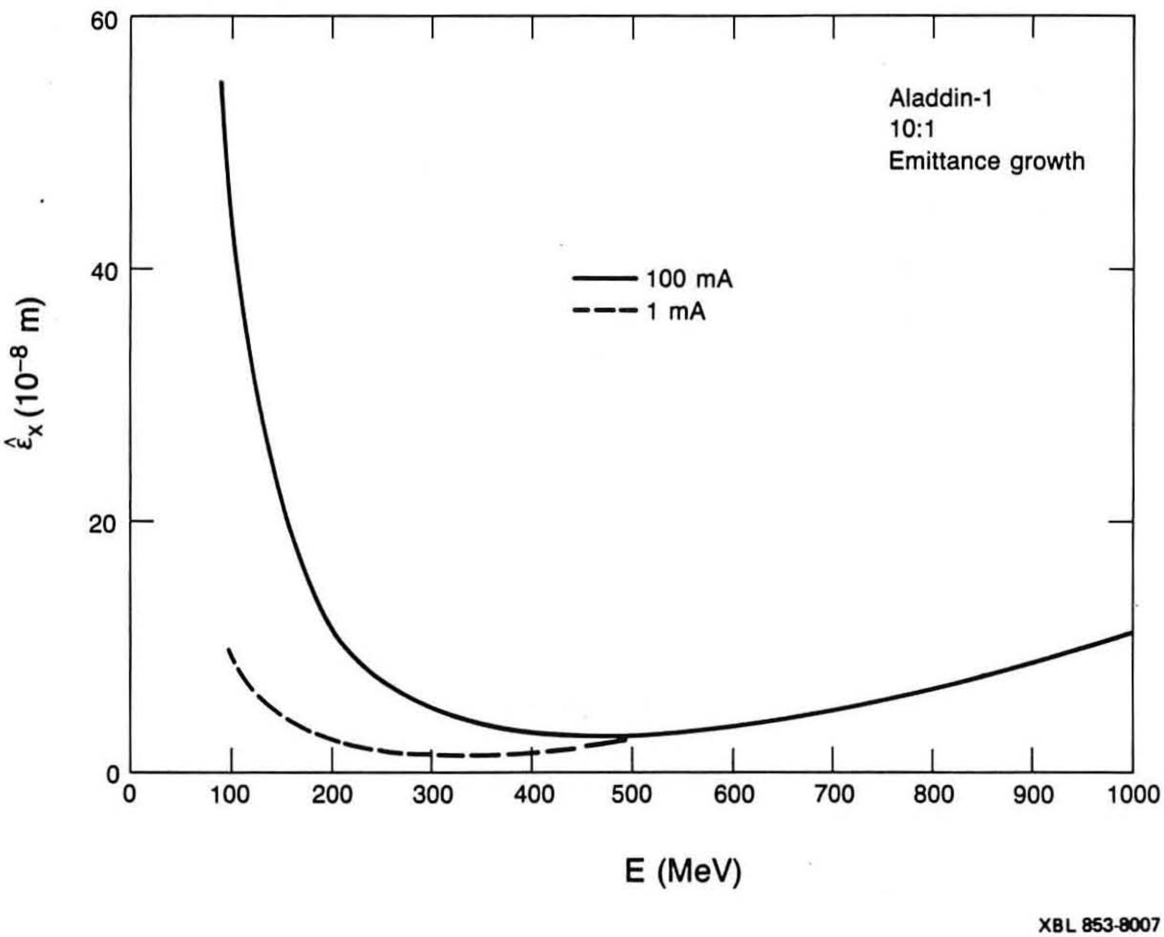
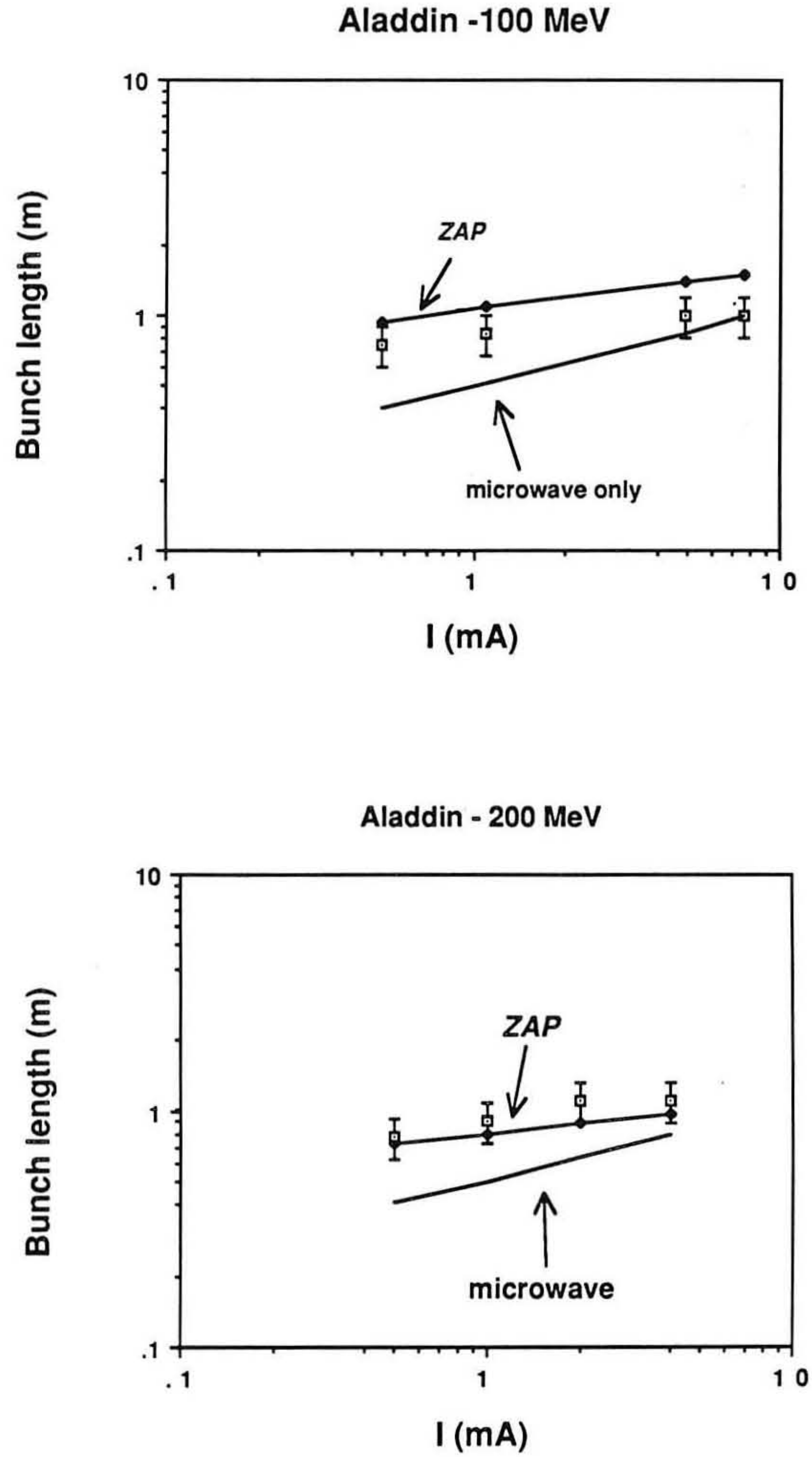

Aladdin-1
10:1
Emittance growth
100 mA
1 mA
$\hat{\varepsilon}_x$ (10^{-8} m)
E (MeV)
0
20
40
60
0
100
200
300
400
500
600
700
800
900
1000
XBL 853-8007

Fig. 12



XBL 8710-4190

Fig. 13