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PARAMETRIC STUDIES OF ALADDIN LATTICES

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I. INTRODUCTION

This paper presents the results of a parametric investigation of the various Aladdin lattices that have been considered as part of the Aladdin Upgrade Study, the overall purpose of which is to assess the problems with the existing Aladdin storage ring and recommend corrective action. In particular, the Study is to confirm the parameters of a full-energy injector for Aladdin and to identify those components that need upgrading or redesigning to guarantee satisfactory performance with the new injector.

As part of the Study, an investigation has been carried out on several different lattices, referred to in this document as Aladdin-1, Aladdin-2, and Aladdin-3. These lattices have been provided as part of the activities of the Lattice Group (led by A. Ruggiero) by various members [1] of the Argonne National Laboratory. The first lattice is intended to be identical to the presently operating Aladdin; the second lattice has the same spatial arrangement of magnets but -- by the addition of power supplies -- more flexibility in optimizing lattice functions (e.g., for injection or for the eventual inclusion of insertion devices); the third lattice corresponds closely to the working BESSY lattice and would require the physical relocation of various magnets (while providing the potential advantage of a significantly improved natural emittance). An abridged parameter list for the three lattices is given in Table I.

TABLE I
Abridged Parameter List

C [m]	88.9	88.9	88.9
σ_{p0} [10^{-4}]*	4.78	4.78	4.78
ϵ_0 [10^{-8} m]*	7.67	7.30	1.77
τ_D [sec]*	0.013	0.013	0.013
β_x [m]	4.0	4.0	7.7
β_y [m]	4.1	3.7	6.0
η_x [m]	0.22	0.26	0.15
α	0.036	0.018	0.0067

*at 800 MeV

In what follows, we will examine the behavior of the three lattice options in terms of bunch lengthening (due to the longitudinal microwave instability), intrabeam scattering (IBS), and Touschek scattering. To assess these effects in a self-consistent manner, we have made use of the computer code ZAP that is now under development at LBL. This code treats instability issues (both single- and coupled-bunch) as well as single and multiple intrabeam scattering. (Although coupled-bunch instability calculations have been performed for the cases under study here, they will be reported in a separate paper [2].)

Because it is clearly important to understand the behavior of Aladdin at its present injection energy of 100 MeV, we will first examine, in Section II,

the consequences of the above-mentioned phenomena at that energy. In Section III we will look at the expected energy dependence to ascertain the benefits of increasing the injection energy to 800 MeV. The predicted behavior at 800 MeV will then be described in Section IV; in this section we will examine the differences between the various lattice choices, as well as commenting on those considerations that reflect on the choice of RF parameters. Finally, Section V will provide a brief summary of our findings.

II. 100 MeV BEHAVIOR

Bunch Length and Momentum Spread

The first issue to be addressed here is the bunch lengthening and momentum spread associated with the longitudinal microwave instability. (For the cases considered here, the transverse threshold is considerably higher than the longitudinal and plays no role.) The peak current limitation from the microwave instability can be written [3]:

$$\hat{I} = \frac{2\pi\alpha (E/e) \sigma_p^2}{Z/n} \quad (1)$$

where α is the momentum compaction, E is the beam energy, σ_p is the rms relative momentum spread, and Z/n is the ring broadband impedance value. At low energies, it is clear from Eq. (1) that the threshold is reached rather quickly, which means that bunch lengthening will occur even at quite modest beam currents. It is also evident from the formula that a large value for the momentum compaction, α , is preferred from this point of view. In this context, the larger momentum compaction of the existing ring (Aladdin-1, see Table I) is an advantage.

In order to evaluate the effects of the microwave instability, it is

necessary to have an estimate of the ring impedance. We have taken a value of $Z/n = 6$ ohms in the present calculations, based on a study of the Aladdin ring carried out by H. Lancaster and J. Bisognano [4]. (We will see later that this value is not of crucial significance at 100 MeV due to the influence of intrabeam scattering, so no attempt has been made to explore what happens as this parameter is varied.) Because of the relationship between the bunch length and the momentum spread of the beam via the RF parameters, we have

$$\sigma_p = \frac{\nu_s}{nR} \sigma_\ell \quad (2)$$

where ν_s is the synchrotron tune, σ_ℓ is the rms bunch length, n is the frequency slip factor, and R is the ring radius. Thus, both the bunch length and the momentum spread will increase.

Threshold current values at 100 MeV for the three lattices under study here are summarized in Table II. As expected, it requires an average current (for 15 bunches) of only about 0.1 mA to cause the bunch to begin to lengthen. The expected behavior of the bunch length and momentum spread are shown for Aladdin-1 and Aladdin-3 in Fig. 1. If Aladdin-3 were to be used at this energy, it would have the poorest behavior due to its low momentum compaction factor. Even Aladdin-1, however, is expected to show considerable broadening at beam currents in the range of 1-10 mA.

TABLE II

Microwave Instability Thresholds at 100 MeV

<u>Ring</u>	<u>$\hat{I}$ (A)</u>	<u>I (mA)</u>
1	0.013	0.1
2	0.007	0.05
3	0.003	0.01

Because the radiation damping time is so long at 100 MeV (about 3.5 and 7 seconds, respectively, for the longitudinal and horizontal emittance), we expect beam growth due to intrabeam scattering. This growth, which can occur in both the horizontal and longitudinal dimensions, will reach an equilibrium value at which there is a balance between the rates due to IBS, quantum excitation, and radiation damping. Thus, for each dimension we must find a solution to an equation of the form

$$[g(\hat{\epsilon})_{\text{IBS}} - g_{\text{SR}}] \hat{\epsilon} + g_{\text{SR}} \epsilon_0 = 0 \quad (3)$$

where g_{SR} represents the synchrotron radiation rate and g_{IBS} that for the intrabeam scattering.

To solve this equation, we have incorporated the formulation of intrabeam scattering due to Bjorken and Mtingwa [5] into the code ZAP. Calculations are performed at various lattice points around the ring (as provided by a lattice code such as SYNCH [6]) and a weighted average rate is computed. For a typical lattice, about 100 points are utilized. ZAP then iterates to find the equilibrium emittance values.

In our previous IBS studies, it has always been found that the horizontal growth was dominant, and longitudinal growth could be ignored. In the present calculations, however, this was not the case. Even after the beam has blown up to the dimensions determined by the microwave instability, the residual growth due to IBS is substantial. After suitable modifications to ZAP, this phenomenon was investigated, with the results shown in Fig. 2. At a beam current of 1 mA, we expect (Fig. 2a) a bunch length of about 14 cm for Aladdin-1, and a corresponding momentum spread of 4×10^{-4} . Compared with the natural bunch length and momentum spread, these values correspond to an increase of more than a factor of seven. For Aladdin-3, with its lower

natural emittance, the bunch lengthening due to IBS would have been even more severe, as illustrated in Fig. 2b. Rough measurements of the Aladdin bunch length at 100 MeV have yielded two different values [7], about 13 cm or 32 cm. The former value agrees well with our predictions, while the latter measurement seems well beyond what can be explained by the considerations discussed here.

Transverse Emittance Growth

As mentioned earlier, IBS is expected to lead to growth in the transverse emittance of the beam. This effect is especially pronounced at low beam energies because the countervailing effect of radiation damping, which scales as E^3 , is greatly diminished. In addition, the initial rate for the IBS is relatively high because the natural emittance of the beam is quite small at 100 MeV.

The expected emittance growth due to IBS for Aladdin-1 is shown in Fig. 3 as a function of beam current. Three different curves are presented, corresponding to three different values of the x and y emittance coupling. Because the rate of IBS is related mainly to the overall 6-dimensional beam density, a lower value for the coupling (which corresponds to a lower beam density) gives the smallest predicted growth.

It can be seen from Fig. 3 that the equilibrium emittance values are extremely large. At a beam current of 100 mA and a coupling of 10:1, for example, the emittance grows from its natural value of 1×10^{-9} m to 4×10^{-7} m, or a factor of 400 increase. If the coupling were 100:1, the increase would be roughly a factor of 700. Even at the more realistic beam current of 10 mA, the emittance increase for 10:1 coupling is a factor of almost 200. It is important, however, to put these results in context. In

terms of rms beam size, the emittance values shown in Fig. 3 correspond to only about 2 mm. Moreover, at the presently attained beam current of about 10 mA, the emittance value is only about a factor of 3 above that at 800 MeV, where the present lattice appears to operate with reasonable lifetime. Thus, the beam blowup due to IBS does not appear by itself to explain the difficulties observed at 100 MeV.

Although not shown, the behavior of the other possible Aladdin lattices is similar to that in Fig. 3. Aladdin-2, with a natural emittance about the same as that for Aladdin-1, would be almost indistinguishable from the curves shown in Fig. 3. In this regime, however, it is the emittance growth ratio that is roughly constant from lattice to lattice. Thus, Aladdin-3 curves would be roughly a factor of four lower than those shown in Fig. 3.

Touschek Scattering

In electron storage rings, the lifetime of the stored beam is often limited by Touschek scattering, i.e., single large-angle scattering that causes a particle's momentum to change by an amount larger than can be contained within the RF momentum acceptance of the ring. (Strictly, the lifetime-determining acceptance is the smallest of that due to the RF, the physical aperture, or the dynamic aperture.) This phenomenon is also treated with the code ZAP, based on the formalism of Bruck [8]. As for the IBS calculations described above, the Touschek lifetime is evaluated at each individual lattice point and a weighted average for the ring is computed.

The results of the calculations for the Aladdin-1 lattice are shown in Fig. 4. As for the IBS results, a lower value for the emittance coupling (a lower beam density) gives a longer lifetime. A value of 0.6% was used for the RF bucket half-height in these calculations. This corresponds to the

3 kV RF voltage determined empirically to be optimum for the present Aladdin ring. It can be seen from Fig. 4 that, in the range of beam currents presently attained in Aladdin, the Touschek lifetime is of the order of 1-10 hours. Thus, it seems clear that the fast beam loss mechanism seen at 100 MeV is not related to Touschek scattering. To see if the lifetime depends strongly on the exact lattice configuration of Aladdin-1, these calculations were also performed for the other two lattices at 100 MeV; the Aladdin-1 results shown in Fig. 4 remain essentially unchanged.

III. ENERGY DEPENDENCE

To explore the potential efficacy of a full-energy (800 MeV) injector, we will turn now to addressing what happens as the energy of Aladdin is increased.

Bunch Length and Momentum Spread

As can be seen by inspection of Eq. (1) and from Fig. 5, the longitudinal microwave instability threshold increases considerably as the energy increases. As a consequence, the bunch length and corresponding momentum spread calm down considerably. The values expected for Aladdin-1 are illustrated in Fig. 6, assuming the RF voltage has been varied in such a manner as to keep the momentum acceptance fixed at a value of 0.8%. It can be seen that at energies beyond 200 MeV there is no additional longitudinal growth due to IBS.

Transverse Emittance Growth

Because the radiation damping rate increases rapidly with energy, and the IBS growth rate decreases rapidly, the large emittance growth expected

at 100 MeV comes quickly under control as the energy is raised. This is illustrated for Aladdin-1 in Fig. 7, which shows the expected equilibrium value for the horizontal emittance, as a function of energy, for an assumed emittance coupling of 10:1. At a modest beam current of 1 mA, the emittance growth is not so pronounced. At the design current of 100 mA, however, the benefits of a higher energy are clearly apparent. (The rise of the emittance curve at energies above 500 MeV is not related to IBS but merely reflects the fact that the natural emittance of an electron storage ring increases as E^2 . In this energy regime there is essentially no growth due to IBS.)

Touschek Scattering

The Touschek lifetime improves with energy approximately as

$$\tau_T \sim \frac{(\Delta p_{RF})^3 E^2 \sqrt{\epsilon_x \epsilon_y} \sigma_\ell}{N_b} \quad (4)$$

where Δp_{RF} is the RF momentum acceptance, $\epsilon_{x,y}$ are the horizontal and vertical emittance values, σ_ℓ is the rms bunch length, and N_b is the number of particles per bunch. Calculated values for Aladdin-1 as a function of energy are shown in Fig. 8. Again, the benefits from a higher energy are clearly apparent.

IV. 800 MeV BEHAVIOR

Having (hopefully) by now set the stage for an 800 MeV injection energy, in this section we will examine in detail the behavior of the various candidate lattices at this energy. In addition to the choice of the lattice itself, there is a choice to be made regarding the RF system.

In the present Aladdin ring there is a 50 MHz RF system. However, the injector system proposed for the upgrade is likely to have a 500 MHz RF system. Because of the smaller size of a 500 MHz RF system and because of possible simplifications for the injection process, it was decided as part of the Study to consider both a 50 MHz and a 500 MHz RF system for the upgraded accelerator. There are many ramifications of this choice, e.g., coupled-bunch instabilities, feedback systems, and ion trapping considerations, that are beyond the scope of this paper. These issues, which are discussed in Ref. [2], clearly dominate the choice of RF system. However, the choice of RF system does have implications for the matters under discussion here and will therefore be discussed below in this context.

Bunch Length and Momentum Spread

At 800 MeV, the longitudinal microwave instability lies at much higher current than at 100 MeV. The expected values for the three lattices under consideration are summarized in Table III, assuming a broadband impedance value of $Z/n = 6$ ohms. The reason for the difference between the lattices is that the value for the momentum compaction (see Table I) is highest for Aladdin-1 and considerably lower for Aladdin-3. Values are listed in Table III for three different RF scenarios: i) a 50 MHz system with all 15 buckets filled; ii) a 500 MHz system with 15 (out of 150) buckets filled; and iii) a 500 MHz system with all 150 buckets filled.

As can be seen in Table III, the average current corresponding to the specified threshold peak current is lower by a factor of 10 for the second scenario. The reason for this is straightforward. Compared with the first case, the 15 bunches at 500 MHz must contain the same number of particles (to achieve the same average current) but in a bunch length that, at the higher

frequency, is nearly a factor of 10 shorter than that at 50 MHz. Thus, the average current corresponding to a given peak current is about a factor of 10 lower. In the third case, the shorter bunch length (compared with that at 50 MHz) is compensated by the lower number of particles per bunch required to achieve a particular average current.

TABLE III
Microwave Instability Thresholds at 800 MeV

<u>Ring</u>	<u>$\hat{I}$ (A)</u>	<u>I (mA)</u>	<u>RF*</u>
1	6.8	230	i
	"	26	ii
	"	260	iii
2	3.5	106	i
	"	13	ii
	"	133	iii
3	1.3	31	i
	"	4	ii
	"	46	iii

*

i: 50 MHz/15 bunches

ii: 500 MHz/15 bunches

iii: 500 MHz/150 bunches

Because of the higher threshold currents, the problem of bunch lengthening and momentum spread is more or less eliminated for beam current values below about 100 mA. This is illustrated for Aladdin-1 in Fig. 9, which shows the expected bunch length and momentum spread as a function of beam current for various RF scenarios. Aside from the shorter bunch length for the

500 MHz case, it is clear that there is no significant preference for either RF frequency from these considerations. On the other hand, for the reasons discussed above there is a clear preference for a scenario where all RF buckets are filled. Although Aladdin-2 behaves in a manner roughly similar to that shown in Fig. 9, the lower momentum compaction for Aladdin-3 leads to somewhat more extreme behavior; this is illustrated for selected cases in Fig. 10.

In all cases, the values expected at 800 MeV and a beam current of 100 mA are better than those at 100 MeV and a beam current of only 10 mA.

Transverse Emittance Growth

As already mentioned, the faster radiation damping rate along with the slower IBS growth rate mean that emittance growth is essentially eliminated at 800 MeV. This is shown in Fig. 11 for all three candidate lattices as a function of beam current. The lower values for Aladdin-3 are simply a reflection of the lower natural emittance of this design. In all three cases the natural emittance is maintained at least up to a beam current of 100 mA.

Touschek Scattering

Calculated values for the Touschek lifetime for Aladdin-1 are shown in Fig. 12 for three values of the emittance coupling. Even for the most severe case of 100:1 coupling and a beam current of 200 mA, the expected lifetime is about 4 hours. A comparison between the three candidate lattices is shown in Fig. 13. Because of its lower emittance (and hence higher beam density), Aladdin-3 has a somewhat poorer lifetime than do the other lattices, but the lifetime does not appear to be unacceptably short given the possibility of running in a "top-off" mode.

A comparison of the various RF scenarios is shown for Aladdin-1 in Fig. 14. For the same reasons discussed in the context of bunch lengthening, there is a preference for the cases with all RF buckets filled compared with the cases where only some buckets are filled. Again, there is no significant preference for the frequency per se.

V. SUMMARY

In this document we have attempted to examine the collective behavior of the Aladdin candidate lattices and to investigate the properties of the existing Aladdin-1 lattice at the present injection energy of 100 MeV.

Based on the considerations here, no "fatal flaws" were discovered in the present 100 MeV lattice. It is clear, however, that the significant growth expected in bunch length, momentum spread, and transverse beam size must lead to some degradation of performance.

From the point of view of collective effects, the present Aladdin-1 lattice generally gives the most favorable performance at 800 MeV. This is due to the larger momentum compaction and larger natural emittance values for this design compared with Aladdin-2 and Aladdin-3. The expected performance of Aladdin-2 is typically close to that of Aladdin-1; the former design has essentially the same natural emittance value as the latter, but suffers from a momentum compaction value a factor of two lower. Aladdin-3, with significantly lower values for both natural emittance and momentum compaction than the other two designs, generally has poorer performance in the areas of interest to this paper. It does not, however, lead to performance that would be deemed unacceptable.

From lifetime and bunch lengthening considerations, there is a preference for an RF scenario where all buckets are filled. The choice of RF frequency,

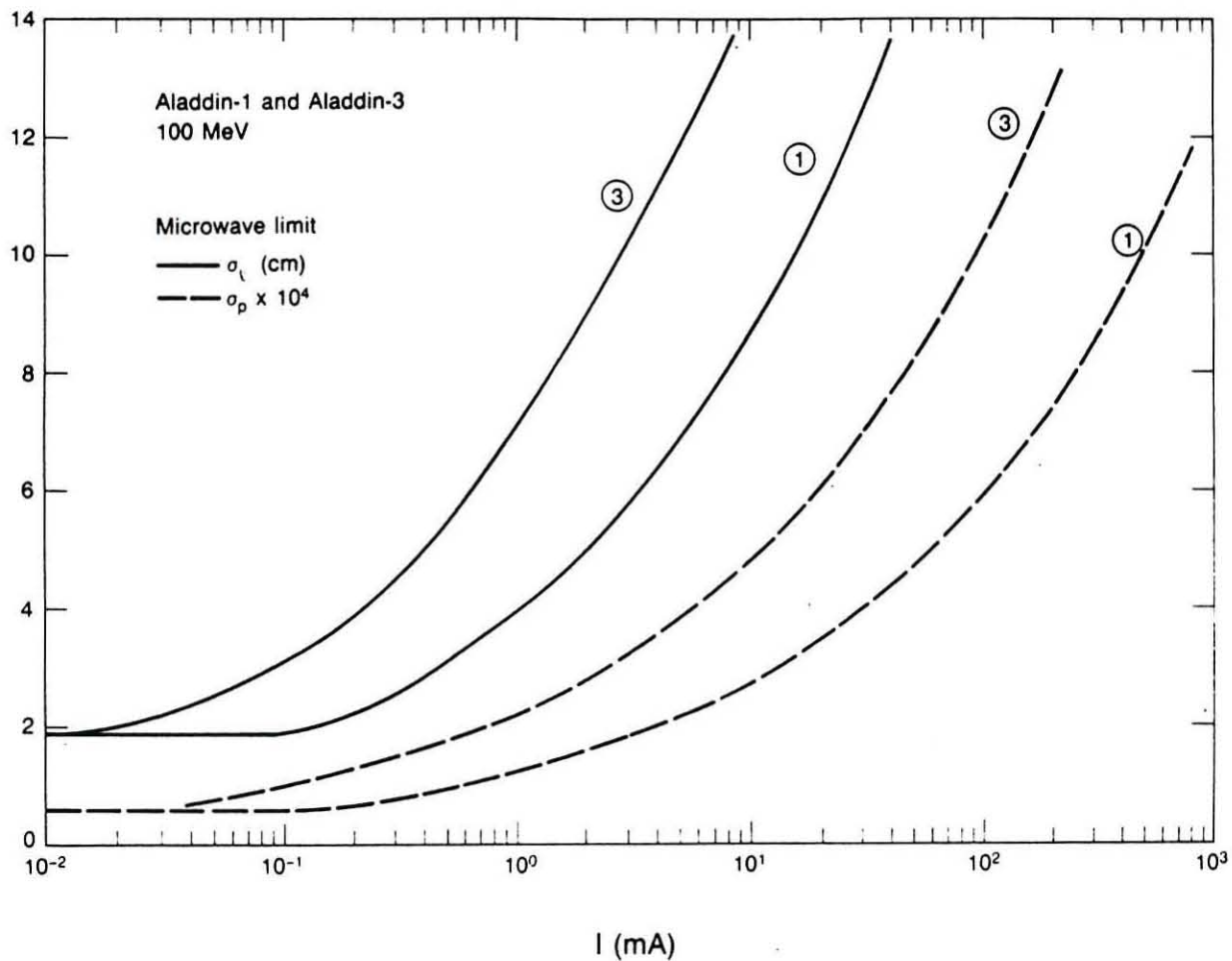
however, is not influenced by the considerations presented here. (From the "user" viewpoint, there may be some preference for the shorter bunch length available with a 500 MHz RF system; no such preference has yet been expressed, however.)

Acknowledgments

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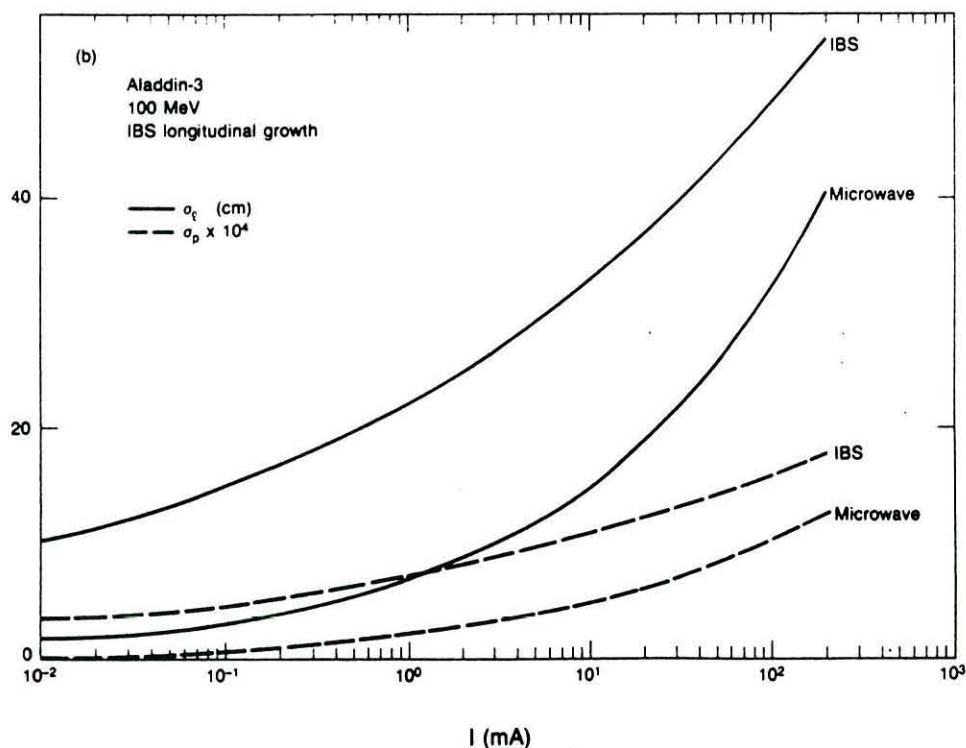
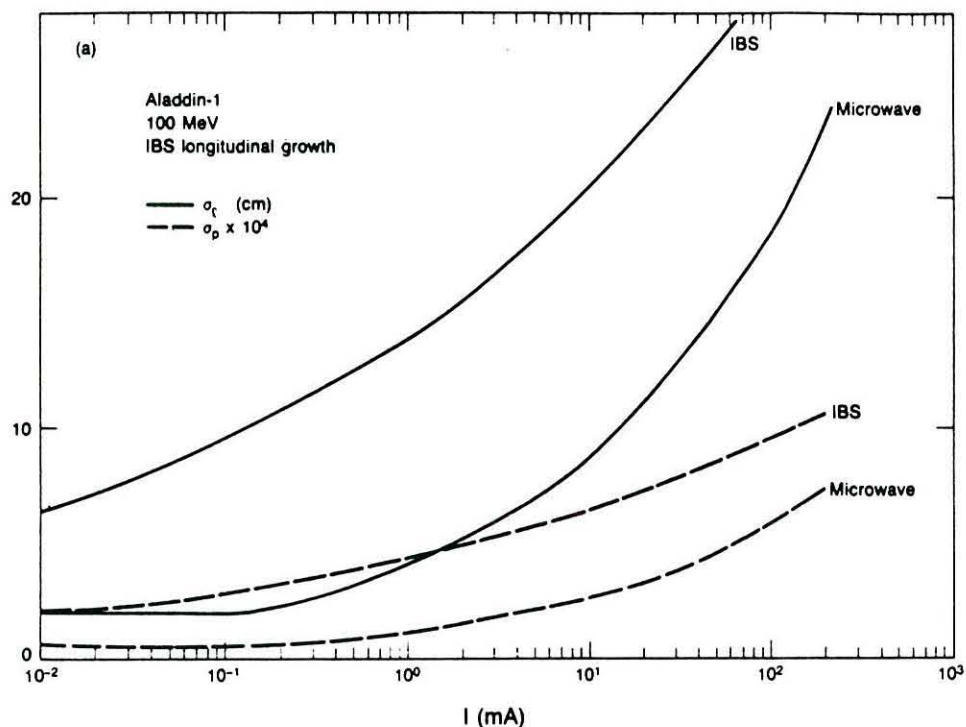
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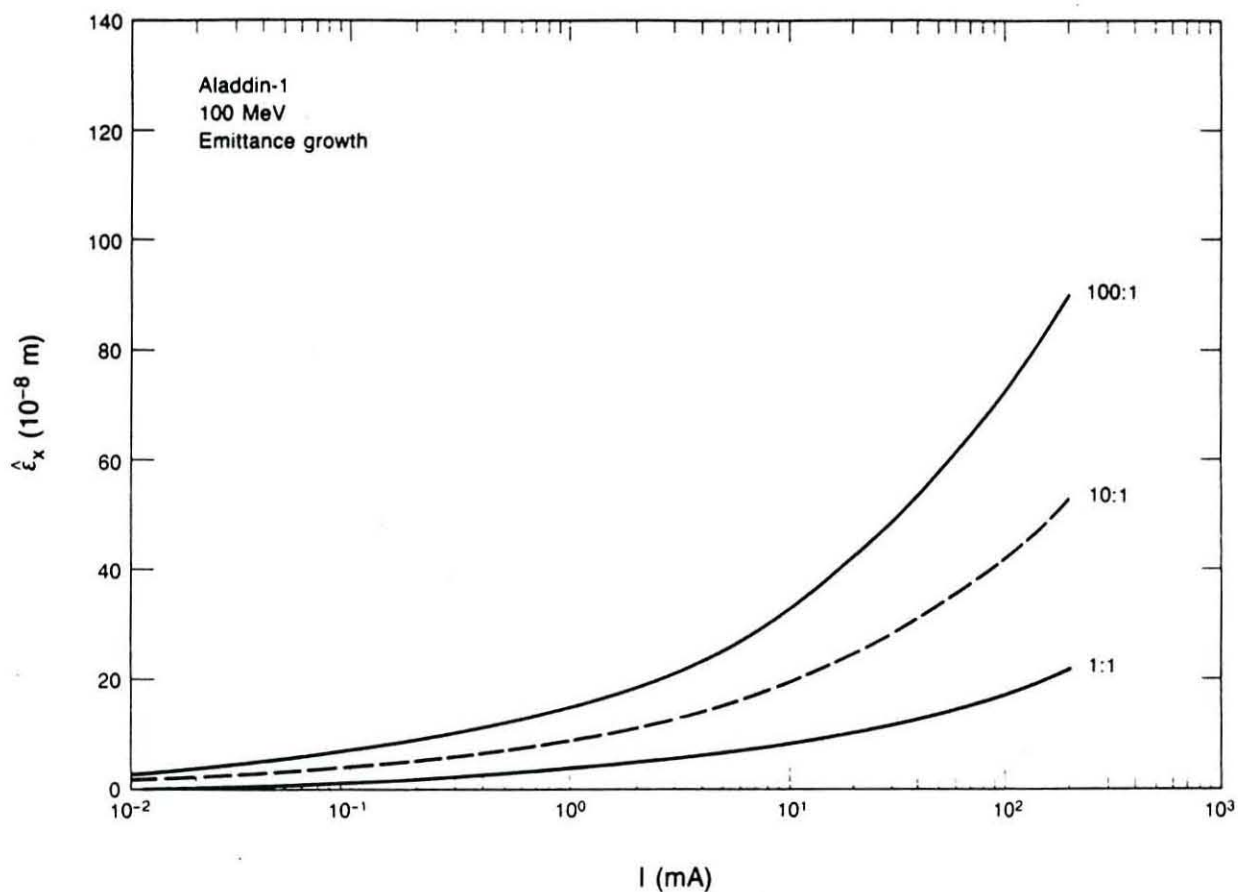
XBL 853-7097

Fig. 1. Expected bunch length (solid curves) and corresponding momentum spread (dashed curves) from the longitudinal microwave instability for Aladdin-1 and Aladdin-3 at 100 MeV. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled. A ring broadband impedance of 6 ohms was used in estimating the threshold current.



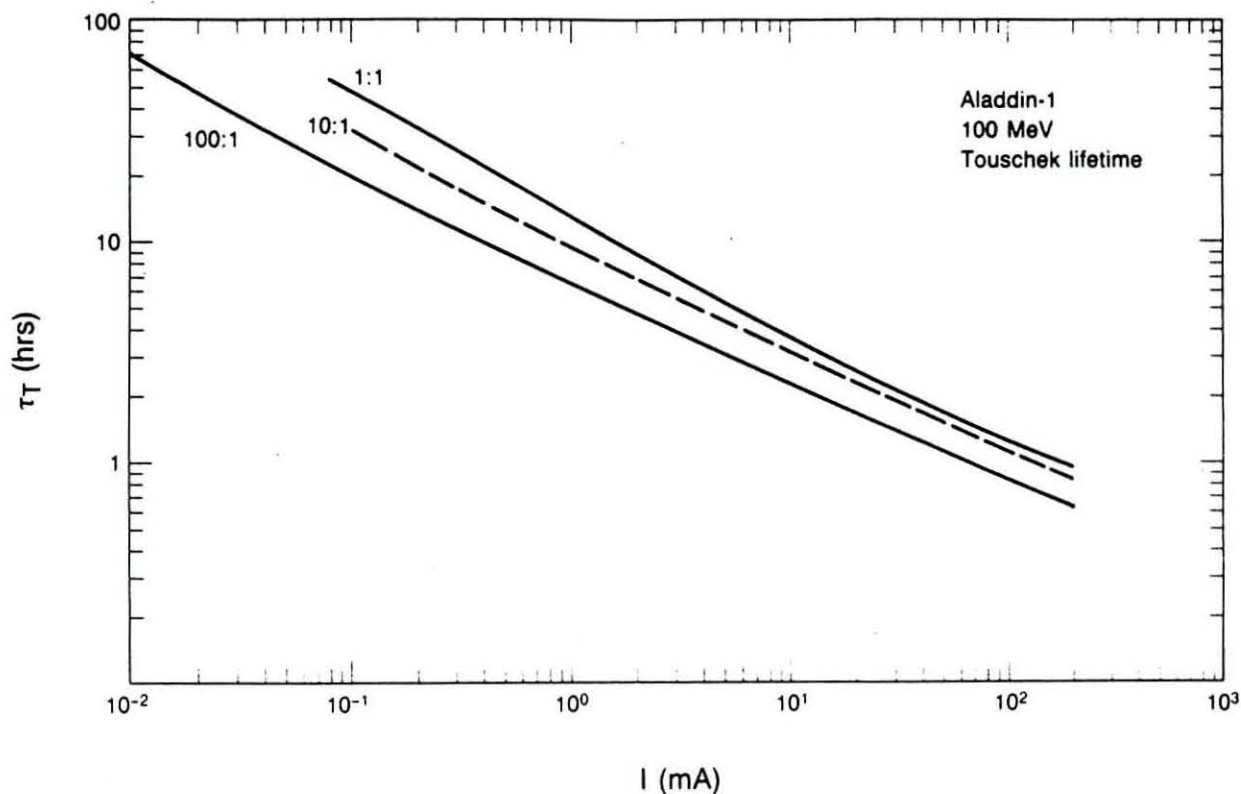
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Fig. 2. (a) Expected bunch length (solid curves) and corresponding momentum spread (dashed curves) for Aladdin-1 at 100 MeV, including the longitudinal growth due to intrabeam scattering. Values for the microwave growth are the same as for Fig. 1. The IBS calculations assume an emittance coupling of 10:1. (b) As in (a), but for Aladdin-3. The expected growth is greater here because of the lower momentum compaction and natural emittance of Aladdin-3 compared with Aladdin-1.



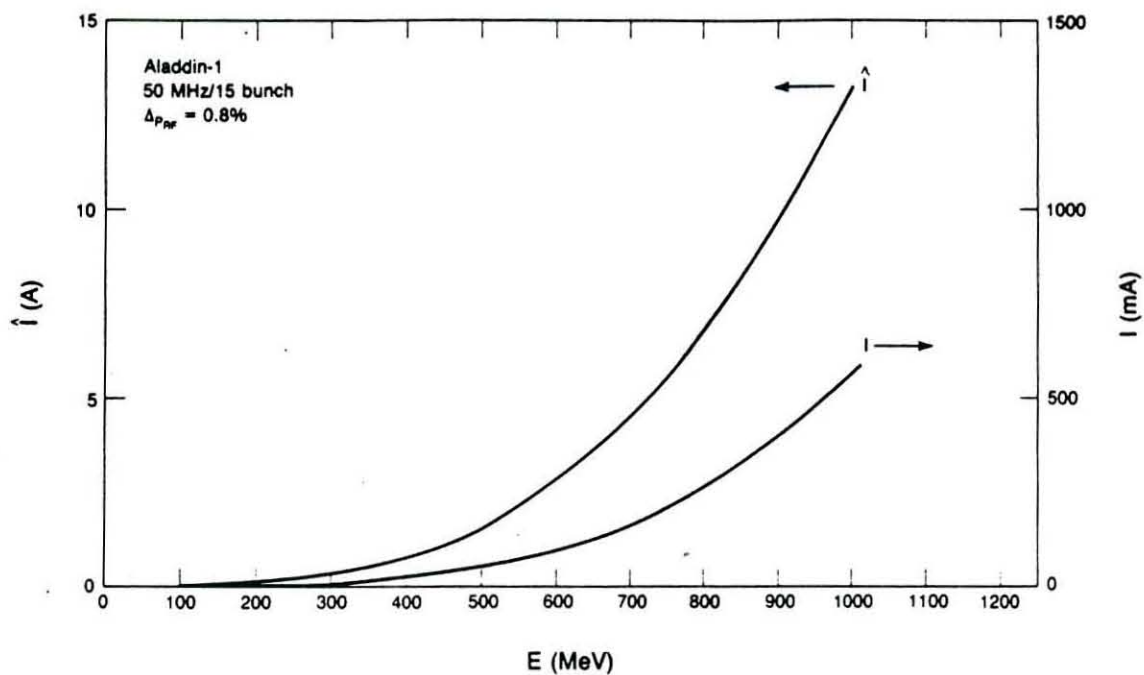
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Fig. 3. Equilibrium transverse emittance values from IBS for Aladdin-1 at 100 MeV. Results are shown for three different values of emittance coupling: 1:1; 10:1; and 100:1. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



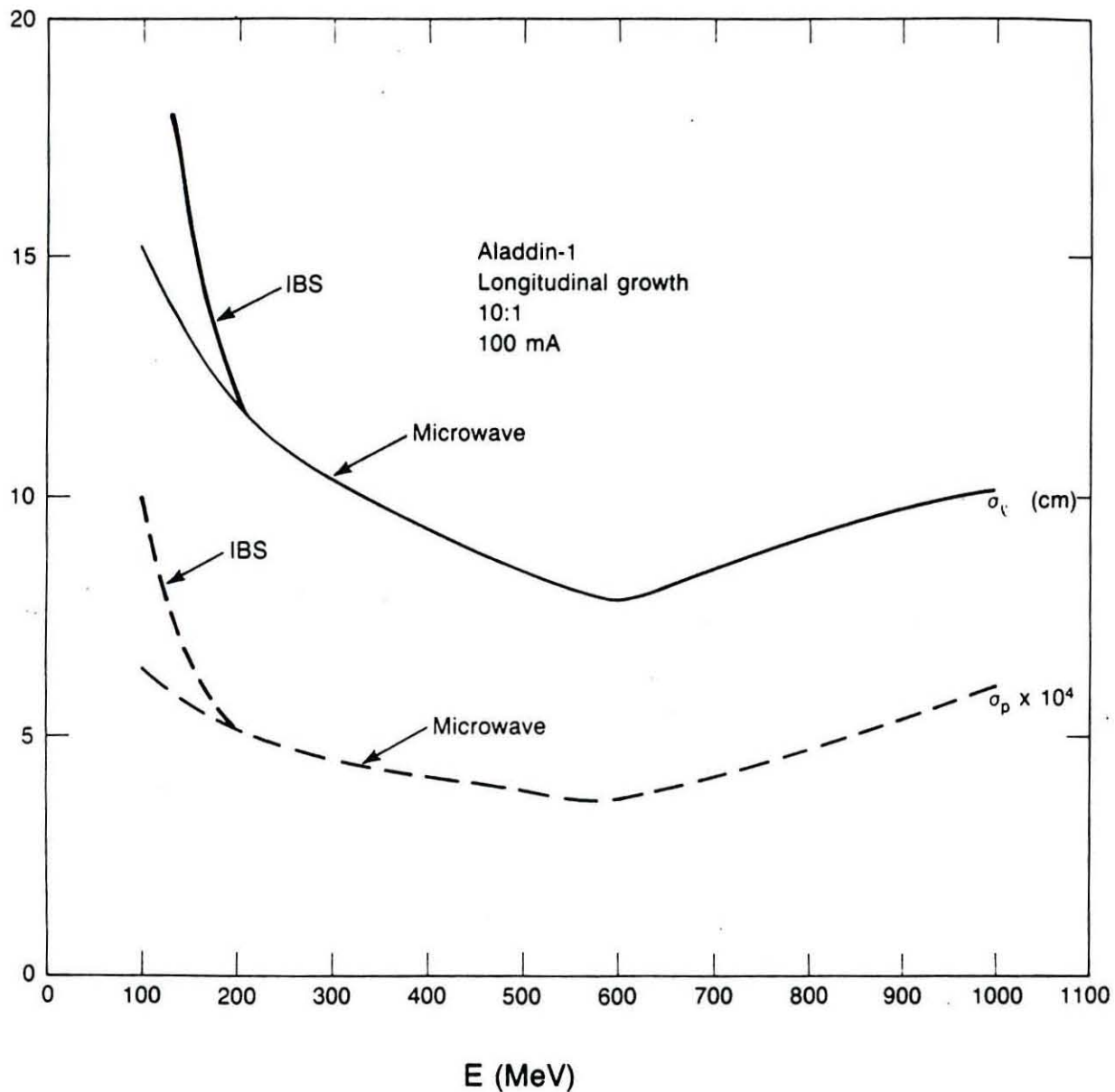
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Fig. 4. Touschek lifetime values for Aladdin-1 at 100 MeV at the equilibrium emittance conditions corresponding to Fig. 3. The RF bucket half-height was 0.6%, which corresponds to the 3 kV operating voltage now used at Aladdin. Results are shown for three different values of emittance coupling: 1:1; 10:1; and 100:1. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



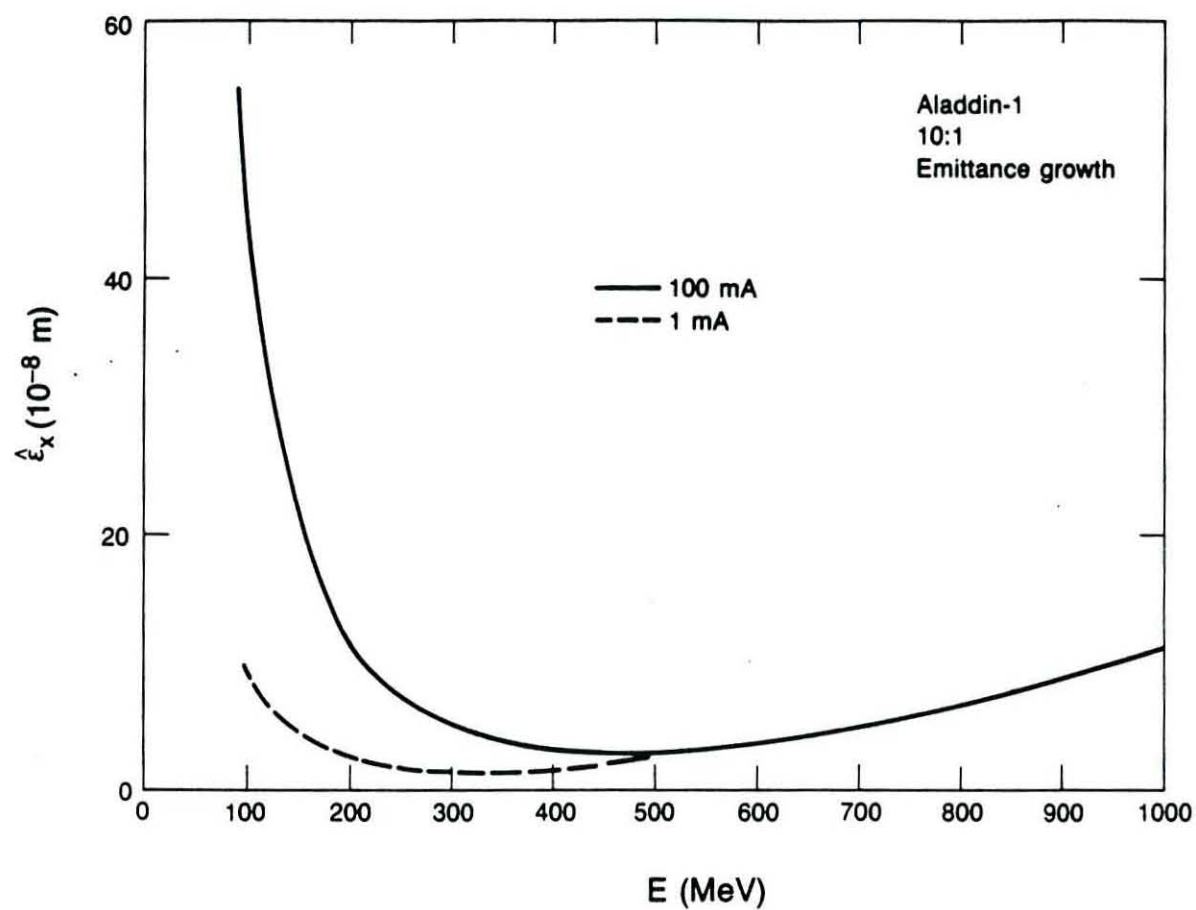
XBL 853-8006

Fig. 5. Energy dependence of longitudinal microwave instability threshold. The RF voltage was varied in such a way as to keep the momentum acceptance fixed at 0.8%. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



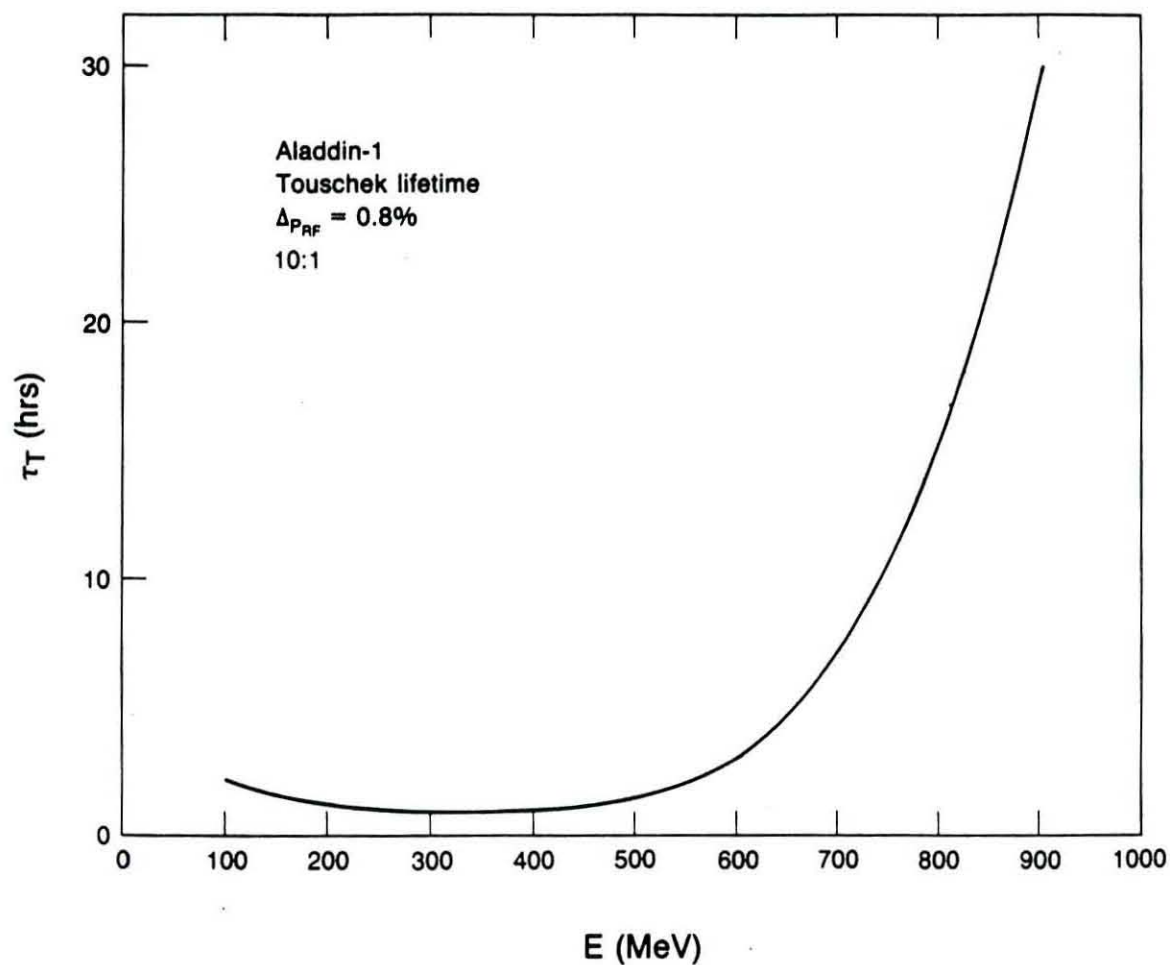
XBL 853-8003

Fig. 6. Energy dependence of bunch length and momentum spread for Aladdin-1. The additional contribution from IBS at low energies is included. The RF voltage was varied in such a way as to keep the momentum acceptance fixed at 0.8%. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



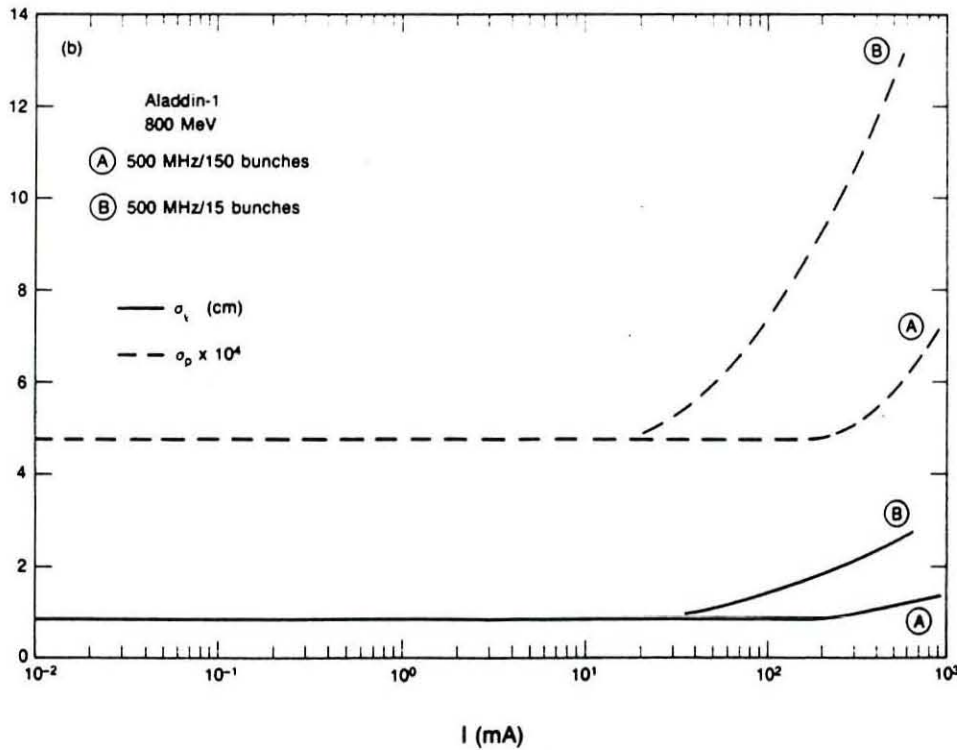
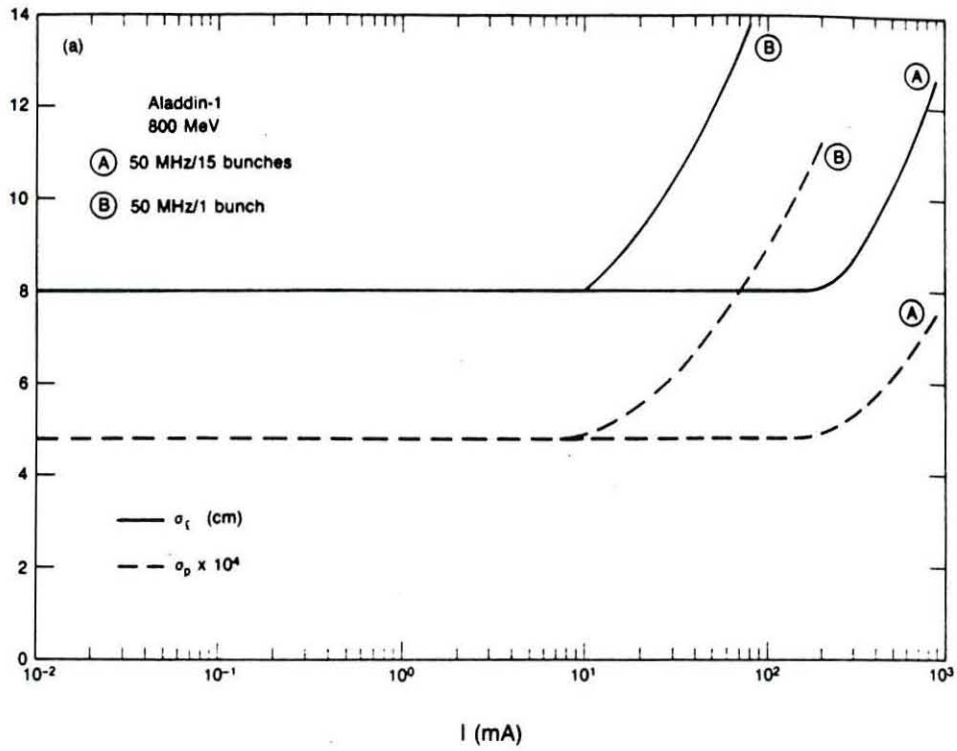
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Fig. 7. Energy dependence of equilibrium transverse emittance for Aladdin-1 at 10:1 emittance coupling and a beam current of 100 mA (solid curve) and 1 mA (dashed curve). Parameters correspond to those shown in Fig. 6.



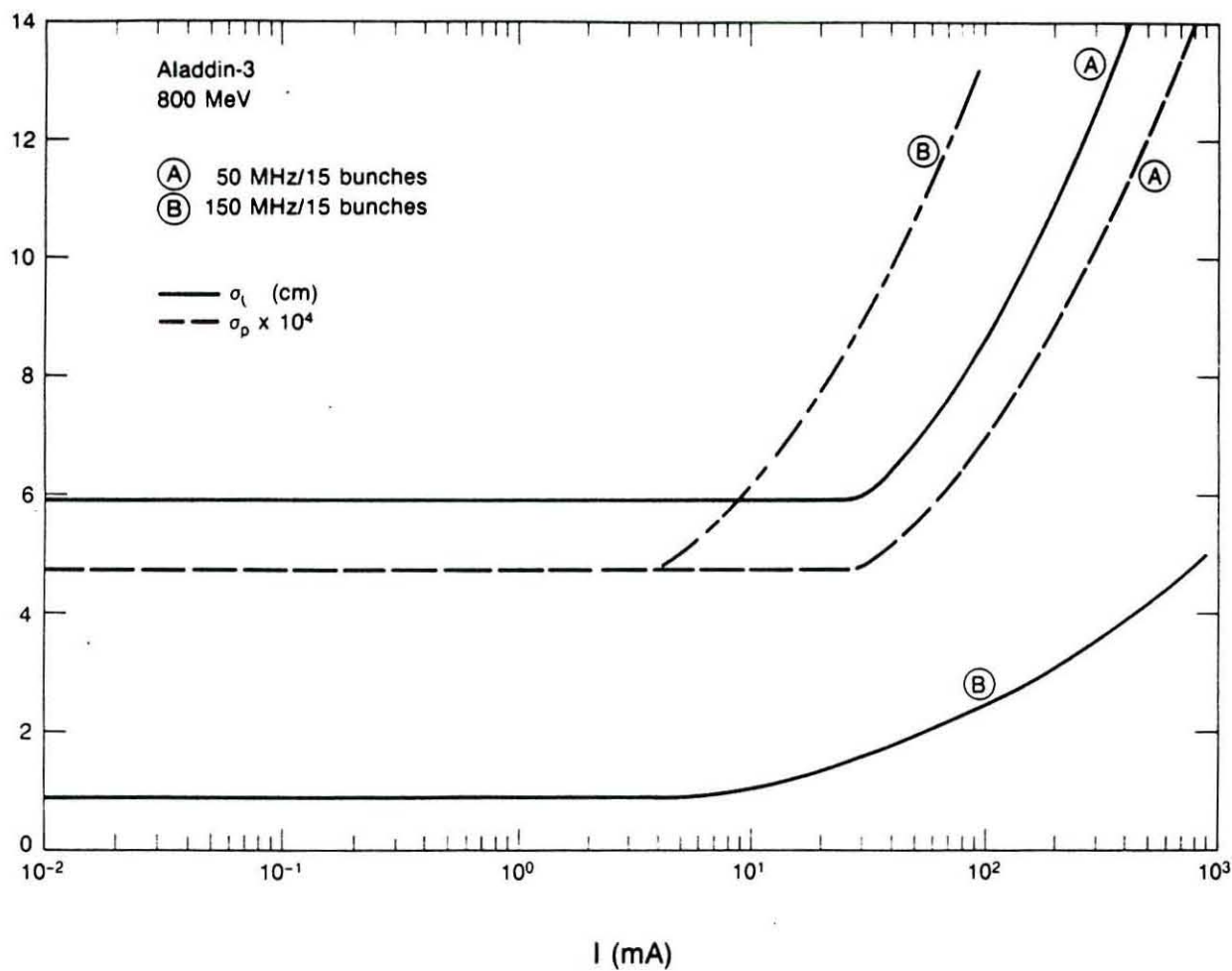
XBL 853-7094

Fig. 8. Energy dependence of Tauschek lifetime for Aladdin-1 at 10:1 emittance coupling and a beam current of 100 mA. Parameters correspond to those shown in Figs. 6 and 7.



XBL 863-7082

Fig. 9. (a) Bunch length (solid curves) and momentum spread (dashed curves) for Aladdin-1 at 800 MeV. A 50 MHz RF system is assumed. (b) As in (a), but for a 500 MHz RF system.



XBL 853-8005

Fig. 10. Bunch length (solid curves) and momentum spread (dashed curves) for Aladdin-3 at 800 MeV for various RF scenarios.

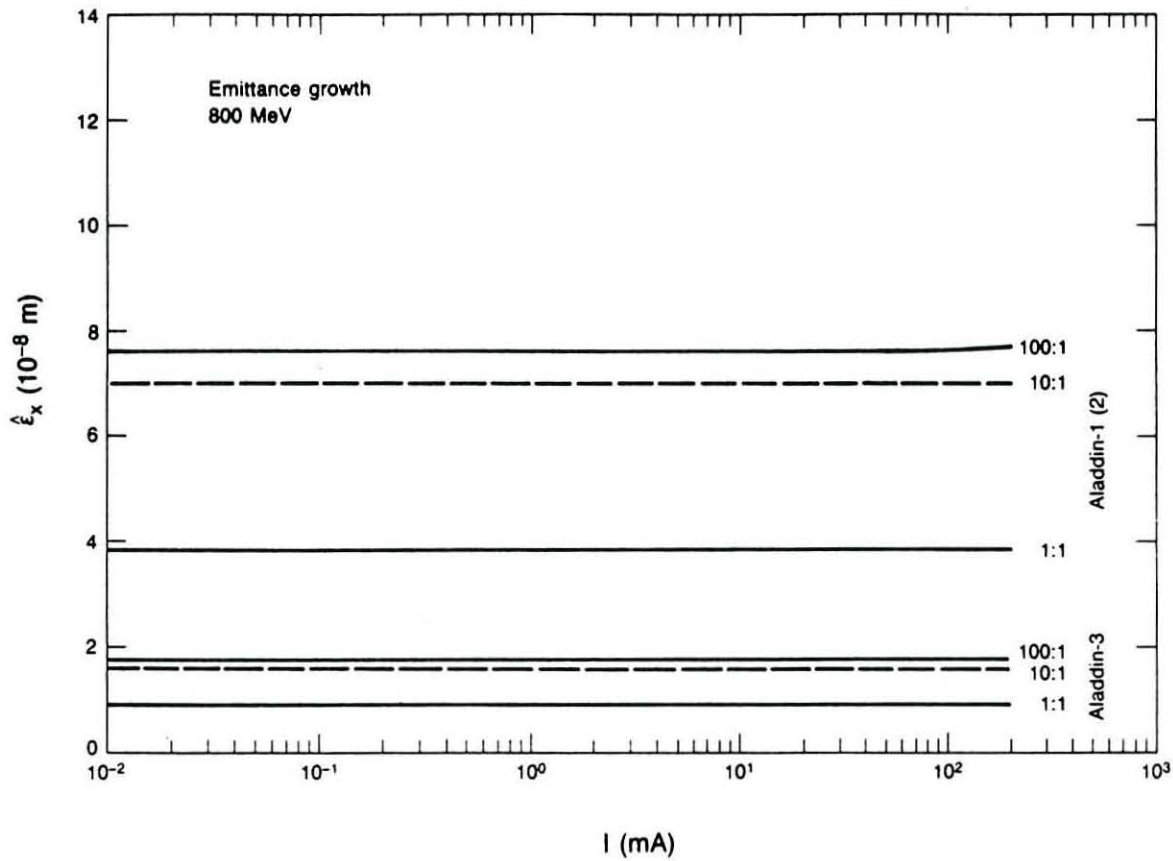
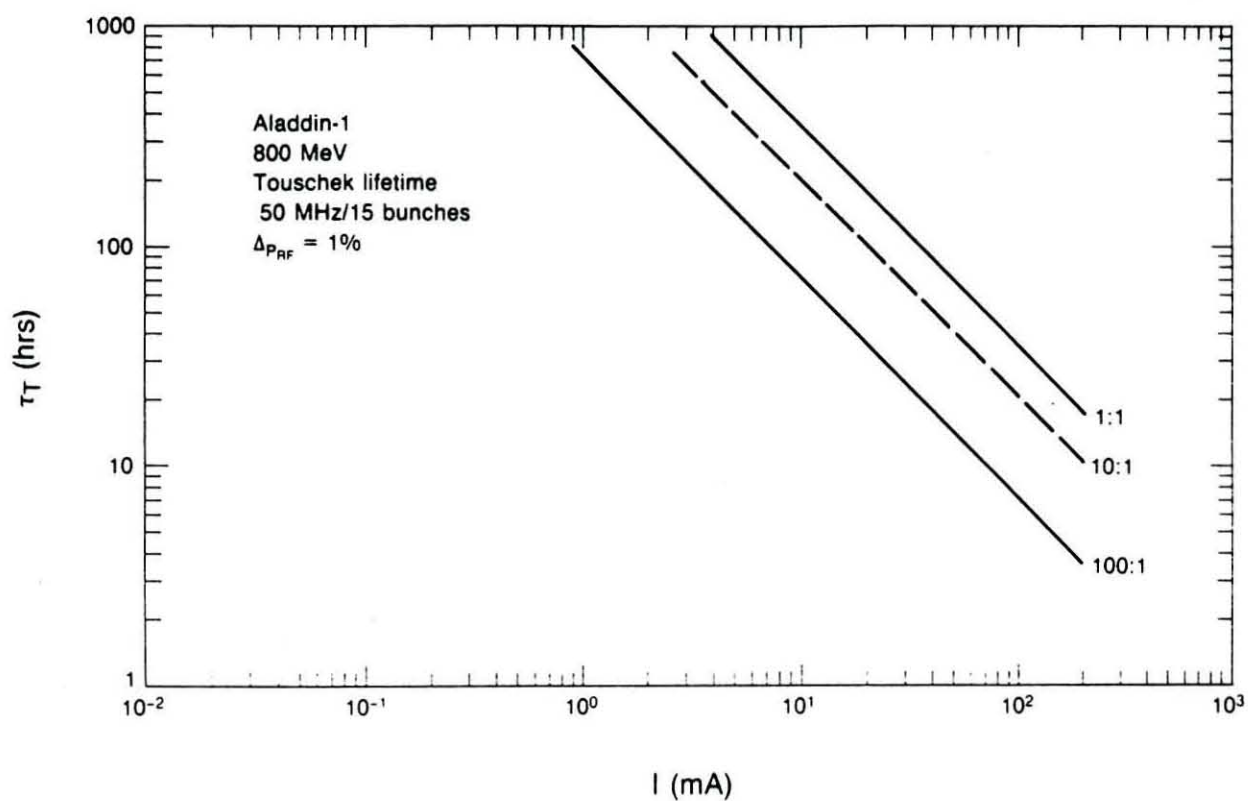
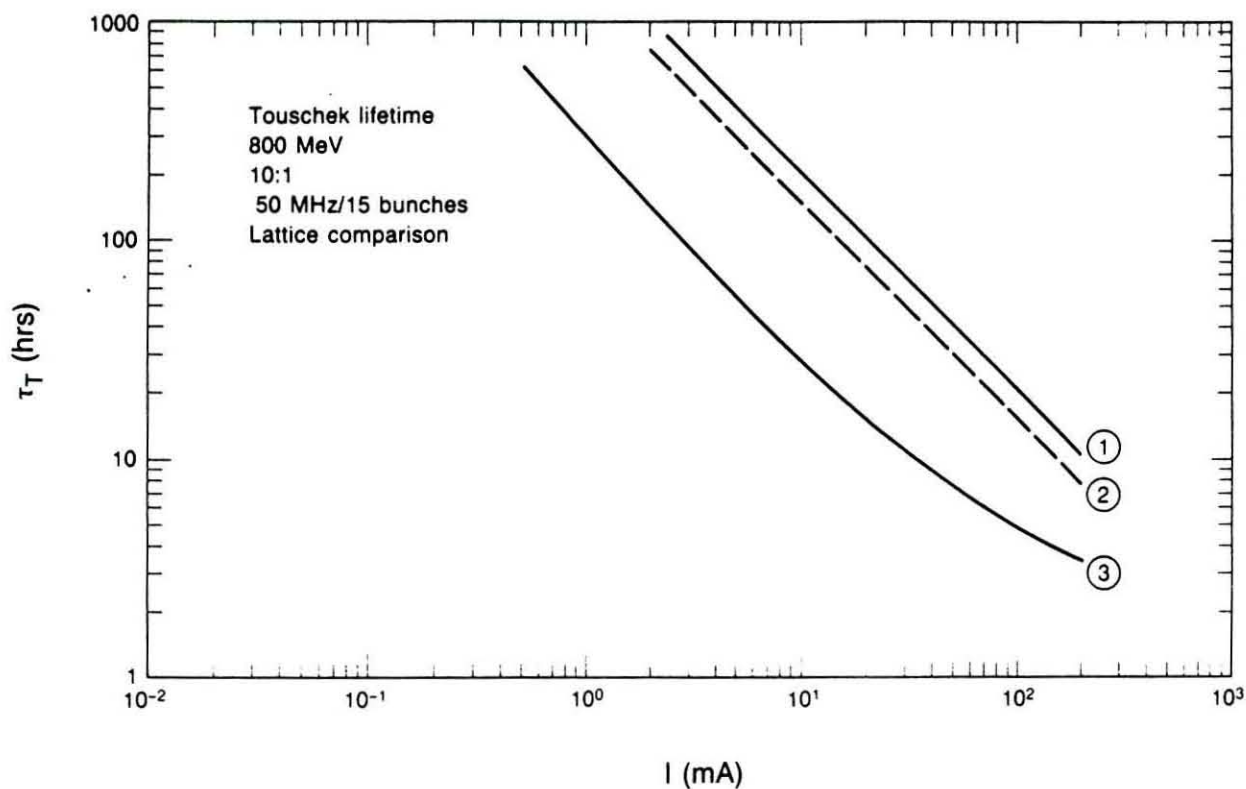


Fig. 11. Equilibrium transverse emittance values for Aladdin-1 and Aladdin-3 at 800 MeV. Various values for the emittance coupling are shown. Although neither lattice shows any emittance growth due to IBS, the values for Aladdin-3 are lower due to its lower natural emittance. Aladdin-2, with nearly the same natural emittance as Aladdin-1, would be indistinguishable from the curves shown here for Aladdin-1.



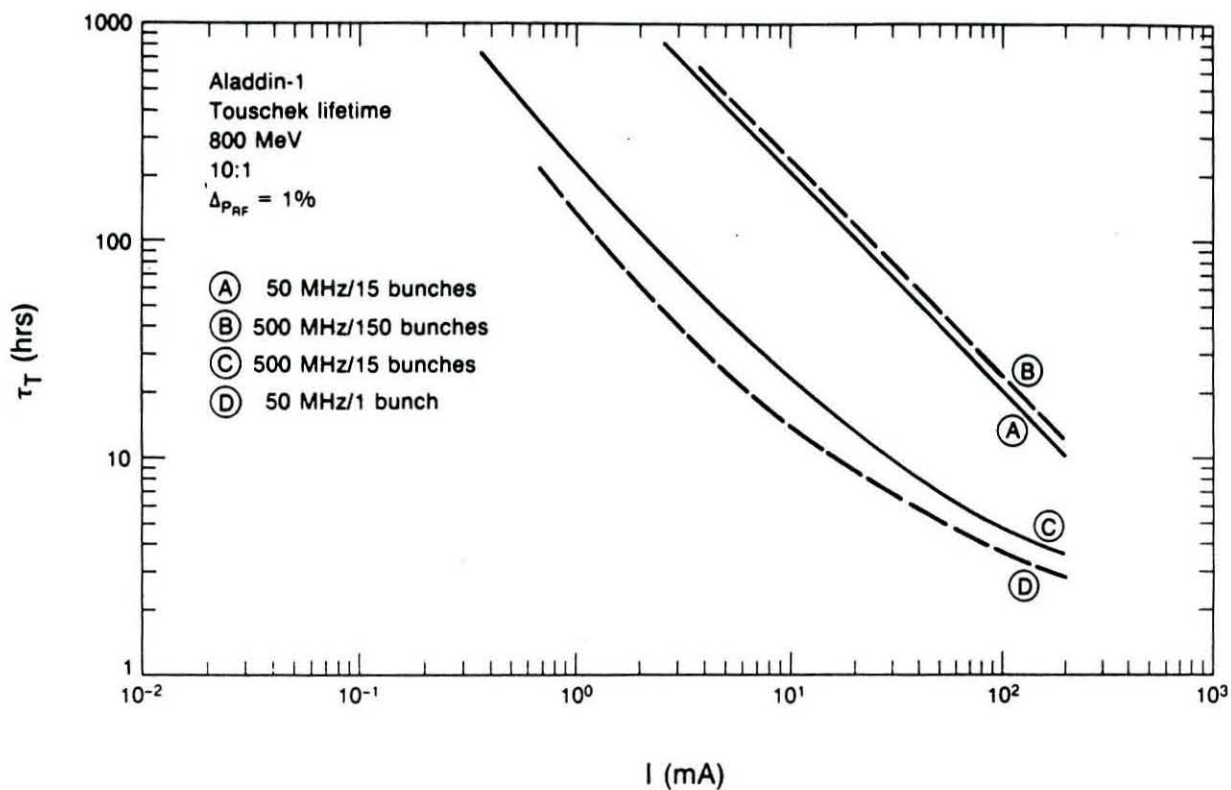
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Fig. 12. Touschek lifetime for Aladdin-1 at 800 MeV. Various values for the emittance coupling are shown. A momentum acceptance of 1% was assumed. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



XBL 853-7099

Fig. 13. Comparison of Touschek lifetime for all three Aladdin lattices for an assumed emittance coupling of 10:1. Average current values are related to peak currents assuming a 50 MHz RF system with 15 buckets filled.



XBL 853-8004

Fig. 14. Comparison of Touschek lifetime for Aladdin-1 at 800 MeV and an emittance coupling of 10:1. Various RF scenarios are illustrated. There is a preference for having all RF buckets filled, but the frequency itself does not matter greatly.