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COHERENT INSTABILITY AND ION TRAPPING CONSIDERATIONS
FOR ALADDIN LATTICES*

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I. Introduction

This paper presents the results of an investigation of the effects of ions and coherent collective instabilities on bunched electron beams circulating in the various Aladdin lattices considered in the Aladdin Upgrade Study. It is aimed particularly at identifying those collective and ion phenomena that may be limiting the performance of the present Aladdin with low energy (100 MeV) injection, at ascertaining which of these phenomena would still remain and limit the performance with a full energy (800 MeV) injector for any of the proposed lattices, and at suggesting possible diagnostic experiments and correction schemes (either active or passive) to alleviate the performance impact of these phenomena; overview of the behavior at low and high energy (and current), the dependence of this behavior on the RF frequency, and the resulting implications for the upgraded Aladdin operations will emerge in the course of this report.

The study has been confined to the three different lattices provided and examined by the Lattice Group of the Study;^[1] we refer to them here as Aladdin-1, Aladdin-2 and Aladdin-3. The first lattice is kept identical to the design specifications of the presently operating Aladdin. The second lattice preserves the azimuthal configuration

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of the magnets but has additional power supplies that make it more flexible regarding optimization of lattice functions, which may be required for injection or inclusion of insertion devices later. The third lattice requires azimuthal rearrangement of various magnets and closely resembles the working BESSY lattice; it provides an electron beam with improved brightness resulting from a significantly smaller natural emittance compared to that provided by the other two lattices. The main machine parameters relevant for instabilities and ion effects are listed in Table I for the three lattices. The RF related parameters will be given separately in the section on coherent instabilities.

The behavior of the three lattice options in terms of intrabeam scattering, Touschek scattering and longitudinal microwave bunch lengthening has been reported in a separate paper.^[2] In the following, we begin in Section II with a study of the coherent effects. We discuss the beam storage ring impedances and the RF parameters used for these calculations, followed by an examination of the longitudinal and transverse coupled bunch instabilities, simple threshold considerations of single bunch fast instabilities, potential-well distortion by the high current beam in a single bunch mode and simple considerations of Landau damping. Feedback systems and higher harmonic Landau cavities required to suppress the growing instabilities are discussed next in Section III. In Section IV, the ion trapping condition and the effect of trapped ions are studied by means of a simple linear model as well as via a numerical simulation that treats the nonlinear electric field of a transversely bi-Gaussian bunch exactly. Tune shifts, tune spreads and the increase in the equivalent background gas pressure (which limits the beam lifetime by multiple gas scattering) due to ions are also investigated. Finally we close in Section V with a summary and suggestions for useful future experiments on Aladdin.

II. Coherent Instabilities

There are already indications of coherent instabilities in the present low current operation of Aladdin with low energy (100 MeV) injection. Observed bunch lengths are compatible^[2] with turbulent bunch lengthening due to longitudinal microwave instability. There is also evidence of longitudinal coupled bunch modes being excited in the beam by the storage ring impedance. Transverse coupled bunch modes are not observed, but the beam transverse motion is plagued by the accumulated ion effect, as we shall see in Section IV. The large transverse tune spread due to trapped ions destroys transverse coherence of the beam via phase-mixing and Landau damps the transverse instability. In order to obtain estimates of coherent growth rates, frequency shifts etc. for the Aladdin lattices, we first need estimates of the beam-storage ring longitudinal and transverse coupling impedances. The values we used for our calculations are discussed in the following.

Impedances

The primary elements in a storage ring that cause a bunch to feel the wake fields created by the other bunches ahead of it and thus produce coupled bunch coherent effects, are narrow-band resonator type objects, e.g., the RF cavities themselves, with all their higher order, high Q electromagnetic modes. These modes can be characterized by a resonance frequency ω_r , a quality factor Q and a shunt impedance R_S in ohms for longitudinal modes (or R_T in ohms per meter for transverse deflecting modes). The longitudinal and transverse impedances of any of these cavity resonances as a function of frequency are given by:

$$z_{\parallel}(\omega) = R_S \frac{\left(\frac{\omega}{\omega_r}\right)^2 - iQ \left(\frac{\omega}{\omega_r}\right) \left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]}{\left(\frac{\omega}{\omega_r}\right)^2 + Q^2 \left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]^2} \quad (1)$$

and

$$z_{\perp}(\omega) = R_T \frac{\left(\frac{\omega}{\omega_r}\right) - iQ \left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]}{\left(\frac{\omega}{\omega_r}\right)^2 + Q^2 \left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]^2} \quad (2)$$

For Aladdin-1, we have used the resonant modes of the existing Aladdin RF cavity. For Aladdin-2 and Aladdin-3 we have used the resonant modes of a PETRA cavity having a fundamental longitudinal RF frequency of 515.459 MHz and a 50.4473 MHz fundamental RF cavity designed by H. Lancaster at LBL for the Upgrade Study. The shunt impedances, quality factors and resonant frequencies of the higher modes for all three cavities are also provided by H. Lancaster and D. Brodzik (LBL), based upon the computer code URMEL.^[3] These are listed in Tables II, III and IV. The motivation for considering two RF frequencies (50.4473 MHz and 515.459 MHz) with harmonic nos. 15 and 150 respectively is to know how the instabilities depend on RF frequency, so that a viable 150 harmonic option may be considered for the Aladdin Upgrade.

The energy acceptance of the RF buckets was always chosen to be 20 times the natural rms energy spread of the beam, thus allowing room for bunch lengthening by microwave blow up and intrabeam scattering.

We also used an estimated impedance of the whole vacuum chamber including all the installed elements other than the RF cavities. These include contribution from the smooth round pipe and rectangular sections giving an overall resistive wall impedance, reactive components coming from the bellows and pick-ups, contribution from transitions etc. The impedances have been estimated by J. Bisognano and H. Lancaster^[4] for the Aladdin vacuum chamber and correspond to a broadband longitudinal impedance of $|z_{\parallel}/n| \approx 6$ ohms. This value is used as the shunt impedance of a $Q = 1$ resonator centered at the cut-off frequency to simulate the broadband

component of the ring impedance. In our calculations we have also used the direct space-charge impedance^[5] of the beams determined by their transverse dimensions and the width of the vacuum chamber (taken to be 0.03651 meters). Resistive-wall impedances^[5] have been calculated for stainless steel vacuum chamber, but other materials such as copper and aluminum have also been investigated, with no significant change in the results. The broadband transverse impedance is simply calculated from the corresponding longitudinal one by the approximate relation^[5]

$$z_{\perp}(\omega) = \frac{2c}{b^2} \frac{z_{\parallel}(\omega)}{\omega} \quad (3)$$

where c is the speed of light and b is the effective chamber radius, taken to be 0.03651 meter.

Coupled Bunch Mode Instabilities

To examine the coupled bunch mode instabilities, we have made use of the computer code ZAP that is now being developed at LBL. At present, in addition to computing various other single particle and collective effects, the code calculates the coherent growth rates and real frequency shifts of longitudinal and transverse couple bunch modes using theoretical expressions developed by F. Sacherer.^[5,6]

For M identical bunches, there are M number of coupled bunch modes characterized by $s = 0, 1, 2, \dots, (M-1)$ which determine the relative phase between adjacent bunch oscillations

$$\Delta\theta = \frac{2\pi}{M} \cdot s \quad (4)$$

The individual bunches themselves can have different bunch-shape modes μ in synchrotron phase-space ($\mu = 1$ dipole rigid bunch, $\mu = 2$ quadrupole etc.) The

frequency spectrum of the longitudinal coupled bunch modes consists of lines at

$$\Omega_n = (nM + s + \mu Q_s) \omega_0 \quad (5)$$

and the spectrum of transverse coupled bunch modes consists of lines at

$$\Omega_n = (nM + s + Q + \mu Q_s) \omega_0 \quad (6)$$

where n is an integer ($-\infty < n < +\infty$), Q_s is the synchrotron tune and Q is the betatron tune. In a spectrum analyzer observing real positive frequencies only, one obtains a spectrum containing upper and lower side-bands around the revolution harmonics.

Higher order synchrotron modes are harder to excite and are less harmful to the beam. We have therefore restricted our studies to synchrotron modes up to $\mu = 4$ for the various coupled bunch modes. Of all these modes, we are interested in those with the fastest growth. These highest rates, for the various lattices at 100 MeV and 800 MeV, as a function of average beam current are shown in Figs. 1-5. Figure 1 provides the fastest longitudinal coupled bunch growth rates for the Aladdin-1 lattice as a function of the average beam current for three different emittance couplings of 100:1, 10:1 and 1:1 at an energy of 100 MeV. The growth rates are not too sensitive to the emittance coupling, indicating insignificant contribution from the beam space-charge impedance. The fastest transverse coupled bunch growth rates for Aladdin-1 at 100 MeV are plotted in Fig. 2 for a 10:1 coupling, as a function of average beam current. The transverse growth is seen to be an order of magnitude slower than the longitudinal. In Fig. 3 we plot the longitudinal coupled bunch fastest growth rates for all three lattices at 800 MeV, 10:1 emittance coupling and 15 bunches in 15 buckets (same as in Figs. 1 and 2). We observe that the coupled bunch instabilities are relatively insensitive to the details of the particular lattices. In Figs. 4 and 5, we show the longitudinal and transverse fastest growth rates

respectively at 800 MeV with a 10:1 coupling for the three cases of 15 bunches in 15 buckets, 15 bunches in 150 buckets and 150 bunches in 150 buckets. Figure 4 is calculated for Aladdin-2 and Fig. 5 for Aladdin-1. Comparing Fig. 1 and 3, we observe that growth rates are an order of magnitude smaller at 800 MeV relative to those at 100 MeV. Figures 4 and 5 indicate that the growth rates of coupled bunch modes are insensitive to the distribution of the beam into a number of buckets, for the same RF frequency and average beam current. However the 50 MHz RF seems to provide smaller growth rates for the particular cavity studied in this report.

We note that the growth rates are linear in current with a very weak nonlinear dependence given by a form factor $F(I/M)$:

$$g \propto \left(\frac{I}{M}\right) F(I/M) \quad (7)$$

Typically we have found that approximately half of the total number of coupled bunch modes grow, and half are damped. By switching off various components of the ring impedance, and using different wall materials, we have ascertained that the growth is mainly due to RF cavities.

The low energy (100 MeV), low current (1-10 mA) behavior of existing Aladdin-1 is characterized by a longitudinal coupled bunch instability growth rate of $g_{coh} \approx 100 \text{ sec}^{-1}$ ($\tau_{gr} \approx 10 \text{ ms}$) at most, whereas the synchrotron radiation damping rate is $g_{SR} \approx -0.15 \text{ sec}^{-1}$ ($\tau_{damp} \approx 6.7 \text{ sec}$). Thus

$$|g_{coh}| \gg |g_{SR}|$$

and we expect coupled bunch instability.

The high energy (800 MeV) behavior is qualitatively the same for all three lattices.

We have at low currents (1-50 mA):

$$g_{coh} \lesssim 7 \text{ sec}^{-1}; \quad \tau_{gr} \gtrsim 143 \text{ ms.}$$

and at high currents (100-200 mA):

$$g_{coh} \approx 50 \text{ sec}^{-1}; \quad \tau_{gr} \approx 20 \text{ ms.}$$

At 800 MeV, the synchrotron radiation damping rate is $g_{SR} \approx -75 \text{ sec}^{-1}$ ($\tau_{damp} \approx 15 \text{ ms.}$). Thus

$$|g_{coh}| < |g_{SR}|$$

and longitudinal synchrotron radiation damping is expected to tame the instability to some degree.

In all cases, real coherent frequency shifts are large and coherent tune-shifts up to 10^{-3} are obtained: e.g.,

$$\begin{aligned} \frac{(\Delta\omega)_{coh}}{\omega_0} &\sim 9 \times 10^{-4} & \mu &= 1 \\ &\sim 1.2 \times 10^{-3} & \mu &= 2, 3, 4 \end{aligned}$$

for 800 MeV Aladdin-1 operation with average current of 200 mA and harmonic number $h = 15$.

Coherent Single Bunch Effects

Single bunch longitudinal fast blowup due to microwave instability does not cause beam loss but simply lengthens the bunch until the bunch peak current falls below the threshold of the microwave instability. The coupled bunched modes calculated above have already taken into account this effect by using microwave lengthened bunches (including any lengthening due to intrabeam scattering) for calculations.^[2] Transverse fast blowup instability (analogous to the longitudinal microwave instability) can cause beam loss however. Transverse and longitudinal fast instability thresholds coincide when^[7]

$$\sigma_{\epsilon}^0 \approx \frac{b}{\sqrt{8\pi} \bar{\beta}} \quad (8)$$

where b is the radius of the vacuum chamber and $\bar{\beta}$ the average beta-function in the transverse direction under consideration. If $\sigma_{\epsilon} < \sigma_{\epsilon}^0$, the transverse threshold is higher than the longitudinal. Since the beam is always slightly below longitudinal threshold in its equilibrium situation, this inequality would guarantee that the beam is safe from transverse blowup effects. For Aladdin-3 at 800 MeV with the 515.459 MHz PETRA cavity and 15 bunches, we have

$$\sigma_{\epsilon}^0 = 1.82 \times 10^{-3} \quad \text{and} \quad (\sigma_{\epsilon})_{\max} \approx 1.67 \times 10^{-3}$$

even when an average current of 200 mA is put in a single bunch. Aladdin is not expected to suffer seriously from transverse fast blowup effects.

There is the possibility of another fast transverse instability, different from above and known as the transverse fast head-tail instability. It arises from transverse mode coupling even with zero chromaticity (synchrotron modes 0 and -1 confluence and couple with each other). The threshold for this instability is given by^[7]:

$$I_{th}^{av.} = \frac{4\pi Q_S E \sigma_\ell b^2 M}{e \bar{\beta} \sqrt{\pi} 2R^2 (Z_{\parallel, n/n})} \quad (9)$$

where we have used for the transverse impedance

$$iZ_{\perp}(0) = Z_{\perp}(\omega_c) = \frac{2R}{b^2} \frac{Z_{\parallel, n}}{n} \quad (10)$$

Only the broadband part of the impedance will contribute significantly to this single bunch effect. For Aladdin-1 at 100 MeV, $\sigma_\ell \approx 0.019$ m at vanishing current, $M = 15$, $b = 3.651 \times 10^{-2}$ m, $Q_S = 0.001598$, $\bar{\beta} \approx 4$ m, $R = 14.16$ m, $Z_{\parallel, n}/n = 6.0$ ohms and we get

$$I_{th}^{av} = 45 \text{ mA} .$$

For Aladdin-1 at 800 MeV and RF harmonic of $h = 15$, $M = 15$, $\sigma_\ell \approx 0.089$ m, at 200 mA average current, $b = 3.651 \times 10^{-2}$ m, $M = 15$, $Q_S = 0.001598$, $\bar{\beta} \approx 4$ m, $R = 14.16$ m, $Z_{\parallel, n}/n = 6.0$ ohms and we get

$$I_{th}^{av} = 1.8 \text{ Amp} .$$

So while fast head-tail instability may occur at low energy (100 MeV) for currents above 45 mA approximately, 200 mA of average current at high energy (800 MeV) is expected to be immune to this transverse mode-coupling instability.

Single bunch operation at 800 MeV with an average current of 200 mA put in a single bunch will experience potential well distortion and bunch lengthening.^[5] For all

the Aladdin lattices this potential well bunch lengthening is modest and largely overwhelmed by the microwave lengthening which keeps the bunch below microwave threshold. For the $h=15$ harmonic RF system, the incoherent synchrotron frequency shift due to potential well distortion is typically

$$\left(\frac{\Delta\omega_s}{\omega_s} \right) \approx 10\%$$

for all three lattices.

Landau Damping

For small bunches, the synchrotron frequency as a function of oscillation amplitude, a (in radians) is given by

$$\omega_s(a) = \omega_{s0} \left(1 - \frac{h^2 a^2}{16} \right) \quad (11)$$

For a maximum amplitude of $a_{\max} = \sigma_\theta$, the frequency spread in the bunch is

$$\frac{(\Delta\omega_s)}{\omega_{s0}} \approx \frac{h^2 \sigma_\theta^2}{16} \quad (12)$$

For a bucket height of $20 \sigma_p$, $h\sigma_\theta \approx (\pi/20)$. The natural synchrotron tune spread in bunches due to bucket nonlinearity is typically

$$\frac{(\Delta\omega_s)_{\text{beam}}}{\omega_0} \approx \left(\frac{\pi}{20} \right)^2 \cdot \frac{1}{16} \cdot \left(\frac{\omega_{s0}}{\omega_0} \right) \approx 3.8 \times 10^{-6}$$

for the Aladdin lattices at 800 MeV. For the μ^{th} synchrotron mode,

$$\mu \cdot \frac{(\Delta\omega_s)_{beam}}{\omega_0} \approx \mu \times 3.8 \times 10^{-6} \ll \frac{(\Delta\omega)_{coh}}{\omega_0} \approx 10^{-3}$$

Coherent frequency is thus shifted beyond the natural width of μ^{th} synchrotron band. Landau damping is thus poor and insufficient to stabilize the beam. We would require either active feedback or larger synchrotron tune spreads to stabilize the beam.

III. Feedback Systems and Landau Cavities

It is apparent that we would need to suppress the potentially growing coupled bunch modes in future upgraded Aladdin operation at 800 MeV even with a new injector. One way to stabilize the beam is to add a higher harmonic Landau RF cavity in addition to the fundamental accelerating cavity. If properly chosen, such a cavity would flatten out the RF potential well and provide a significantly larger synchrotron tune spread due to increased nonlinearity of synchrotron motion.^[8] Landau damping is thus enhanced and helps stabilize the beam. A proper choice would be a cavity with a frequency that is a harmonic N of the fundamental and a voltage (V_{RF}/N) , where V_{RF} is the voltage on the fundamental RF cavity. A third harmonic cavity is a usual choice. Landau cavities can also be used to slightly detune the synchrotron frequency from bunch to bunch which acts as an effective tune-spread and provides Landau damping for the coupled bunch modes.

Another way to suppress the coupled bunch modes would be via an active feedback damping system.

Consider a longitudinal feedback system as an example. The system would have to act on all M bunches, i.e., affect all M coupled bunch modes. It is clear from Fig. 6, that a bandwidth $W = (Mf_0/2)$ is sufficient to act on all M modes. We then

need a bandwidth of approximately 25 MHz for the $h = 15$ harmonic system and 250 MHz for the $h = 150$ harmonic system, if all the buckets were filled with bunches. The sample of particles suffering longitudinal feedback correction thus contains $(Nf_0/2W) = N/M = N_b$ particles, i.e., a single bunch. This ensures bunch by bunch feedback. Typically for a growth rate of $g_{coh} = 50 \text{ sec}^{-1}$ ($\tau_{gr} \sim 20 \text{ ms}$), the fractional correction per turn is $(\Delta E/\bar{E})_{turn} = (g_{coh}/f_0) \approx (1/60,000)$. The particles would experience an energy change of $(e\Delta V_k)$ per turn where ΔV_k has to be

$$\Delta V_k = 2\bar{E} \cdot \frac{g_{coh}}{f_0} \quad (13)$$

If $\bar{E} = \epsilon E_0$, then

$$\frac{\Delta V_k}{\epsilon} \approx 27 \text{ keV at } E_0 = 800 \text{ MeV}.$$

For $\epsilon = 0.1\%$, this corresponds to a voltage of $\Delta V_k = 27 \text{ V}$ on the kicker. Synchrotron damping at 800 MeV will reduce this value substantially.

The useful damping signal power into the kicker is $(\Delta V_k)^2/(R_k)_{in}$ where $(R_k)_{in}$ is the input resistance to the kicker. The kicker signal would be proportional to the average energy deviation $\bar{E}$ of the sample of particles. The required power to the kicker is

$$P_k^S = \left[\left(\frac{\Delta E}{\bar{E}} \right)_{turn} \right]^2 \frac{|\bar{E}|^2}{K^2 (R_k)_{in}} \text{ per mode} \quad (14)$$

where K is the dimensionless kicker sensitivity. Total power to the kicker required to damp all modes is $P_k = \sum_S P_k^S$. At 800 MeV, with a kicker sensitivity K of unity and $(R_k)_{in} \sim 50 \text{ ohms}$, we get for the $h = 15$ harmonic (50 MHz) system:

$$P_k \leq \frac{1}{2} \text{ kilowatt .}$$

Low frequency electronics for feedback dampers can be estimated to cost about 100-200 \$/Watt. The cost of a 1 KW feedback damper would thus be less than \$200K approximately.

Design of a 25 MHz bandwidth feedback system is straightforward. Longitudinal phase signals (proportional to energy error $\Delta\phi = \alpha \bar{E}$) can be detected by a sum pickup (PU), amplified and applied as voltage across a kicker RF-cavity that modulates the longitudinal signal and amplitude. One could also detect the phase error and apply a phase correction, or detect the energy error and apply a phase correction, etc. For example, the pickup could be a difference pickup (position monitor) in a dispersive region. The PU signal then is proportional to the energy error and the kicker will modulate the phase of the longitudinal oscillation. Some filters may be necessary following the PU to eliminate unwanted modes of the cavity fundamentals, coherent revolution harmonics, etc. Gain of the amplifier will depend on the required PU sensitivity to get a reasonable signal-to-noise ratio. A reasonable model for the Aladdin feedback system would be the already operating 50 MHz longitudinal feedback damper at the Brookhaven VUV ring.^[9]

Feedback with a 500 MHz RF cavity and all the buckets filled is more difficult. Broadband electronics and power amplifiers with a bandwidth of 250 MHz are expensive. Bunch-by-bunch feedback of 150 bunches either by multiplexing in the time-domain or 75 independent channels, with quadrature mixers in each in the frequency domain (actually one would require for fewer than 75 channels in practice) is complicated but not impossible. Of course, the 500 MHz system could always be run with only 15 bunches, in which case the feedback will be similar to the 50 MHz system. One can also envisage selecting a very high central operating frequency (in the GHz range) for the

500 MHz system, in order to ease electronics and handling of the coherent bunch frequency lines.

IV. Ion Effects

It is by now recognized that the existence of trapped ions, created by the fast electrons in the beam striking residual gas molecules in the vacuum chamber, is one of the primary beam current limiting factors in the present Aladdin. The ions are focused by the passing electron bunches and defocussed during the drift in between the bunches. They execute transverse betatron motion in the potential well of the electron bunches. In a linear theory, one models these focusing and defocussing effects by thin lenses and it follows from simple single particle optical considerations that the transverse motion is stable (i.e. an ion is trapped) if the distance between successive equi-spaced bunches is less than or equal to four times the focal length of the thin lens modelling the electron bunch (or equivalently, if the trace of the cumulative transfer matrix for the transverse phase-space coordinates, consisting of the basic focusing and defocussing units, is less than or equal to two). The focal strength of the electron bunches, as experienced by an ion, is inversely proportional to the mass of the ion; the bunch-to-bunch spacing is inversely proportional to the number of bunches in the ring. Heavy ions are easily trapped even with large bunch-to-bunch spacing, and for many-bunch operation, the spacing may be small enough to trap light ions also. The focal strength of an electron bunch is proportional to the amount of current per bunch and depends on the transverse dimensions of the bunch, which determine the charge density. It follows that for any storage ring there is a "critical mass" A_c (in atomic mass units), depending on the current per bunch, the number of bunches, the bunch transverse dimensions and the ring circumference, such that the ions with mass A are stable and trapped if $A \geq A_c$. The critical mass A_c is given by linear theory as follows:^[10]

$$A_c = \frac{1}{2} \left(\frac{2\pi R}{M} \right)^2 \cdot \frac{m_e}{m_p} \cdot \frac{I}{I_A} \cdot \frac{1}{\sigma_{z,x}(\sigma_x + \sigma_z)} \quad (15)$$

where $C = (2\pi R)$ is the circumference of the machine, M the number of equi-spaced electron bunches, I the total current circulating in the ring, $\sigma_{x,z}$ the horizontal and vertical r.m.s. beam dimensions, $m_e(m_p)$ the electron (proton) mass and $I_A = 17045$ Amp the Alfven current. The effective critical mass is determined by the smaller of the two transverse dimensions.

For the Aladdin lattices with 88.9 meter circumference and emittance coupling such that the vertical beam dimension is always smaller than or equal to the horizontal beam dimension, we have

$$A_c = 1.2626 \times 10^{-4} \frac{I_{[amp]}}{M^2} \cdot \frac{1}{\sigma_z(\sigma_x + \sigma_z) [m^2]} \quad (16)$$

For a given average beam current I , number of bunches M and emittance coupling (ϵ_x/ϵ_z) , the $\sigma_{x,z}$ are given by the equilibrium beam dimensions determined by a balance between the radiation damping, quantum fluctuations, intrabeam scattering and longitudinal blow-up due to fast microwave instability.^[2]

We have considered emittance couplings of 1:1, 10:1 and 100:1, average beam currents ranging from 1 mA to 200 mA, for all three Aladdin lattices, with 150 bunches (500 MHz RF case), 15 bunches (either 500 MHz or 50 MHz RF case) and one bunch in the ring. For all the lattices, with a bunch in every bucket (15 bunches in 15 buckets for the 50 MHz RF case or 150 bunches in 150 buckets for the 500 MHz RF case), the critical mass for ion trapping is very low for average currents up to 200 mA; we have

$$A_c \lesssim 1$$

According to linear theory, then, ions are always trapped in the full multi-bunch mode and potentially harmful to the beam ($A_c \sim .01$ at 2 mA and $A_c \sim 1$ at 200 mA).

For all three lattices with all the beam in a single bunch, the critical mass for ion trapping is still low for low average currents but very high at a current of 200 mA:

$$\begin{aligned} A_c &\sim 2 && \text{at 2 mA} \\ &\sim 200 && \text{at 200 mA} \end{aligned}$$

As we increase the current per bunch by putting all the beam in a single bunch, intrabeam scattering is enhanced due to increased beam density. However the change in equilibrium beam dimensions $\sigma_{x,z}$ is modest enough that the critical mass is changed dominantly by the increased inverse ratio of the number of bunches squared, M^2 . For $M = 15$, say, this ratio is 225 and enough to pull the high current critical mass from the value $A_c \sim 2$ to the safe value of $A_c \sim 200$. However the low current number is changed from $A_c \sim .01$ to only 2, which is still quite small. Thus, while single bunch operation at high current is safe from ion trapping, for low currents single bunch operation is still plagued by effects of trapped ions.

It is also clear that higher the emittance coupling (ϵ_x/ϵ_z), the smaller the vertical beam dimension σ_z and the higher the critical mass A_c . Higher coupling is thus preferable from the ion trapping point of view.

All the above predictions of the linear theory are confirmed to a large extent by a numerical simulation that tracks ion motion over many turns in the nonlinear transverse electric field of electron bunches having Gaussian transverse distributions in x and z . The simulation is based on a program called TRAPION developed at LBL by D. Douglas.^[11] The transverse distribution is taken to be of the form:

$$f(x, z) \propto \exp \left[-\frac{1}{2} \left(\frac{x^2}{\sigma_x^2} + \frac{z^2}{\sigma_z^2} \right) \right] \quad (17)$$

The transverse electric field is generally given in terms of error functions. For round Gaussian beams with $\sigma_x = \sigma_z = \sigma$, the radial electric field is given by:

$$E(r) = \frac{N e}{2\pi\epsilon_0 M \ell_B} \cdot \frac{1}{r} \left[1 - e^{-(r^2/2\sigma^2)} \right] \quad (18)$$

where ℓ_B is the bunch length, (N/M) the number of particles per bunch and e the electron charge. The program allows for different r.m.s. dimensions in x and z and is limited to the case of $\epsilon_z \leq \epsilon_x$, number of bunches $M \leq 304$ and maximum number of turns to track ion motion equal to 2000. The program also provides various phase-space plots of the motion e.g. (x, x') , (z, z') , (x, z) and (x', z') planes. For $\epsilon_z < \epsilon_x$, it is the vertical overfocusing that determines the unstable ion motion, i.e., it is ϵ_z that establishes the ion trapping limit. Unlike the linear model, however, the stability of an ion in this nonlinear simulation depends very much on the location of the ion within the beam. There is a critical radius r_{cr} , above which an ion may not be trapped, although it is trapped for $r \leq r_{cr}$. If r_{cr} is of the order of a few beam radii, the ion is trapped while if r_{cr} is very small compared to the beam radius, the ion is untrapped for all practical purposes.

A typical tracking result for a CO_2 -ion ($A = 44$) moving in the fields of the electron bunches in Aladdin-1, for example, is shown in Table V for three different average currents, various bunch to bucket number configurations and various starting conditions (x_0, z_0) .

Trapping of ions in the multi-bunch mode can be avoided by leaving a large gap in the train of bunches. The ions simply may find sufficient time in the gap to drift away

and escape from the beam. In the linear approximation, the effective focal length of a series of M thin lenses, each with a focal length f , is $F = (f/M)$. For an ion to be unstable, the "gap" in the train of bunches will have to satisfy

$$t = \alpha T_0 \geq 4F = 4(f/M) . \quad (19)$$

where t is the beam gap (in secs) and T_0 is the revolution period in the storage ring. If h is the number of buckets in the ring, $M \sim (1-\alpha)h$ and the above inequality reduces to

$$\alpha(1-\alpha) \geq \frac{4f}{hT_0} \quad (20)$$

For any ion experiencing a focal length f from the successive electron bunches, the minimum gap to circumference ratio $\alpha_{\min}$ is determined by the physical solution of the quadratic equation given by the equality sign above and is seen to be

$$\alpha_{\min} \sim \frac{1}{2} \left[1 - \left(1 - \frac{16f}{hT_0} \right)^{1/2} \right] \quad (21)$$

Indeed the simulation results shown in Table V illustrate that multi-bunch operation at high current can be made safe by leaving a gap in the train of bunches e.g. 10 consecutive bunches, followed by a 5-bucket gap at 200 mA or 5 bunches followed by a 10 bucket gap at 100 mA, etc.

We may thus summarize, as far as the simple condition for ion trapping is concerned, as follows: for all three Aladdin lattices, ions are always trapped at low average currents (1-50 mA) both in single and multi-bunch mode. Ions are also trapped at high currents (100-200 mA) when all the buckets are full, but probably not trapped in

the single bunch mode. However the multi-bunch mode at high current can be made safe from ion trapping by leaving a gap of appropriate length in the train of bunches. Higher emittance coupling (ϵ_x/ϵ_z) makes the electron beam less prone to ion trapping. The ion trapping condition depends on the number of bunches and not on the harmonic number h of the RF cavity directly. If all the buckets are kept filled, the critical mass $A_c \propto (1/h^2)$. Thus ion trapping for a 500 MHz RF system with all buckets filled is 100 times worse compared to that for a 50 MHz RF system with all buckets filled. The flexibility offered by a 500 MHz RF system in adjusting the beam-gap ratio is only marginally advantageous at high current (200 mA) and useless at low currents anyway.

Given that the ions are trapped and start to accumulate, we will now look at the effect of these accumulated ions. The accumulation continues until the defocussing force due to ion space-charge in the drift region is strong enough for the stability limit to be reached. The limiting ion density d_i in this equilibrium accumulation limit is obtained by replacing the drift length by a defocussing thick lens and is given by^[10]

$$d_i = \beta \cdot \frac{1}{B} \cdot d_e \quad (22)$$

where d_e is the actual density of the e^- bunches, $\beta = v_e/c$ and $B = (2\pi R/M\lambda_B)$ is the bunching factor. The neutralization factor is then simply $\eta = (d_i/d_e) = (\beta/B)$. Time to reach this equilibrium with neutralization η is^[10]

$$t = \eta B \tau_i = \beta \tau_i \quad (23)$$

where $\tau_i = [1/d_m \sigma_i(\beta c)]$ is the ionization time (time taken by one electron to create one ion), d_m being the residual molecular density and σ_i the ionization cross section.

Typical neutralization times are $\tau_{\text{neutr.}} \sim .5$ sec. at a background gas pressure of 10^{-9} torr and $\tau_{\text{neutr.}} \sim 50$ sec. at 10^{-11} torr, both at room temperature of 300°K.

The tune-shift caused by accumulated ions is given by^[10]

$$(\Delta Q_{z,x})_{\text{ions}} = r_e \cdot \frac{m_e c^2}{E} \int_0^{2\pi R} ds \frac{d_i}{\left(1 + \frac{\sigma_{z,x}(s)}{\sigma_{x,z}(s)}\right)} \beta_{z,x}(s) \quad (24)$$

while the incoherent Laslett tune-shift due to space-charge is given by^[10]

$$(\Delta Q_{z,x})_{\text{sc}} = r_e \cdot \frac{m_e c^2}{E} \cdot \frac{1}{\gamma^2} \int_0^{2\pi R} ds \frac{d_e}{\left(1 + \frac{\sigma_{z,x}(s)}{\sigma_{x,z}(s)}\right)} \beta_{z,x}(s) \quad (25)$$

Since $d_i = \eta d_e$, we have

$$(\Delta Q_{z,x})_{\text{ions}} = \eta \gamma^2 (\Delta Q_{z,x})_{\text{sc}} \quad (26)$$

Vertical betatron tune-shifts due to ions are of the order of 10^{-2} at 2 mA and 1~5 at 200 mA for all the Aladdin lattices at a coupling (ϵ_x/ϵ_z) of 10:1; their dependence on energy is weak. Assuming full neutralization, the tune shift is not affected by the neutralization factor η , which decreases only slightly due to the smaller longitudinal beam dimensions at a higher energy. These large tune shifts can be appreciated by looking at the Laslett tune-shifts for Aladdin-1 at 100 MeV and 800 MeV shown in Figs. 7 and 8 respectively as a function of beam average current and remembering that $\eta \gamma^2$ is a large number. These tune-shifts were calculated from Eq. (25) by using the computer code ZAP, mentioned earlier in Section II.

The equivalent background gas pressure for gas scattering is raised due to the accumulated ions. Ion pressures at full neutralization, as computed with ZAP, at 100 MeV and 800 MeV for Aladdin-1 are plotted in Fig. 9 and 10 respectively as a function of beam current. In Fig. 11 we show the dependence of ion pressure on energy for Aladdin-1. Note the hump in this last curve at around 400 MeV where the beam equilibrium transverse emittance is minimum.^[2]

Our investigation of ion trapping effects does indicate improved performance of Aladdin at high current, but not at high energy. However there is an important distinction between the low energy and high energy regimes as far as ions are concerned. We note that the damping times are of the order of 10 secs. at 100 MeV and 10 m-sec. at 800 MeV, while the neutralization time is about (1/2) sec. at both energies. Thus

$$\begin{array}{ll} 100 \text{ MeV;} & \tau_{\text{neutr.}} \ll \tau_{\text{damp.}} \\ 800 \text{ MeV;} & \tau_{\text{neutr.}} \gg \tau_{\text{damp.}} \end{array}$$

Neutralization is therefore expected to be complete at low energy and incomplete at high energy. High energy may not be as harmful from the ion point of view. However the high energy regime is prone to electron-ion collective oscillations. The transverse quadrupole throbbing motion of the beam-ion system is unstable for any integer $n > 2Q_z$ if^[12]

$$|n - 2Q_z - 2Q_i| < \left(\frac{\Delta Q_e}{z} \right) \sqrt{\frac{Q_i}{Q_z}} \quad (27)$$

is satisfied. This is approximately the beam-ion quadrupole resonance condition

$$(n - 2Q_z) \approx 2Q_i \quad (28)$$

The growth rate of the instability is given by^[12]

$$g = \left[\frac{\Delta Q_e^2 Q_i}{16 Q_e} - \frac{(2Q_i - 2Q_e - n)^2}{4} \right]^{1/2} \omega_0 \quad (29)$$

The ion tune Q_i increases as the beam size decreases and at some point the resonance condition is satisfied. The interplay between the radiation damping and the growing instability leads to a throbbing mode, which increases the effective size of the beam. For comparable rates of damping and neutralization time, an equilibrium may be reached, determined by the balance of radiation damping and instability growth.

Ion trapping is an elusive and poorly understood subject. However electron storage rings in this energy range (1 GeV) seem to operate favorably in a high current (few hundred mA) mode, with associated large transverse tune-spreads due to trapped ions. Ions are more of a gift in that they stabilize an otherwise unstable transverse motion via Landau damping due to large tune-spread. It seems to be nature's way of making electron rings at a few GeV energy work. Once the initial barrier of getting enough current into the ring is crossed with the help of a full energy injector, Aladdin is expected to benefit from the ions rather than suffer because of them. The tune spread due to nonlinearity in the transverse electric field is expected to be of the same order of magnitude as the incoherent tune-shift due to ions, which is large as we have seen above and far exceeds any coherent frequency shift due to ring transverse impedances.

V. Summary and Suggested Experiments

It is clear from our investigation that coherent instabilities and ion effects that limit the present Aladdin operation will not be removed completely by a full-energy injector. However operation at 800 MeV with a full-energy injector is certainly more

favorable and susceptible to various means of cure. Single bunch coherent phenomena are not expected to be serious at 800 MeV up to 200 mA average beam current. Coupled bunch modes will persist but the transverse coupled bunch instability will be heavily Landau damped by the betatron tune-spread due to accumulated ions, while the longitudinal coupled bunch modes could be damped by a carefully designed feedback system. RF cavities could be designed anew to reduce higher order mode impedances. Longitudinal growth rates at 800 MeV with the newly designed 50.4473 MHz cavity are two orders of magnitude smaller than those at 100 MeV and certainly encouraging. The 50 MHz RF cavity seems preferable to a 500 MHz RF cavity from the point of view of simplicity and cost of a feedback system design. Longitudinal and transverse coupled bunch growth rates also seem to be faster with the higher frequency RF cavity, but this could be due to accidental tuning of resonances and can probably be avoided by redesigning the RF cavity.

Ion trapping is expected to be just as prevalent at 800 MeV as at 100 MeV. However, at 800 MeV, trapping could be avoided by leaving a large gap in the train of bunches. At low energy, even such a strategy seems to be useless. It is easier to inject more beam at a higher energy and ion trapping gets better at high currents anyway. Moreover the residual of trapped ions will be beneficial from the transverse stability point of view.

Performing a few crucial experiments to gain a better understanding of Aladdin is highly desirable at present. The actual impedance of the whole ring, as seen by real beam, is not known. In this context one could perform a longitudinal quadrupole mode beam transfer function measurement of the bunches. The quadrupole mode could be excited simply by modulating the RF cavity voltage and the resulting phase and amplitude response will contain information about the longitudinal coupling impedance and the beam phase-space and frequency distribution. Similar measurement of the transfer function of the longitudinal dipole mode, excited by phase modulation of the

RF cavity (equivalent to frequency modulation) would also provide information about the longitudinal coupling impedance. Another experiment could be to measure the parasitic mode loss of the bunch by measuring the shift in the synchronous angle. The energy lost to the storage ring is dependent on the longitudinal impedance of the beam-storage ring system. Measurement of the background pressure in the vacuum chamber as a function of the position of a set of ion-clearing electrodes will be extremely useful in diagnosing ion accumulation zones and their densities. Monitoring the beam signal and its spectrum by a pick-up would be invaluable in attempting to understand the tune and frequency distribution in the bunch and may be helpful in directly observing the tune-spread in the beam. For this purpose design of a dedicated diagnostic pick-up is strongly recommended.

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TABLE I
Parameters of Aladdin Lattices

Machine Parameters	Aladdin-1	Aladdin-2	Aladdin-3
Circumference $C = 2\pi R[\text{m}]$	88.9	88.9	88.9
Horizontal Tune Q_x	7.16	5.24	5.82
Vertical Tune Q_z	7.12	6.28	3.77
Momentum Compaction $\alpha [10^{-2}]$	3.57	1.83	0.674
Average $\bar{\beta}_x [\text{m}]$	3.95	4.02	7.71
Average $\bar{\beta}_z [\text{m}]$	4.06	3.68	6.02
Corrected Chromaticity ξ	0.00525	0.0027	-0.0389
Chamber radius, $b [\text{m}]$	0.037	0.037	0.037
* Equilibrium Longitudinal Mom. Spread $\sigma_{p0} = (\Delta p/p_0)_{\text{rms}} [10^{-4}]$ (zero current $I = 0$)	4.78	4.78	4.78
* Equilibrium Horizontal Emittance $\epsilon_{x0} [10^{-8} \text{ m-rad}]$	7.67	7.30	1.77
* Transverse Synchrotron Damping Time $(\tau_D)_x [\text{sec}]$	0.013	0.013	0.013

* at 800 MeV and a coupling $(\epsilon_x/\epsilon_z) = 100:1$

TABLE II

Present Aladdin Cavity Modes

Beam pipe cutoff: 3.142 GHz (long.); 2.406 GHz (transv.)

Longitudinal			Transverse		
f_r (MHz)	Q	R_S (M Ω)	f_r (MHz)	Q	R_T (M Ω /m)
50.53143	15900	2.2686	216.5782	33965	3.07×10^{-2}
150.7772	27142	0.6354	278.84	37386	0.139×10^{-2}
249.0088	33809	0.3655	358.5143	41608	0.291
345.6368	37978	0.6932×10^{-1}	440.9213	43730	2.546
442.9125	41239	0.1840	509.7018	40185	4.644
542.5408	44454	0.111	580.7148	43884	1.243
622.4181	31231	0.7818×10^{-2}	652.6766	35306	2.49×10^{-2}
636.7786	34081	0.3854×10^{-1}	667.1484	42875	7.744×10^{-2}
646.3482	41557	0.3422×10^{-1}	675.5793	40572	1.18×10^{-1}
671.6671	33949	0.1802	698.0932	36988	3.584×10^{-3}
711.1572	33560	0.1683	708.3145	37754	0.396
749.964	46918	0.1863×10^{-2}	750.1036	45044	0.179
764.7136	37453	0.1109	774.3242	45175	4.883×10^{-3}
822.9875	34588	0.9784×10^{-2}	812.7495	44858	0.213

TABLE III

50.4473 MHz RF Cavity Designed at LBL

Beam pipe cutoff: 3.143 GHz (long.); 2.406 GHz (transv.)

Longitudinal			Transverse		
f_r (MHz)	Q	R_s ($M\Omega$)	f_r (MHz)	Q	R_T ($M\Omega/m$)
50.4473	15670	2.14	201.450	22700	0.1567
213.959	25300	0.0561	283.935	30300	0.0022
351.758	26800	0.0696	410.996	32300	0.4601
420.339	31000	0.948×10^{-2}	448.859	36400	0.0301
450.896	28500	0.0399	479.974	32200	0.0698
504.965	29600	0.851	556.816	37200	0.9833
567.204	28000	0.724	630.435	51000	0.8162
627.543	37400	0.130	640.857	42800	0.7012
696.239	35800	0.0449	682.205	35000	4.9302
799.910	40600	0.0119	723.041	35400	1.3086
833.521	39900	0.0119	776.479	72800	0.0086
850.735	36600	0.24×10^{-2}			
875.781	44400	0.35×10^{-4}			
897.640	39700	0.0106			
959.374	42000	0.0288			
982.746	41200	0.0290			
1067.28	43800	0.168			

TABLE IV

515.459 MHz PETRA Cavity

Beam pipe cutoff: 1.912 GHz (long.); 3.047 GHz (transv.)

Longitudinal			Transverse		
f_r (MHz)	Q	R_s (M Ω)	f_r (MHz)	Q	R_T (M Ω /m)
515.459	27500	4.149	855.117	36900	20.33
1247.5	26500	0.144	1252.73	29500	0.272
1287.53	42400	0.353×10^{-2}	1445.33	32700	11.1
1826.64	31100	0.418	1585.86	44800	0.056
			1669.18	54800	0.502
			1964.27	31900	9.5
			2183.94	43700	0.079
			2284.94	54600	5.15
			2372.62	50900	0.011
			2444.99	52400	2.683
			2546.96	51600	0.053
			2730.18	41800	1.647
			2817.37	37500	1.37
			2938.13	111000	0.032
			3016.41	58000	0.073

TABLE V

Ion Tracking in Nonlinear Fields for (Aladdin-1, $A = 44$)

Average Current	No. of Buckets	No. of Bunches	(x_0, z_0)	No. of Turns	Ion Motion
2 mA	15	15	$.5 \sigma_x, .5 \sigma_z$	2000	Stable
	15	1			Stable
100 mA	15	15	$.5 \sigma_x, .5 \sigma_z$	2000	Stable
	15	1	$.5 \sigma_x, .5 \sigma_z$		Unstable
	15	10	$.2 \sigma_x, .2 \sigma_z$		Stable
	15	5	$.5 \sigma_x, .5 \sigma_z$		Unstable
	15	5	$.1 \sigma_x, .1 \sigma_z$		Unstable ($\geq 100 \sigma_{x,z}$) [*]
200 mA	15	15	$.2 \sigma_x, .2 \sigma_z$	2000	Stable
	15	10			Unstable
	15	1			Unstable

* Unstable here means that the growing ion oscillations reach amplitudes of $100 \sigma_{x,z}$ and greater at the end of 2000 turns!

XCG 853-154

Fig. 1. Fastest Growth Rates for Longitudinal Coupled Bunch Modes for Aladdin-1 at 100 MeV with (RF + Broadband + Space-Charge + Resistive Wall of Stainless Steel).

XCG 853-155

Fig. 2. Fastest Growth Rates for Transverse Coupled Bunch Modes for Aladdin-1 at 100 MeV with (RF + Broadband + Space-Charge + Resistive Wall of Stainless Steel).

XCG 853-156

Fig. 3. Fastest Growth Rates for Longitudinal Coupled Bunch Modes for Aladdin-1, 2 and 3 at 800 MeV with (RF + Broadband + Space-Charge + Resistive Wall of Stainless Steel).

XCG 853-157

Fig. 4. Fastest Growth Rates for Longitudinal Coupled Bunch Modes for Aladdin-2 at 800 MeV with (RF + Broadband + Space-Charge + Resistive Wall of Stainless Steel).

XCG 853-158

Fig. 5. Fastest Growth Rates for Transverse Coupled Bunch Modes for Aladdin-1 at 800 MeV (RF + Broadband + Space-Charge + Resistive Wall of Stainless Steel).

XCG 853-164

Fig. 6. Line Spectrum of Coupled Bunch Modes for Five Punches, as Seen by a Spectrum Analyzer in Real Positive Frequency.

Fig. 7. Laslett Tune Shifts for Aladdin-1 at 100 MeV.

Fig. 8. Laslett Tune Shifts for Aladdin-1 at 800 MeV.

XCG 853-160

Fig. 9. Ion Pressure at Full Neutralization for Aladdin-I at 100 MeV.

XCG 853-181

Fig. 10. Ion Pressure at Full Neutralization for Aladdin-1 at 800 MeV.

XCG 853-162

XCG 853-163

Fig. 11. Ion Pressure at Full Neutralization for Aladdin-1 as a Function of Energy.

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