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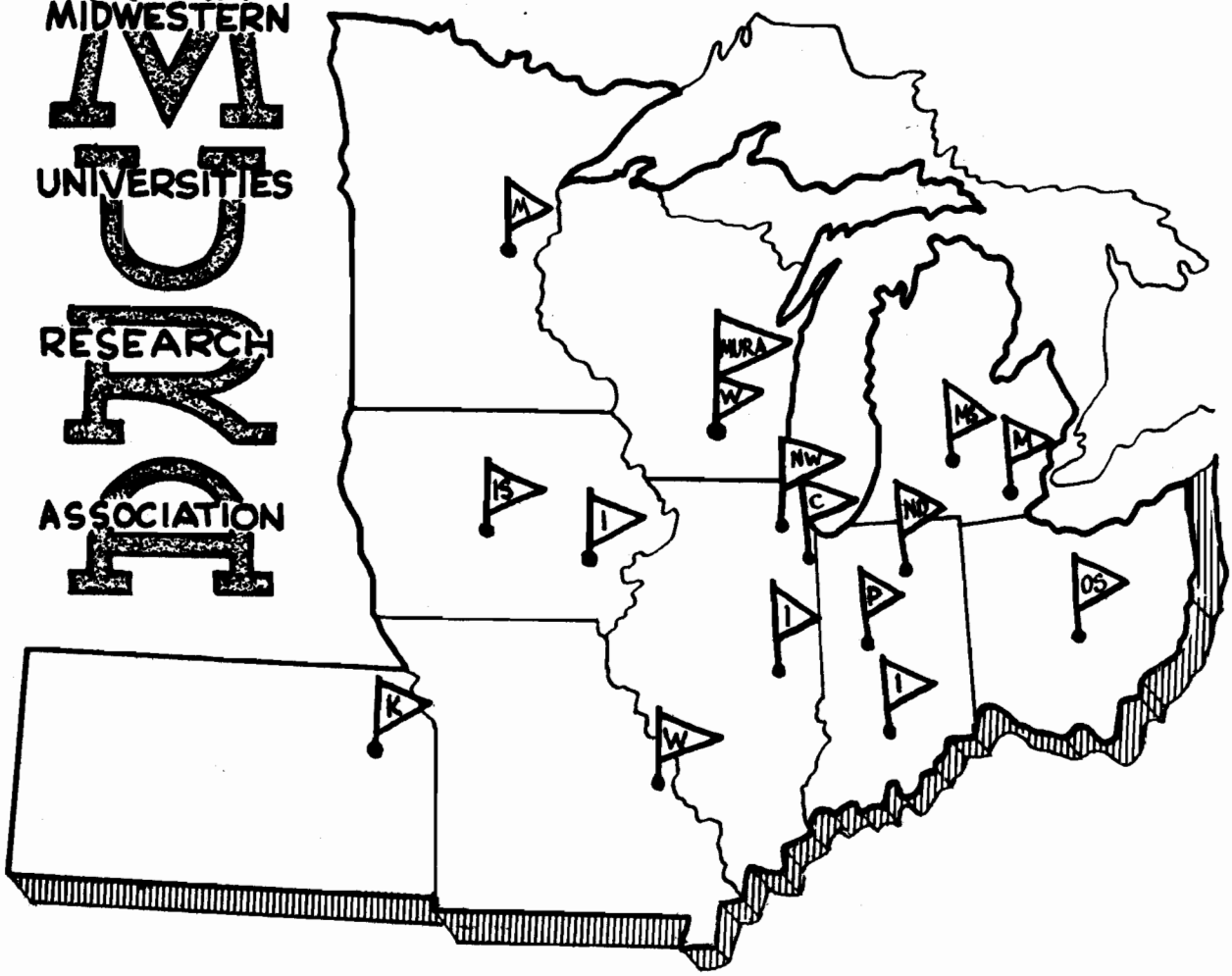

NOTES ON THE BERKELEY BUDKER CONFERENCE

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INTRODUCTION

During the month of August a small group gathered at the University of California Radiation Laboratory to study and discuss the suggestion of Budker that intense, moderate energy circulating electron beams might pinch down to provide very strong local magnetic fields which might be capable of serving as guide fields for multi-Bev protons. The following is a summary of the notes taken by the author during the last week of these discussions and this consequently is not, for the most part, original work by the author. Further, as a summary of notes, this paper may well contain errors; it was prepared to aid in informal discussions among members of the technical group, and should not be construed as a substitute for a careful, complete report being compiled at Berkeley with contributions from all participants. Contributors to the Berkeley discussions were David L. Judd, Ernest D. Courant, and Lloyd Smith for the full time in addition to Jacob Enoch, L. Jackson Laslett, Tihiro Ohkawa, and L. W. Jones for shorter periods.

SUMMARY OF THE BUDKER CONFERENCE

I. Equations of Motion

A. Derived independently by group, essentially same as Budker (except for numerical factors) leading to steady state equilibrium conditions.

B. Conclusions from them about damping time, parameters, etc.

II. Problems not included in equations of motion

A. Stability

1. Radial Stability (oscillation about equilibrium r*,)

2. Longitudinal Stability (unsolved)

B. Ion Behavior

1. Loss from beams initially due to betatron acceleration.

2. Trajectories in self field, trapping (dePackh wrong).

3. Gas scattering. Loss by single scattering.

C. Resonances of Electron

D. Rf instead of betatron acceleration

1. Electrostatic potential required.

2. Positive ion escape time.

3. Bending of accelerated protons by electron bunches.

E. Damping in external magnetic field

F. Damping due to accumulation of positive ions

G. Proton phase space available

III. Schemes

A. dePackh

B. Bennett

C. Finkelstein

D. Courant

F. FFAG

I. Equations of Motion

A. Derivation and Statement.

These equations were evolved by the group and are stated below without derivation. They apply to a group of electrons of energy in a uniform longitudinal field E neutralized by an equal number of stationary positive ions. The electrons are assumed to be moving in the direction and uniformly distributed in a tube of radius r*. x or b are radial coordinates.

$$\frac{d}{dt}\langle p_x^2\rangle = \frac{4(mc)^2 r_0 c L \nu_i}{r^{*2}} \qquad \text{scattering term}$$

(1)

$$\frac{d}{dt}\langle p_x^2\rangle = -\frac{16 r_0 c}{3 r^{*4}}\left\{\nu_e(1-\beta\bar{\beta})-\nu_i\right\}^2 \gamma \langle p_x^2 r^2\rangle \qquad \text{radiation term}$$

where r_0 is the classical electron radius, ν_e and ν_i are the number of electrons and positive ions respectively per length r_0, and L is the log term in the scattering; generally equal to about 30. Partly from [1],

$$\frac{d}{dt}\langle p_z^2\rangle = 2\gamma mc\, eE - \frac{16}{3}\frac{\nu^2 e^2 \gamma^3}{r^{*2}} mc\,\alpha_2$$

(2)

$$\frac{d}{dt}\langle p_x^2\rangle = \frac{4(mc)^2}{r^{*2}} r_0 c\nu\left[L - \frac{(\gamma\nu)^2}{3}\alpha_4'\right] + \frac{\lambda}{\gamma}\frac{d(\gamma/\lambda)}{dt}$$

where
$$\alpha_2 = \frac{2\langle x^2\rangle}{r^{*2}} = \frac{\langle r^2\rangle}{r^{*2}}$$

$$\alpha_4 = \frac{8\langle p_x^2\, x^2\rangle \lambda^2}{r^{*4}\,(mc)^2}$$

$$\alpha_4' = \alpha_4 + \frac{1}{2}\alpha_2^2$$

$$\lambda^2 = \frac{r^{*2}\gamma}{2\nu} = \frac{Bc}{dB/dx}$$

α_2 and α_4 are of order of magnitude unity.

The working equations resulting from (2) are

$$\frac{d}{dt}(b^2) = -\frac{1}{2}\Big[\underbrace{\frac{eE}{\gamma mc}}_{a)} + \underbrace{\left(\frac{\nu}{4\gamma}-1\right)\frac{(r^{*2})^{\cdot}}{r^{*2}}}_{b)}\Big]b^2 - \underbrace{\frac{2}{3}\gamma\nu^2 r_0 c\left(\frac{b^2}{r^{*2}}\right)^2}_{c)} + \underbrace{\frac{2r_0 cL}{\gamma}}_{d)} \tag{3}$$

$$\frac{1}{\gamma}\frac{d\gamma}{dt} = \Big[\underbrace{\frac{eE}{\gamma mc}}_{e)} - \underbrace{\frac{8}{3}\frac{\gamma\nu^2 r_0 c}{r^{*2}}\left(\frac{b^2}{r^{*2}}\right)}_{f)}\Big] + \underbrace{\frac{\nu}{4\gamma}\frac{1}{r^{*2}}\frac{d}{dt}(r^{*2})}_{g)}$$

where the terms may be identified with a) usual adiabatic damping, b) damping due to decrease in λ (increasing spring constant), c) radiation damping, d) coulomb multiple scattering, e) acceleration in externally applied field, f) radiation loss, and g) acceleration due to changing self inductance of beam (usually negligible). The first of (3) can be rewritten as

$$\frac{1}{2}\left(1-\frac{\nu}{4\gamma}\right)\frac{d}{dt}r^{*2} = -\frac{1}{2}\frac{eE}{\gamma mc}r^{*2} - \frac{2}{3}\frac{\gamma\nu^2 r_0 c}{K} + \frac{2Kr_0 cL}{\gamma} \tag{4}$$

where $r^{*2} = K\overline{b^2}$.

B. Immediate Conclusions from the Equations of Motion

Setting $\frac{d\gamma}{dt} = \frac{db}{dt} = 0$ one arrives at the Budker conditions

$$\gamma\nu = \text{constant} \cong 2 \text{ to } 6 \tag{5}$$

$$r^{*2}E = \text{constant} \cong (4 \times 10^{-3})^2 \text{ volts cm} . \tag{6}$$

These are remarkable; they relate the four variables with two independent relationships. If further one requires that for interest in this scheme as a guide field for high energy protons, the maximum self magnetic field must be at least 10^5 gauss, (2) and (3) lead to

$$\gamma r^* < 10^{-1} \tag{7}$$

$$E > 1.6 \times 10^{-3}\gamma^2 \tag{8}$$

Substituting typical values in (4) such as $\gamma \cong L \cong 30$, E = 1 v/cm,

$$\frac{1}{2}\frac{d}{dt}r^{*2} = -10^3 r^{*2} - \frac{5\times10^{-2}\nu^2}{K} + 17\times10^{-3}K .$$

Since K is about one or two, and ν is about 10^{-1}, the first term dominates down to about r* of 10^{-2}. (3) can be solved neglecting scattering, radiation, and self inductance terms to find the initial damping rate of the beam.

Thus $$r^{*2} = \frac{r_i^{*2}}{1+\frac{eEt}{\gamma mc}} + \frac{r_i^{*2}}{1+\frac{e\int E dt}{\gamma mc}} = b_i^2 \frac{\gamma_i}{\gamma} . \tag{9}$$

For constant E, r^* damps almost linear with time and for $E \simeq 1$ volt/cm, $\gamma \cong 30$ this gives a characteristic time t of 10^{-3} seconds, so for r^* to decrease by 10^3 requires 10^3 seconds! This result is pessimistic for several reasons, but it points up one of the constantly recurring problems - the long damping time of an intense electron beam before it reaches the self-pinched Budker state.

II. Problems not Included in the Equations of Motion

A. Stability

1. Stability of r^*, γ in equations of motion.

Judd and Courant rewrote (3) as

$$\frac{d}{dt} r^{*2} = -r^{*2} \frac{1}{\gamma}\frac{d\gamma}{dt} + \frac{4 r_0 c \nu}{\alpha_2 \gamma}\left[L - \frac{\alpha_2}{4}(\gamma\nu)^2\right]$$
$$\frac{d}{dt}\gamma = \frac{eE}{mc} - \frac{8}{3}\frac{(\gamma\nu)^2}{r^{*2}} r_0 c \alpha_2 . \tag{10}$$

These may be rewritten, using $x = x_0 + \Delta x$ and $\gamma = \gamma_0 + \Delta\gamma$ as

$$(\Delta\dot{x}) = -\frac{x_0}{\gamma_0}(\Delta\dot{\gamma}) - \frac{2c_1}{\gamma_0^2}\Delta\gamma$$
$$(\Delta\dot{\gamma}) = E\left[\frac{\Delta x}{x_0} - \frac{2\Delta\gamma}{\gamma_0}\right], \tag{11}$$

giving $$(\Delta\dot{x}) = -\frac{x_0}{\gamma_0} E \frac{\Delta x}{x_0} + 2\left(\frac{x_0 E + c_1}{\gamma_0^2}\right)\Delta\gamma \tag{12}$$

Ohkawa solved this by making a change of variables, writing a transformation from $\Delta x, \Delta\gamma$ to ξ, η and obtaining solutions

$$\xi = \xi_0 e^{\lambda_1 t} \quad \text{and} \quad \eta = \eta_0 e^{\lambda_2 t}$$

where

$$\lambda_{1,2} = -\frac{3}{2}\frac{E}{\gamma_0} \pm \sqrt{\frac{9}{4}\frac{E^2}{\gamma_0^2} - \frac{2Ec_1}{x_0\gamma_0}} \,. \tag{13}$$

Thus for typical values the solution executes damped oscillations with a Q of about 3 and characteristic times of milliseconds. The Budker beam is consequently radially and enegetically stable for small perturbations.

2. Longitudinal Stability

Ohkawa raised the question of whether the Budker beam is longitudinally stable. This question has not been answered.

B. Behavior of Positive Ions

1. Loss from Beam Initially due to Acceleration

When self field effects are negligible, positive ions subject to betatron acceleration may be accelerated out of the beam region. For ions to remain trapped,

$$\frac{Mv_z^2}{R} < eE + \frac{e}{c} v_z B_g \quad \text{to prevent escape from outside}$$

$$\frac{Mv_z^2}{R} + eE > \frac{e}{c} v_z B_g \quad \text{to prevent escape from inside} \tag{14}$$

where M is the ion mass, v_z is the ion z velocity, R is the major radius of the orbit, B_g is the guide field, and E is the electric field toward the beam center due to the excess of electrons over ions. That positive ions are rapidly accelerated can be seen by considering a betatron field of 1 volt/cm and finding the time for the ions to reach 10^{10} cm/sec. For protons, assuming classical dynamics, the time required is 10 milliseconds. Using $v = aT$, the time T can be expressed in terms of numbers of protons N_p and electrons N_e per unit length of beam corresponding to two criteria suggested by (14):

$$\frac{e}{c} v_z B_g = eE \tag{15}$$

$$\frac{M v_z^2}{R} = eE \tag{16}$$

From (15),

$$\frac{e v_z B_g}{c} = 2\frac{e^2 (N_e - N_p)}{r^*},$$

therefore

$$T = \frac{2(N_e - N_p) M c}{B_g E_e r^*} \tag{17}$$

The time between ionizations of protons by the beam electrons is

$$t = \frac{\Lambda}{c N_e} \tag{18}$$

where Λ is about 10^8 cm for relativistic electrons in a vacuum of 10^{-6} mm. The equilibrium number of protons will then be

$$N_p = \frac{T}{t} = \frac{N_e (N_e - N_p)\, 2Mc^2}{B_g E_\ell r^* \Lambda} \tag{19}$$

where E_ℓ is the longitudinal (betatron) field. Simplifying, we have

$$N_p = \frac{N_e^2}{N_e + 7 \times 10^{10}} \tag{20}$$

for $\Lambda = 10^8$ cm, $Mc^2 = 1.6 \times 10^{-3}$ erg, $E_\ell = 3 \times 10^{-3}$ stat $\frac{\text{volts}}{\text{cm}}$ (=1 v/cm), $r^* = 1$ cm, and $B_g = 500$ gausses. This gives $N_p = .8\, N_e$ for $N_e = 4 \times 10^{11}$/cm (corresponding to $\nu = 0.1$).

From (16) by a similar method,

$$\frac{N_p^2}{N_e^2} = \frac{2c^2 R M}{\Lambda^2 E^2 r^*} (N_e - N_p), \tag{21}$$

or,

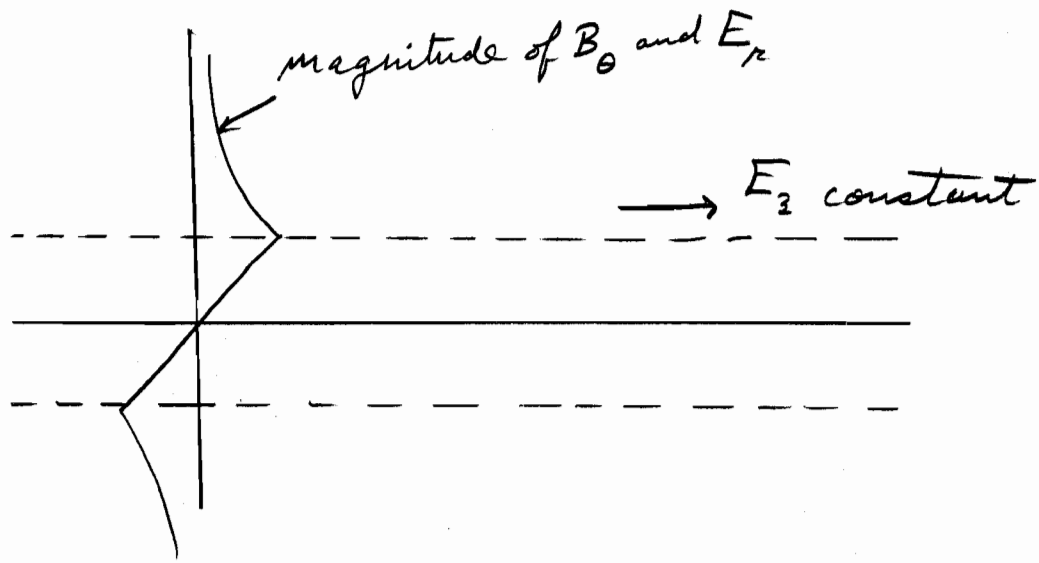
$$N_p^2 + 3.2 \times 10^{-12} N_e^2 (N_p - N_e) = 0 \tag{22}$$

For the same values as above with also $R = 100$ cm, $N_p \cong 1/2\, N_e$.

This criterion, therefore is not a serious limitation since positive ions almost keep the beam neutralized for large r*; when they are more vital, r* is small.

2. Ion Trajectories in the Self Field

As the beam pinches down and the self magnetic field becomes important the ions are subjected to a complex field as represented on the following page:



It appears that the action of these crossed fields will be to suck ions into the center of the beam where they will find themselves accelerated by the betatron field E_z . This is in marked contradiction to dePackh who believes that they will be lost rapidly from the beam.

3. Large Angle Single Scattering of Electrons

This appears a very serious loss mechanism when one recalls that, at r* of 4×10^{-3} cm, there should be about 4×10^{11} protons/cm giving an ion density of $8 \times 10^{15}/\text{cm}^3$. This corresponds to a vacuum of only 0.2mm Hg. Smith has estimated the lifetime of an electron against large angle single scattering to be

$$\tau = \frac{\gamma r^{*2}}{2 c r_0} \tag{23}$$

which gives about 30 milliseconds for the pinched down beam. If additional positive ions are present, as in 2, above τ will be further reduced. This loss is a major reason for the concern about long damping times.

C. Electron Resonances

As the electrons damp in their self field, the number of electron wavelengths per revolution, Q, will increase from order unity (no self field effects) to a few thousand (for typical Budker values). Since the electron center of gravity follows a single particle trajectory in the external field small oscillations about it will be subject to the same integral and half-integral resonances due to imperfections of the guide field as a conventional accelerator. Ohkawa formulated this problem for integral resonances, considering the beam radius r* limited to no less than the closed orbit oscillation due to the bump for simplicity. Since such resonances would be encountered less frequently in early stages of the pinch, they would be crossed more slowly then and therefore are more likely to be dangerous. Since Q is a function of r*, a resonance may limit r* to some value just larger than r* of that resonance and prevent the beam from ever pinching smaller. It seems fairly certain that the least effect of resonances would be to increase the damping time of the beam. Ohkawa's treatment may be summarized as follows: A and Φ are the oscillation amplitude and phase respectively. A bump due to a field error ΔH over length ℓ may be represented as

$$\epsilon = \frac{\ell \Delta H}{\gamma m c \beta} = \frac{\epsilon_0}{\gamma} .$$

$$\Delta A_j = \pi \epsilon \cos \Phi_j$$

$$\Delta \Phi_j = \Delta \Phi_{j-1} + \frac{\pi \epsilon \sin \Phi_1}{2A_1} + 2(Q-M) \cong \Delta \Phi_{j-1} + 2\pi(Q-M).$$

Therefore

$$\frac{dA}{dt} = \frac{\omega \lambda}{2\pi} \epsilon \cos\Phi \tag{24}$$

$$\frac{d\Phi}{dt} = \omega(Q-M)$$

Using

$$\lambda^2 = \frac{r^{*2}\gamma}{2\nu}$$

$$Q = R/\lambda \tag{25}$$

$$K^2 A^2 = r^{*2}$$

(24) becomes

$$\frac{dA}{dt} = \frac{\omega}{2\pi} KA \sqrt{\frac{\gamma}{2\nu}} \frac{\epsilon_0}{\gamma} \cos\Phi$$

$$\frac{d\Phi}{dt} = \omega \left[\frac{R}{KA}\sqrt{\frac{2\nu}{\gamma}} - M \right] \tag{26}$$

These can be added to the Budker Equations (3) and the results simplified assuming γ almost constant and radiation and scattering terms unimportant for simplicity (except insofar as they determined (25)). Thus (3) and (26) become

$$\frac{dA}{dt} \simeq \left[-\frac{eE}{\gamma mc} + \frac{\omega}{2\pi} K\sqrt{\frac{\gamma}{2\nu}} \frac{\epsilon_0}{\gamma} \cos\Phi \right] A$$

$$\frac{d\Phi}{dt} = \omega \left[\frac{R}{KA}\sqrt{\frac{2\nu}{\gamma}} - M \right]. \tag{27}$$

These may be derived from a hamiltonian; setting $W = -\ln A$,

$$H = \frac{\omega}{2\pi} K\sqrt{\frac{\gamma}{2\nu}} \frac{\epsilon_0}{\gamma} \sin\Phi - \frac{eE}{\gamma mc}\Phi + \frac{\omega}{2\pi}\left[\frac{R}{K}\sqrt{\frac{2\nu}{\gamma}}\, e^{W} - MW \right], \tag{28}$$

or, letting $W = W_0 + \Delta W$ and defining W_0 by

$$e^{W_0} \cdot \frac{R}{K}\sqrt{\frac{2\nu}{\gamma}} = M$$

we have

$$H = \frac{\omega}{2\pi} K\sqrt{\frac{\gamma}{2\nu}} \frac{\epsilon_0}{\gamma} \sin\Phi - \frac{eE}{\gamma mc}\Phi + \omega\left[M(1-W_0) + \frac{M}{2}\Delta W^2 \right] \tag{29}$$

which is similar to the hamiltonian for synchrotron phase oscillations. Passing through resonances corresponds to buckets of zero area in this case; finite buckets correspond to particles trapped to a range of amplitudes by a resonance.

D. Rf Acceleration of Electrons

1. Electrostatic Potential to be Overcome

To supply the longitudinal electric field required to accelerate the electrons, pinch them, and maintain the pinched beam while the protons were accelerated would demand a sizable betatron core. It was therefore attractive to consider rf acceleration of the electrons. Since the electrons are very numerous, bunching them (while leaving the positive ions uniformly distributed) could require high coulomb potentials, and consequently large cavity voltages. The potential required can be calculated to be of order

$$V \cong \frac{q}{\gamma^2 r} \tag{30}$$

for electrons of charge q. The charge of each electron bunch will be

$$q = \frac{\nu}{r_0}\lambda \tag{31}$$

and r in (30) will be of order $\lambda/2$ at least. Therefore

$$V \cong \frac{2\nu e}{\gamma^2 r_0} \quad \text{statvolts}, \tag{32}$$

For $\nu = .1$, this is about 100 kilovolts at low γ, decreasing to only a hundred volts or so for typical final energies.

Thus rf might be difficult if the entire intense beam were to be

accelerated in this way from injection, although at higher γ this criterion does not appear a serious one.

2. Positive Ion Escape Time

If the relativistic, pinched beam is bunched by rf, the positive ions will repel each other between electron bunches. A limitation on the rf wavelength should then be that it be short enough so that r* does not grow appreciably in one rf period. The ions feel a radial field

$$E_r = \frac{N_p e}{2\pi r^*}\left(\frac{r}{r^*}\right). \tag{33}$$

For each particle r/r^* will be constant. Consider the particles of $r \cong r^*$; then

$$E_r = \frac{N_p e}{2\pi r}, \qquad \ddot{r} = \left[\frac{N_p e^2}{2\pi M}\right]\frac{1}{r} = \frac{\kappa}{r}. \tag{34}$$

A first integral, letting $r/r_i = e^{u^2}$, is

$$\frac{\kappa^{\frac{1}{2}} t}{r_0} = 2\int_0^a e^{u^2} du. \tag{35}$$

For $a = 1$ (corresponding to a growth of e)

$$t \cong \frac{2r_i\,(1.5)}{\kappa^{1/2}} \tag{36}$$

This leads to a time $t \cong 8 \times 10^{-10}$ seconds for $r \cong 4 \times 10^{-3}$ cm and $N_p = 10^{12}$/cm. Thus the rf should be 1000 Mc or higher frequency; even this somewhat expands the beam.

3. Bending of Accelerated Protons by Electron Bunches

If the electrons are bunched, protons being accelerated will be bent impulsively as they pass the electron groups. While they may still find their way around the machine, they will probably have a smaller phase space available, and may not have closed orbits for the same ν and r* and the same proton energy as in the unbunched beam. A reasonable criterion for avoiding the worst problems is that the proton orbit (a Polygon) not deviate more than r* from the electron path (a circle). Thus

$$\frac{R}{\lambda/2} > \frac{\lambda/2}{r^*}$$

or

$$\lambda^2 < 4Rr^* \qquad (37)$$

For $R = 100$ cm, $r^* = 4 \times 10^{-3}$ cm, $\lambda < 1.2$ cm or a frequency of 25,000 Mc. This is not a convenient operating frequency. One might therefore conclude that although rf might be used in lieu of betatron acceleration, it must be carefully considered, and unless of a very high frequency may severely impair the properties of the Budker beam.

E. Damping in an External Magnetic Field

Damping of the amplitude of the beam due to radiation in the external guide field is a small effect for most sets of parameters considered. Although it has not been studied in detail, it should be given by a relationship such as

$$b \propto e^{-\frac{1}{2}\int \frac{W}{E} dt}$$

where W is the energy radiated per unit time and E the electron total energy. Typical damping times for γ of order 20 are seconds or tens of seconds, therefore too long to be helpful. It is important to note, however, that in some schemes this damping leads to special results (such as its use in the Bennett scheme).

F. Damping due to Positive Ion Accumulation

Equation (3) assumes $\nu_i = \nu_e$. If ν_i is initially zero and grows to ν_e, the λ of the electrons will decrease due to cancellation of the electric repulsion. This damping may reduce the total damping time somewhat. Judd was intending to look at this further.

G. Proton Phase Space

Laslett has looked into the behavior of protons in the guide field of the electrons. They execute non-linear oscillations and must pass through many resonances during the course of acceleration. A more fundamental limitation may be the phase space available to them: as usually calculated, the maximum electron self field is available to the protons in a zero phase space orbit. Adopting one milliradian-centimeter as the desirable proton injection phase space at 50 Mev and assuming adiabatic damping, Laslett found the phase space available to the protons shrank to the value resulting from this at an energy of a half or third of the maximum proton energy calculated for typical Budker parameters.

III. Budker-like Schemes

A. dePackh

dePackh proposes using higher energy electrons ($\gamma \gtrsim 200$) and thus lower currents; neutralizing the beam partially only with the accelerated protons. This system, perhaps modified by concepts of positive ion behavior (he probably couldn't keep them out of the beam) is subject in general to the same problems as Budker's systems. Although the higher energy would reduce single scattering problems, it would require a bigger betatron core, etc., for a given proton energy. This system was not discussed extensively.

B. Bennett

Bennett's accumulation of electrons in a D.C. magnet is essentially an experimental device and not intended to be a guide field for protons. As such it is interesting, although it is doubtful whether it would accumulate the electrons from a linac that he advertises (for example, he neglects the energy spread of the linac; further his "gripper" would require megajoules of energy). In his scheme electrons feed in and out of the steady state high intensity current in a simple way only if self fields are unimportant. As self fields become important not only the electrons <u>in</u> the beam but those approaching it (from larger radii) find themselves moved onto resonances.

C. Finkelstein

Ohkawa pointed out that Finkelstein's ultra-high field, fast betatron might work only if H has a maximum in the machine center (so that A has a minimum on a desired equilibrium orbit). Further he suggests that it might inject from a phase in which it is run as a conventional magnetron, where of order 100 amperes/cm^2 of electrons of a few kilovolts fill the useful-field region. Most of the group felt that it was a more interesting device in itself than a practical way of achieving Budker's objectives.

D. Courant

Courant suggested a cycle of operation of a Budker-like betatron which at least had damping times of only 2.5 seconds. In this proposal electrons would be betatron accelerated to, say, 20 Mev rapidly and then held there, supplying the radiation losses until it pinched down. Then the core voltage would relax allowing the beam to drop to 10 Mev, for a desirable γ r* and smaller radiation loss during the proton acceleration time.

E. F.F.A.G.

It appears to the author that the proposed M.U.R.A. 50 Mev electron accelerator will be in a good position to study some of these questions. In fact the first limitation on beam current that can be accumulated by stacking appears to be due to detuning on to a resonance from self field focussing. A beam of 100 amperes stacked at 50 Mev

would represent a $\gamma\nu$ of 0.5, which approaches Budker's value.

IV. Conclusions

The general atmosphere toward the end of the conference was one of discouragement. The practical realization of Budker's objectives seems fraught with many pitfalls, and at this point noone sees how they are to be overcome. It still seems that the easiest way of achieving very high center of mass energies is with FFAG synchroclash, although Ohkawa suggests that it may be appropriate to consider Budker's machine now as in the same state as the Thomas cyclotron in 1938; it may yet be the machine of the future. However, it seems that real breakthroughs will be required before its realization.