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Sergey Shewchuck

February 10, 1953

Berkeley, California

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I. Cosmotron and High Energy Accelerators Discussed at Brookhaven Accelerator Conference. E. Lofgren.

A number of slides were shown illustrating some of the construction features of the cosmotron and the results of numerous tests on the performance characteristics of the magnetic field and the beam. The cosmotron has a C-shaped magnet with a 9.5 inch gap but with a usable net gap of 6.5 inches and a width of about two feet. Separate pole face coils are included to correct the magnet field and to provide a dB/dt signal to control the frequency. The particles are injected by a 3.5 Mev Van de Graaff with a pulsed rating of about 1 ma. It runs continuously at about 2 ma. for voltage regulation. An unusual technique has been devised at Brookhaven by the use of "chopper plates" to get single pulses for the purpose of observing the beam around the machine. It is possible to make a detailed plot of the first six or seven orbits as various injection parameters are varied. Detailed studies of the magnetic field have also been made. An unexplained phenomenon is the odd shape of the remanent magnetic field as a function of the pulse length. As the length of the pulse is increased, the remanent magnet field decreases; if the magnet is shorted out, the curve for the field becomes flat.

For protons the maximum beam is 2.3 Bev with 3×10^9 protons per pulse.

A rough estimate of the cost for the high energy strong focusing machines was given by Livingston as about $200,000 per Bev. The design dimensions for various proposed high energy accelerators taking advantage of the strong focussing principle were listed as follows for groups A, B and C according to the size of the machines:

	Designed by Livingston		By European Group
	A	B	C
Energy	10 Bev	100	30
Field	14 kg	14	10
Radius	85 ft	800	100 m
Gap	1.5 cm	2 in	5 cm
N	90	480	350
Mag length	6 ft	13	1.8m
Straight section	1.2 ft	3	0.5m 1.0m
P_{ave}	168 kw	1800	
f	15 Mc	20	
Injection	2 Mev	12	

II. Problems in Very High Energy Accelerator Theory Discussed at Brookhaven Conference. D. L. Judd.

Prof. R. Serber, chairman of the session on accelerator theory at the conference mentioned that most novel proposals for accelerators go through three descriptive stages: first, strong initial enthusiasm, great plans, everything seems easy; second, very serious doubts raised because of effects not thought of at first, "heavy gloom"; and third, patient plodding to resolve the difficulties, task finally seems possible with very careful technology but it is no longer easy and simple. This sequence applies in the case of the multi-Bev proton synchrotrons with alternating gradient focussing as follows:

Stage 1. Original Brookhaven proposal. Designs started:

At Brookhaven	30 Bev and 100 Bev
At M. I. T.	10 Bev
At Princeton	10 Bev
At European Lab.	30 Bev

Stage 2. Independent discovery at Harwell, Cornell and Brookhaven of an unfortunate resonance effect.

Stage 3. Two approaches to solving the resonance problem:

a. Brookhaven: separate guide and focussing fields.

b. Another idea: shake n value around.

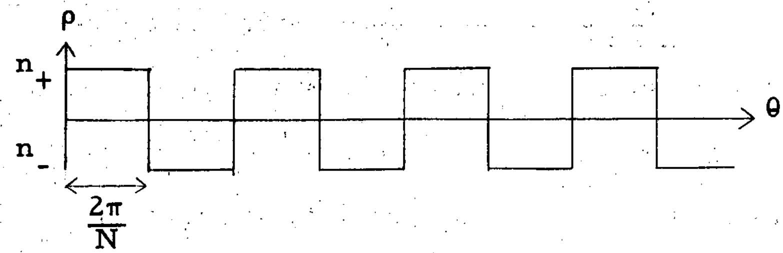
In order to discuss the resonant effect qualitatively, first, a review of the basic idea of alternating gradient focussing is presented: (See UCRL-2055).

Radial motion: $$\frac{d^2\rho}{d\theta^2} + (1-n)\,\rho \simeq 0; \quad \rho = r - R$$

Vertical motion: $$\frac{d^2 z}{d\theta^2} + n\,z \simeq 0\,.$$

The simplest case would be one with no straight sections and the sections being symmetrical, thus:

n(θ)



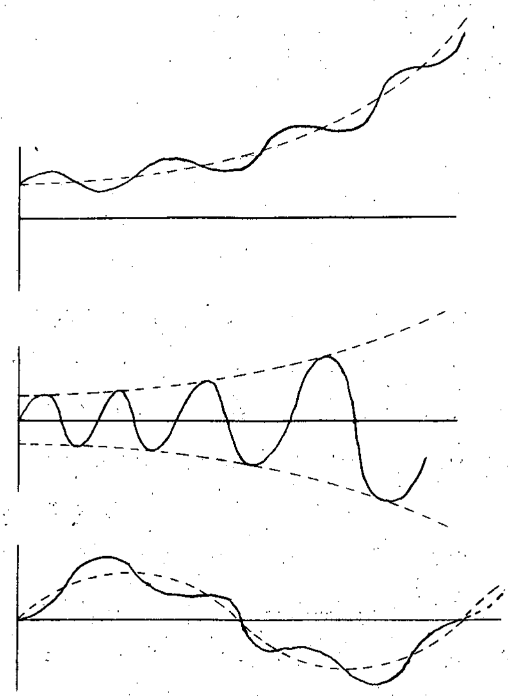
For $|n| \gg 1$, ∴ neglect the term "1" in the ρ equation above. Then both equations of motion become identical differing only in sign of n(θ).

Solution of the differential equations for the case of exact periodicity of n(θ);

$$\left.\begin{aligned} \rho &= A\, e^{i\nu_r\theta} p(\theta) + B\, e^{-i\nu_r\theta} q(\theta)\ ; \\ z &= C\, e^{i\nu_z\theta} p(\theta) + D\, e^{-i\nu_z\theta} q(\theta)\ ; \end{aligned}\right\} \quad \text{we wish } \nu \text{ to be real.}$$

Suppose $n_+ = n_- = n$, then $\nu_r = \nu_z$ and one computes $\cos 2\pi\nu$ readily from recurrence relations:

$$\cos 2\pi\nu = \cos \frac{2\pi\sqrt{n}}{N} \quad \cosh \frac{2\pi\sqrt{n}}{N}$$



The corresponding formulas for $n_+ \neq -n_-$ are only slightly more complicated. One must have $-1 < \cos 2\pi\nu < +1$ for stability. If $\cos 2\pi\nu > +1$, then there is an inadequate restoring force; the motion diverges exponentially as shown at left.

If $\cos 2\pi\nu < 1$, then there is "too much" restoring force; the motion oscillates with exponentially growing amplitude as shown at left.

If $\cos 2\pi\nu \simeq 0$, then $\nu = 1/4$, and the "best"* stable motion results. There will then be four full waves of fast oscillations per one slow oscillation as shown at left.

* Note: This choice is not the best from all points of view but it is surely quite close and greatly simplifies the presentation.

In order to achieve $\cos 2\pi\nu = 0$, one has $N = 4\sqrt{n}$; and, the wavelength of a slow oscillation is

$$\lambda = 8 \cdot \frac{2\pi}{N} \cdot R; \quad \text{in general,} \quad \lambda = \frac{2}{\nu} \cdot \frac{2\pi}{N} \cdot R$$

The ratio of circumference to wavelength of a slow oscillation is

$$\frac{2\pi R}{16\pi R/N} = \frac{N}{8} = \frac{\sqrt{n}}{2}; \quad \text{in general} \quad \frac{2\pi R}{\lambda} = \frac{\nu N}{2}$$

[A reasonable value of n is of the order 3600; then

$$N = 4 \times 60 = 240; \qquad \frac{2\pi R}{\lambda} = 30.]$$

If the two values of n [n_+ and n_-] are not equal, the radial and vertical oscillations obey different equations and one can draw a plot of the stability region as a function of the two n values, as shown in Figure 1.

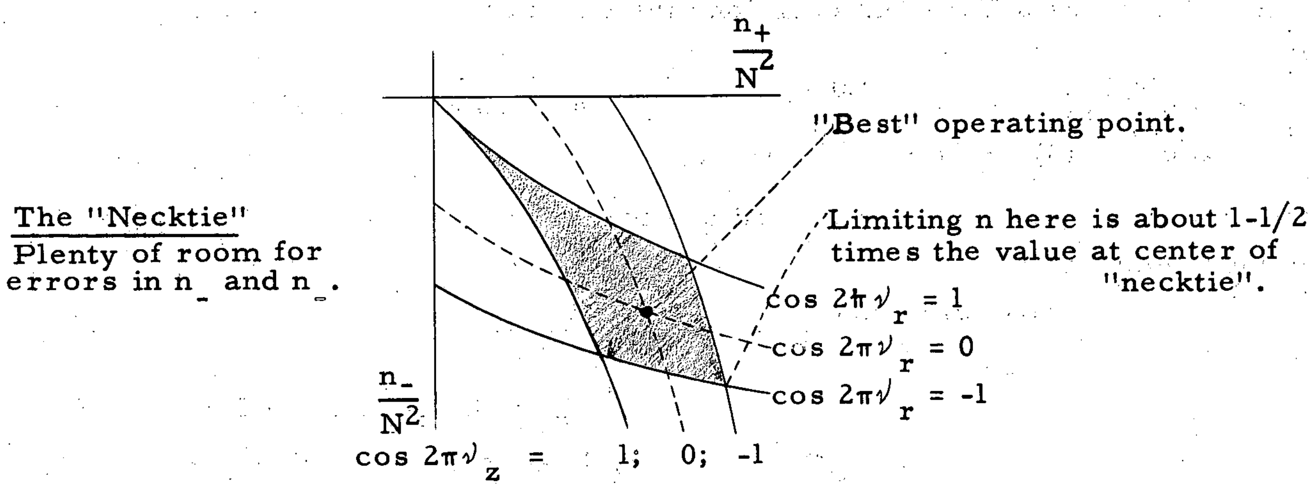


Figure 1

For values of n_+ and n_- at points other than the center of the "necktie" one will no longer have exactly N/8 wavelengths of slow oscillation per circumference, but rather $\nu N/2$; where $\nu = 1/2\pi \cos^{-1} x$, x being an expression for the more general formula giving $\cos 2\pi\nu$ as a function of n_+ and n_-. [Except along the diagonal through the center of the "necktie", the values of ν_r and ν_z will be different of course.] For equal increments of ν the increments of x will vary depending on the value of x. We wish to consider those equal increments in ν which result in a change of unity in the number of slow wavelengths per circumference; i.e.,

$$\Delta \cdot \left(\frac{2R}{\lambda}\right) = 1.$$

Developement of 200μ G-5

1. Presoak @5°C for 1.5 hr. (Water)

2. Developer soak @5°C for 1.5 hr.

3. Warm develope @20-27°C for 0.5 hr. 22°C

4. Short stop @5°C for 1.5 hr.

5. Fixing @5°C for 15 hrs.
6. WASH
7. GLYCERINE SOAK (5%)

Developer: 1000 ccs water, distilled
35 gms Boric Acid
15 gms sod. sulfite
8 ccs Pot. Bromide (10%)
4.5 gms Amidol

Short Stop:
0.5% Acetic Acid

Fixer:
Kodak Acid Hardening Fixer

Then since

$$\frac{2\pi R}{\lambda} = \frac{N}{4\pi} \cos^{-1} x,$$

we have

$$\Delta x = \frac{4\pi \sqrt{1-x^2}}{N}$$

showing that the spacing of lines corresponding to integer values of $(2\pi R/\lambda)$ is greatest near the boundaries of the "necktie" and least near its center. The resulting pattern of "integral lines" is shown in Figure 2. The total number of lines either way in N/4.

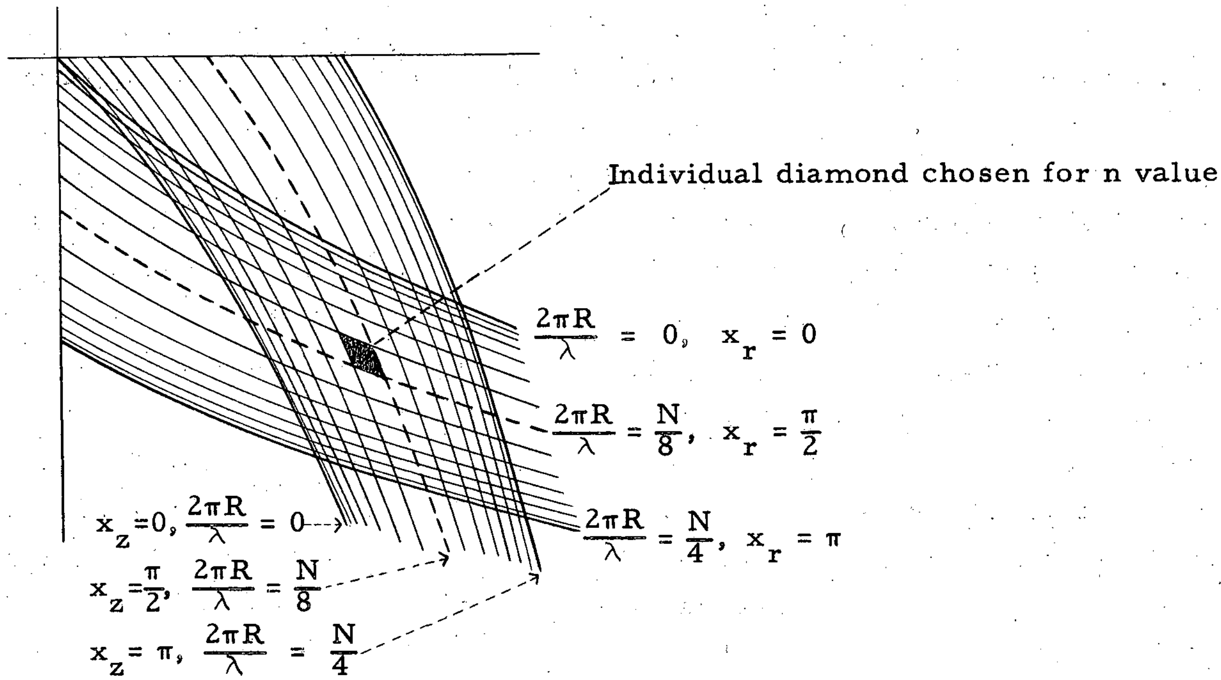


Figure 2

Thus, what appeared as a "necktie" from a distance turns out on closer inspection to have a detailed pattern of diamonds rather like a lead-glass window with the panes becoming smaller near the edges.

Why are we interested in these "integral" lines? Along a line we have an integral number of slow oscillations per turn, so that the motion precisely repeats on each turn. The effect of any small error in field at any one point will increase linearly with the number of turns.

Suppose that one of the N sections of the magnet is out of line by a distance δ. A detailed calculation for a particular design shows that the amplitude of oscillation will increase in one turn by about 5δ. Thus, if $\delta = 10$ mils, only 20 turns will be required for the amplitude to grow to an inch, which is the available clearance in this design. For a 30 Bev machine ($R = 10^4$ cm), 20 turns requires $40\pi R/c$ sec $= 12 \times 10^5/3 \times 10^{10} = 40\mu$ sec. (One turn takes 2μ sec.). Thus it appears that one must stay within a single diamond on the "necktie" and keep away from its boundaries. A more accurate analysis shows that this amounts to about 1.0 percent precision required of the n values. This will be difficult at the start of the cycle (because of eddy current effects) and at the end (due to saturation of the iron).

A possible way in which to meet this requirement is to provide separate alternate regions for guiding and for focussing. By providing a separate current supply to the focussing sections, which could be varied independently, one might be able to effect the necessary trimming adjustments to hold the n values well within an individual diamond of the "necktie", as shown in Figure 2. Precise control of the rate of rise of current in a large magnet is very difficult to achieve because of the "current lethargy" associated with large inductances. Perhaps the bulk of the focussing could be combined with the guide field, and smaller trimming lenses could be used to achieve the needed control.

Another approach is to vary the frequencies of oscillation so rapidly as to smear out the representative point over a large number of diamonds. The smearing would have to be at a rate rapid with respect to 1/20 of the rotation frequency, and it could probably only be accomplished with electric fields. The rate of smearing required might also resonate with the rotation frequency and lead to other troubles.

In any event, one concludes that an originally easy problem has become quite difficult, with about 100 times more precision needed in a time-varying magnetic field than had originally appeared necessary.

Another topic discussed at the meeting by Prof. Milt White of Princeton was the problem of more efficient types of electric accelerating fields for such accelerators. The average space rate of gain of energy is

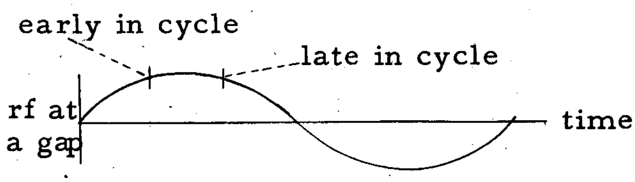
$$\Delta E_1/\Delta x = (E_{final}/T) \times (1/V) \sim \frac{3 \times 10^{10} \text{ volts}}{1 \text{ sec} \times 3 \times 10^{10} \text{ cm/sec}} \sim 1 \text{ volt/cm}$$

Thus there is really no need to have high voltages present in the system if energy can be supplied reasonably continuously and reasonably efficiently. The Princeton group is attempting to study the problem in general terms from this point of view. Clearly one is aiming at something approaching a traveling wave along the accelerating tube, which can be approximated by a very large number of accelerating gaps. No concrete proposal has yet resulted from their study.

The use of rather high harmonics of the rotation frequency seems called for in such accelerators. This results in having many bunches of particles around the machine. The amplitude of radial motion associated with a given amplitude of phase oscillation is much less than with use of the fundamental frequency, varying inversely as the square root of the harmonic order.

In an earlier talk (UCRL-2055) there was mentioned the problem arising from the reversal of sign of the phase oscillation equilibrium point at a certain stage of the acceleration, thus:

$$\frac{\Delta T}{T} = \left[\frac{\sim 5}{|n|} - \left(\frac{mc^2}{E} \right)^2 \right] \frac{\Delta p}{p}$$



This can qualitatively be described as follows: at low energies, a late particle must gain energy to catch up with its bunch; at high energies, an early particle must gain energy since it is early because of having been moving with v=c on too small a circle. At the transition point there is no phase stability and the particles will drift in phase for a considerable time in this neighborhood and may not re-enter the new phase stable region, hence being lost.

A detailed study of this problem has been made by Dr. Lloyd Smith of UCRL, and similar conclusions have been reached by the Brookhaven group. One is saved by the fact that the transition point occurs where the mass of an equivalent oscillator becomes infinite rather than where the spring constant vanishes.

$$\frac{d}{dt} \left(M \frac{d\phi}{dt} \right) + k \, (\sin \phi - \sin \phi_s) = 0$$

$$m \longrightarrow \infty \text{ at } t = t_{trans}$$

$$k = \text{const.} \qquad E_{trans} \sim mc^2 \sqrt{\frac{5}{n}}$$

The result is that the phase velocity vanishes at the transition point. A change in phase of the rf by twice ϕ_s, the synchronous phase angle, can easily be effected during the relatively long time the phase motion is thus halted by slightly shifting the frequency of the rf for a definite number of cycles. If the rf phase can be "locked into" the particle phase, the transition is even easier to make.

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