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THE ANL EXPERIMENT FOR A WAKE FIELD
ACCELERATOR USING AN RF STRUCTURE

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Summary

Experiments are planned at ANL to study a new accelerating concept that has been developed during the last few years named the WAKEATRON.¹ This requires a very special, simple configuration of the beams and of the rf structure involved. It is a unique idea which, to our knowledge, is being studied only at ANL. Therefore we will first explain what are the basic concepts. Like most proposed experimental work, this too was initiated by a considerable amount of computational work, both analytical and numerical, on which we would like to report. We will then describe details of the planned experiments we will carry out at ANL to check some of our predictions for this concept. These experiments concentrate on beam and cavity geometry applicable to the Wakeatron. We will not report in this paper on the use of this device to accelerate electrons to very large energies over relatively short distances. We simply refer to a recent paper where the application to an electron-positron linear collider in the TeV range is demonstrated.¹

THE WAKEATRON CONCEPTS

In Fig. 1 we show the general concept of the WAKEATRON. It consists of a sequence of cylindrical rf cavities or cells. The gap, or cell length is 2 mm, the outer radius is 4 mm and the inner diameter is 1 mm. This looks very much like a conventional linac. The parameters of the geometry have been adjusted so that the fundamental mode, the lowest resonating frequency mode, corresponds to a free space wavelength of 1 cm, or 30 GHz. This is ten times the SLAC frequency and very similar to what many people are considering for an advanced linear collider.

A question is how to power this linac. The Wakeatron proposes to use a very short, intense proton bunch with an initial energy of 100 GeV. Assuming a longitudinal gaussian particle distribution, the rms bunch length is 3 mm. We show for comparison in Fig. 1 the proton bunch, the driver as we like to say, spanning over a length of $\pm$ sigma. The driver, which travels along the axis of the rf structure (i.e. this is a colinear accelerator), leaves behind a wake field of some magnitude which depends linearly on the number of protons N in the bunch. A test particle, either an electron or a positron, also moving along the axis of the structure, would therefore be accelerated, or decelerated, by an amount which depends on the distance from the driver. If we assume 3×10^{11} protons in the bunch, we estimate an accelerating gradient of 80 MeV/m, provided the test particle follows the driver at the proper distance. We will show how this estimate was derived. The expected gradient is of reasonable interest; a fact which contributes to the justification of the proposed experiment at ANL. Moreover, the so called transformer

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ratio for this geometry is 10, that is, with a 100 GeV proton bunch, one should be able to accelerate electrons to 1 TeV. We will show also how this transformer ratio was estimated.

There are two reasons to suggest the use of a proton bunch as a driver. We will describe one of the reasons below. The second, which claims that the use of protons makes the device cost effective and power efficient, has been discussed in a previous paper.¹

We should point out that before this work was done a paper² had already appeared in 1978 in which the idea of using protons to drive an rf structure was discussed. But even before that the idea was already acknowledged in the accelerator community and referred to as the "Proton Klystron". Indeed Fig. 1 is quite suggestive of the mode of functioning of a conventional Klystron. We call the present concept a Wakeatron because many of the physical ingredients are now quite different and because it is a much more thoroughly developed concept.

ANALYSIS OF THE RF STRUCTURE

The geometry we have been investigating is shown in Fig. 1. There are five major parameters: the dimensions of the cavity a , b and g , the driver rms bunch length σ and the distance z of the test particle from the driver. The cavities are assumed of good conductive material at room temperature. A particle travelling along the axis of the structure excites all the cavity modes. The longitudinal wake potential, which we can define as the rate of acceleration per unit of length, can be written as

$$U(z) = \sum_n w_n \cos k_n z \quad (1)$$

which is clearly given by the sum of all modes. The generic mode is described by the amplitude w_n and the wave number k_n . We shall denote with w_0 and k_0 the fundamental mode. For a driver bunch with longitudinal distribution $f(z)$, normalized to unity, and N particles, the wake potential for a particle at location z is

$$U(z) = N \sum_n w_n \int_z^\infty f(z') \cos k_n (z' - z) dz' \quad (2)$$

In particular, for a gaussian distribution with rms length σ and a for a particle which follows at a distance z much larger than σ from the center of the driver

$$U(z) = N \sum_n w_n \exp(-k_n^2 \sigma^2 / 2) \cos k_n z \quad (3)$$

We can also estimate the average energy loss suffered by the particles in the driver bunch

$$\bar{U} = (N/2) \sum_n w_n \exp(-k_n^2 \sigma^2 / 2) \quad (4)$$

This should not be confused with the maximum gradient within the bunch, a frequently used definition in wakefield accelerators driven by electron bunches.³ We calculate the average loss over the whole bunch for the case of a proton beam driver for reasons that will be clear later. For the same reasons, we define the transformer ratio as the accelerating gradient of a following test particle divided by the average energy loss in the driver bunch.

$$r = U(z) / \bar{U} \quad (5)$$

$$= 2 \frac{\sum_n w_n e^{-k_n^2 \sigma^2 / 2} \cos k_n z}{\sum_n w_n e^{-k_n^2 \sigma^2 / 2}}$$

which is clearly a function of z .

In the limit of zero bunch length Eq. (5) becomes

$$r = 2 \frac{\sum_n w_n \cos k_n z}{\sum_n w_n} \quad (6)$$

As one can see, in this case, the transformer ratio can never exceed a factor of 2.

If the bunch length is large enough, only the fundamental mode can be retained in the summations above and the wake potential for a following particle ($z \gg \sigma$) is simply

$$U(z) = N w_0 \exp(-k_0^2 \sigma^2 / 2) \cos k_0 z \quad (7)$$

From this we can derive the maximum gradient

$$U_{\max} = N w_0 \exp(-k_0^2 \sigma^2 / 2) \quad (8)$$

From Eq. (4), the average energy loss rate is

$$\bar{U} = (N/2) w_0 \exp(-k_0^2 \sigma^2 / 2) \quad (9)$$

The transformer ratio for this case now is

$$r = U_{\max} / \bar{U}$$

$$= 2 \exp(k_0^2 \sigma^2 / 2) \quad (10)$$

This can now be larger than 2. This is better demonstrated in Fig. 2, where we show the spectrum of the current associated with a bunch of rms length σ and we show some mode frequencies which could be excited in the rf cavities. By choosing the bunch length properly only one mode, the fundamental, is important and all the others will give negligible contributions. Obviously even the fundamental contribution will be proportional to the amount of the driving current at the wave number k_0 .

For our concept, it is therefore important to estimate the location and the strength of the resonating modes of the rf structure. It is also important to justify the assumption of the average energy loss in the driver when estimating the transformer ratio. These issues are treated below.

CALCULATION OF THE RESONATING MODES

The calculation of the resonating modes in the rf structure of fig. 1 is not an easy task. Some work has been done with analytical methods; see for instance the paper of Chao and Morton.⁴ It is possible to derive an expression for the wake potential generated by a point charge Ne travelling along the longitudinal axis of a pill-box cavity of length g and outer radius b with no inner opening ($a = 0$). This expression is given by a double summation

$$U(z) = \sum_{n,p} w_{np} \cos k_{np} z \quad (11)$$

where z is the distance from the point charge,

$$k_{np}^2 = (j_n/b)^2 + (\pi p/g)^2 \quad (12)$$

and j_n is the n -th zero of the Bessel function, that is $J_0(j_n) = 0$. The amplitude for each mode is

$$w_{np} = \frac{Ne^2(4\delta_p)}{\pi\epsilon_0 g^2} \frac{1 - (-1)^p \cos k_{np} g}{[j_n J_1(j_n)]^2} \quad (13)$$

where $\delta_0 = 1/2$ and $\delta_p = 1$ for $p = 0$.

We have defined $U(z)$ as the energy gain per unit length of a particle with charge e following at a distance z after having traversed the pill-box cavity. Observe how Eq. (13) shows the dependence of the rate with the cavity length g and the outer radius b . These also enter in the expression for the frequency, Eq. (12), of the resonating modes. In Fig. 2 we have shown the location of few of the lowest modes for a cavity with $g = 2$ mm and $b = 4$ mm. These are represented by vertical lines with a height proportional to the amplitude given by Eq. (13). For comparison, we give also the current spectrum for a driving bunch with gaussian distribution and rms length $\sigma = 3$ mm. Clearly only the lowest mode $n = 1, p = 0$ is important and all the others can be neglected because they do not give any significant contribution.

The case shown in Fig. 2 corresponds to a transformer ratio of 10, if one takes the definition given by Eq. (10). Indeed, according to this definition a transformer ratio of 10 can always be obtained by choosing $\sigma/b = 0.75$.

If we retain only the lowest mode, for the case of Fig. 2, and with $N = 3 \times 10^{11}$ protons in the driver bunch, we have from Eq. (13)

$$w_{10} = 350 \text{ MeV/m}$$

that is ($r = 10$)

$$U_{\max} = 70 \text{ MeV/m}$$

It remains to investigate the effect of the cavity opening. This cannot be done by analytical means but one can use one of the many computer codes written for the purpose. To date, we have used TBCI.⁵

Figure 3 gives a typical graphic output of TBCI. The dashed curve is the assumed longitudinal distribution of the driver bunch. The continuous curve is the wake potential, the integrated energy gain for a test particle following the bunch at some distance z . The code allows the calculation of the maximum accelerating gradient $U_{\max}$ for a following particle, which corresponds to point P of the figure. Also the code estimates the average loss rate $\bar{U}$ in the driver bunch. From both $\bar{U}$ and $U_{\max}$ one can then infer the transformer ratio r according to Eq. (10). For the case of Fig. 3, $r = 34$. This case is just an illustration, otherwise not very relevant to our project. It nevertheless shows a case of an rf cavity with an opening $a = 10$.

A feature in the code makes it possible to determine a few of the lowest order modes present in the cavity under consideration. One assumes a driver bunch with gaussian distribution extending only over $\pm 5 \sigma$ and calculates the wake potential extending from the end of the bunch up to a distance of about a hundred σ . A fast Fourier cosine transform is used to determine the wave numbers k_n for $n = 1, 2, 3, \dots$ for the lowest resonating modes. An example is shown in Fig. 4 which has the waveform to the left and the Fourier analysis to the right. It is possible to identify five different resonating modes in this example, which, considering the dimensions of the cavity assumed in this example, have wave numbers given by $k = j_n/b$ in agreement with the pill-box cavity model and Eq. (12). A more interesting case is shown in Figs. 5a to 5d. The wave number of the resonating modes is always found to be in agreement with Eq. (12). In Fig. 5 we keep the geometry of the cavity (a , b , g) unchanged and vary, from Fig. 5a to 5d, the rms bunch length σ . For a short bunch, several modes are present. By increasing the bunch length, the higher order resonating modes are less and less important and eventually, when the bunch length is long enough, only one mode, the fundamental, is important and all the other can be neglected. We find this to be consistent with our single resonance model. In particular, for $\sigma/b = 0.75$, which is shown in Fig. 5d, the only mode present yields a purely oscillating wakefield. This case corresponds to a transformer ratio $r = 10$.

We have used TBCI to study our specific geometry also. The results are shown in Figs. 6 to 9. In all these figures the continuous lines represent what one would expect in the single mode approximation model and according to Eq. (13) for $n = 1$ and $p = 0$. We found that indeed the transformer ratio is $r = 10$ for $\sigma/b = 0.75$ as one can see from Fig. 6. Figs. 7, 8 and 9 reveal that there is general agreement between TBCI and the pill-box cavity model. The opening of the cavity has the effect of reducing somewhat the amount of field excited. Clearly the largest amount is generated in the limit $a = 0$ and $g = 0$ in which case the amplitude w_0 scales with $1/b^2$. For $b = 4$ mm and $\sigma = 3$ mm, this is about 80 MeV/m.

THE MIXING PROCESS

We have to justify the definition of the transformer ratio we have given with Eq. (5) in general and with Eq. (10) in the particular case of a long driver bunch. We have assumed that by using protons as driving particles, because of their larger mass, there is an averaging process to take into account in the energy loss rate of the particles in the driver bunch. Figure 3 compares the longitudinal charge distribution in the driver bunch (dashed curve) with the longitudinal wake potential (continuous curve). There is no energy loss for the particles in the front of the bunch and the rate of loss increases toward the center of the bunch, until a point O where, because of the oscillating nature of the wakefield, the effective loss rate vanishes. Beyond this point there is energy gain. Therefore by adjusting the bunch length and the wavelength excited in the rf structure, it is possible to have one or more points in the middle of the bunch where a particle would neither lose nor gain energy. Point O of Fig. 3 is actually a point of oscillation since the particles in front would lose energy and therefore move backward, whereas the particles behind would gain energy and move toward the front of the bunch. This oscillation causes a shuffling in position between particles and the enhancement of an averaging process of energy loss. We have called this process "mixing". It is because of mixing that we can justify the definition of the transformer ratio as the ratio of the maximum rate of energy gain for a trailing particle P to the average rate of energy loss within the driver bunch.

It is possible to calculate the "mixing frequency" for small oscillation amplitudes and in the case the distribution of the driver bunch does not change appreciably. For a uniform distribution with full length L and with only one mode of the rf cavities excited we have

$$f_M = \frac{cE_0}{2\pi} \sqrt{\frac{3Nw_0}{LE^3}} \quad (14)$$

It is important for this frequency to be as large as possible. This can be achieved by using protons because of their large energy at rest E_0 , with low energy E and short bunch length L. A large peak accelerating gradient Nw_0 would also help. As an example, if we take

an initial energy of 100 GeV with $L = 15$ mm, and $Nw_0 = 400$ MeV/m which, for a transformer ratio of 10, corresponds to a maximum accelerating gradient of 80 MeV/m, we obtain a "mixing period" of 2.2 μ sec.

A computer code has been written to simulate the motion of the particles in the driver bunch as they lose or gain energy. The code solves a continuity equation for a particle distribution in both longitudinal length z and momentum p versus time. It assigns an initial distribution and assumes that the interaction among particles is via one single mode of wavelength λ and amplitude w_0 , and then displays the distribution in the z, p phase space versus time. Figure 10a shows the initial bunch distribution and the wake potential generated. Figure 10b to 10e give the distribution at later times. It can easily be observed that point O of Fig. 10a is indeed a center of oscillation. From these computer results, one can infer an oscillation period of 4.4 μ sec which is in agreement with Eq. (14). With the same code, it is also possible to estimate the average energy loss in the driver bunch, the energy gain for an electron which follows at one of the maxima of the wake potential, and the transformer ratio according to our definition Eq. (10). The results are reported in Fig. 11. The parameters were set for an initial transformer ratio of 10. As the bunch compresses due to the initial rotation, the transformer ratio decreases. This leads to an increase of the energy gain rate. Later the bunch grows again and the transformer ratio increases. We plan to extend the computer simulation further in time to observe subsequent changes and also to simulate more realistic cases where the results should be of value in addressing the problem of phasing.

THE EXPERIMENT

We are now planning experiments using the ANL Advanced Accelerator Test Facility already described in a separate paper in these proceedings.⁶ The facility makes use of a 22 MeV electron Linac which provides very short bunches (6 - 200 psec) with up to 2×10^{11} particles. The facility includes a target which will intercept a small fraction of the beam to generate a second, weaker bunch to follow the first pulse. The two bunches, having different momenta, will travel along separated transport lines shown in Fig. 12. It is possible to vary the longitudinal distance as well as the lateral displacement of the two bunches when they merge together again to traverse an experimental area of one meter length. We plan to locate in this location an rf structure whose geometry is shown in Fig. 13. The rf structure is made of a cylinder of aluminum, two inches in diameter and 50 cm long. Aluminum washers are dropped inside the cylinder and compressed together. One set of washers is of constant thickness (1/16 inch) and of the same inner opening of 1/4 inch diameter to let the beam through. They will alternate with other washers 1/8 inch thick and with an inner diameter varying from 3/4 to 1 3/4 inch. The number of washers in a period of the sequence can also be varied. In this way we can emulate rf structures of varying dimensions which correspond to frequencies up to 15 GHz. The goal of the experiment is to measure the rate of energy losses for the driver bunch and the rate of energy gain for the witness beam for a variety

of cavity geometries and pulse separations. Moreover it will be possible to vary the length and the shape of the bunches. It is also our plan to measure transverse wake fields by laterally separating the two beams. Figure 14 gives the expected energy gain rate versus rms bunch length for several cavity geometries according to TBCI. Figure 15 shows the expected transformer ratios as calculated from our model, Eq. (10). The energy variations for both beams will be measured using a magnetic spectrometer located downstream the one meter long experimental area. The spectrometer bends in the vertical plane to permit simultaneous measurements of the transverse fields produced by offset beams. The experiments are expected to be completed during 1987.

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FIGURE CAPTIONS

- Fig. 1. The Wakeatron concept. For the geometry shown, and with proton bunch parameters $N_p = 3 \times 10^{11}$, $\sigma = 3$ mm, $E_p = 100$ GeV, a transformer ratio of 10 and an accelerating gradient of 80 MeV/m can be obtained.
- Fig. 2. The lowest modes for a pillbox cavity in the $a = 0$ limit. The current spectrum for a 3 mm driving bunch is superposed.
- Fig. 3. TBCI calculation of the longitudinal wake for a 10 mm σ driving bunch through a cavity with $a = 10$ mm, $b = 100$ mm, and $g = 10$ mm. The transformer ratio is 34.
- Fig. 4. The wake potential as calculated by TBCI for $a = 1$ mm, $b = 16$ mm, $g = 2$ mm, $\sigma = 2$ mm and its Fourier transform.

- Fig. 5. TBCI calculations of wakefields and FFTS for $a = 1$ mm, $b = 12$ mm, $g = 2$ mm. a) $\sigma = 2$ mm. b) $\sigma = 4$ mm. c) $\sigma = 6$ mm. d) $\sigma = 8$ mm.
- Fig. 6. TBCI calculations of the transformer ratio r vs cavity radius b , with $\sigma/b = 0.75$. The solid line is the single mode approximation.
- Fig. 7. Maximum energy gain vs cavity gap from TBCI and the single mode approx.
- Fig. 8. Maximum energy gain vs cavity radius b ($\sigma/b = 0.75$).
- Fig. 9. Maximum energy gain vs cavity inner radius a .
- Fig. 10. The evolution of the phase space distribution and wake potential for a proton bunch in the Wakeatron.
a) $t = 0$ ns. b) $t = 405.2$ ns. c) $t = 909.9$ ns
d) $t = 1110.1$ ns. e) $t = 1310.9$ ns.
- Fig. 11. Proton energy E_p , e^+ energy gain ΔE_e , and transformer ratio r vs t in the Wakeatron.
- Fig. 12. The ANL Advanced Accelerator Facility.
- Fig. 13. Wakeatron test cavity for the ANL experiment.
- Fig. 14. Maximum energy gain vs σ/b (TBCI) for the ANL experiments.
- Fig. 15. Transformer ratio vs σ/b for the ANL experiments.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5a

Figure 5b

Figure 5c

Figure 5d

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10a

Figure 10b

Figure 10c

Figure 10d

Figure 10e

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15