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Conceptual Outline of a Nondestructive Swept Electron Beam Diagnostic for the Linac Microbunch Structure at the DTL-CCL Interface

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An electron beam crossing the H^- SSCL Linac beam horizontally at right angles will undergo a vertical deflection each time a Linac microbunch passes by the crossing point. For example, a 10 keV electron, which has a β_z of 0.195, crosses the Linac beam transversely at the DTL-CCL interface in 20.5 picoseconds ($4\sigma_R = 1.2$ mm), while the corresponding microbunch takes 64.8 picoseconds (*i.e.*, $4\sigma_t$) to pass by. So a beam of 10 keV electrons can in principle fairly well resolve these microbunches in time. The maximum vertical deflection angle $\Delta\vartheta$ imparted to such electrons can be crudely estimated from the number N_B of H^- particles in each microbunch, and the bunch's length $\sigma_L = \sigma_t c \beta_{H^-}$ [1]. For the 70 MeV H^-'s at the DTL-CCL interface, $\beta_{H^-} = 0.3661$, so that with the above σ_t, $\sigma_L = 0.178$ cm, and, very roughly[1],

$$\Delta\vartheta_{\max} \approx \frac{\sqrt{2\pi}\, e^2 N_B}{m_e \gamma_z c^2 \beta_z{}^2\, \sigma_L},$$

where e is the electron's charge and m_e is its mass. Taking N_B to be 3.58×10^8 H^-'s per bunch, we obtain an upper bound for $\Delta\vartheta$ for 10 keV electrons of 37 mrad. A more careful numerical simulation of the deflection angle as a function of the electron impact parameter with respect to the center of the H^- beam, using the code ZBEAM [2], yields the curve of Figure 1, whose maximum deflection angle is 22 mrad. If a well collimated, small spot electron beam is used, such deflections amount to several mm at a detection point 20 cm from the beam crossing, and should be readily resolved, for example, by a CCD detector. The gap between the microbunches (2.34×10^{-9} seconds at 428 MHz, or 25.7 cm) provides a convenient undeflected electron beam reference point at the detector. The precise amount of deflection can readily be adjusted to any convenient value less than the maximum by variation of the impact parameter, as Figure 1 indicates.

The purely vertical deflection of the electron beam with microbunch passage does not by itself provide a time scale for analyzing the bunch structure. At the detector, we have something akin to an oscilloscope with a vertical input signal only. We should thus also like to provide a horizontal input signal for the desired timing purpose. In an oscilloscope, the horizontal sweep function is normally accomplished by using deflection plates to impose a time-modulated electric field on the electron beam. One could suppose doing the same to our electron beam after it has crossed the H^- beam. Ideally, the sweep frequency would be a multiple of the 428 MHz bunch spacing, so as to produce overlapping images of many closely similar "nearest neighbor" bunches. This tremendously eases the intensity requirements on the electron beam, allowing the detector image to be built up over very many bunches. It turns out that the extremely short 64.8 picosecond ($4\sigma_t$) bunch is difficult to satisfactorily resolve in time using a 428 MHz sinusoidal horizontal sweep frequency, but that a 1284 MHz (the CCL bucket spacing) sinusoidal sweep frequency is adequate—see Figure 2.

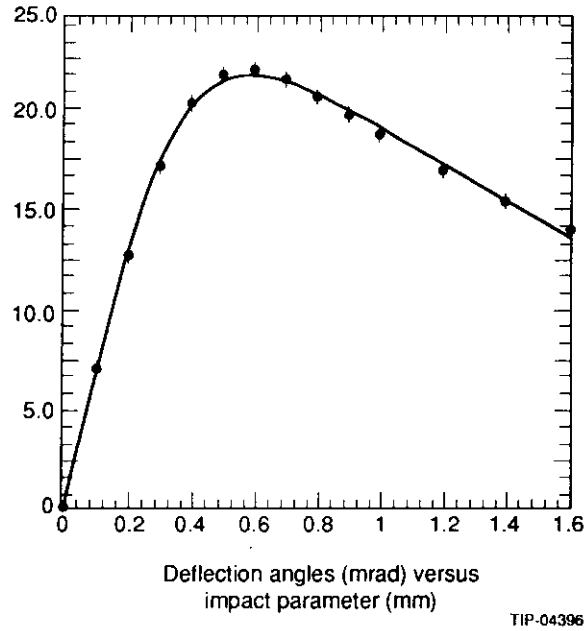

Figure 1. Electron vertical deflection angle versus impact parameter from the center of an H^- bunch. Electron energy is 10 keV, H^- beam energy is 70 MeV, and H^- beam σ_R is 0.3 mm. The H^- bunch has 3.58×10^8 particles, and its σ_L is 0.178 cm.

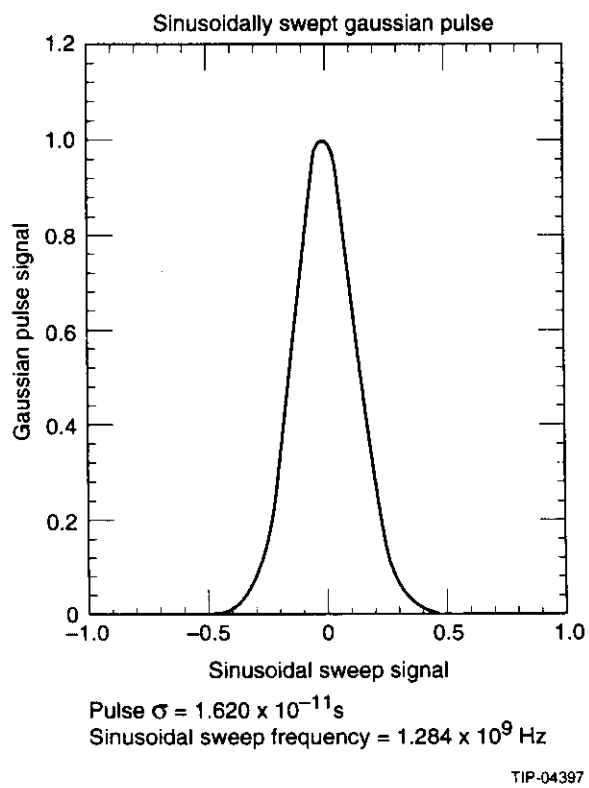

Figure 2. Gaussian time pulse of $\sigma_t = 16.2$ picoseconds (such as would be expected to be imparted vertically on an electron beam by a passing Linac H^- bunch), which is swept horizontally by a sinusoidal signal of frequency 1284 MHz. The Gaussian spike is thus "opened out" to about one third of the sweep amplitude, permitting it to be reasonably profiled in time.

It is, however, difficult to provide much horizontal sweep deflection of the 10 keV electron beam by using deflection plates at such a high frequency as 1284 MHz. The proposed solution for this problem is to use a 1284 MHz resonant cavity in lieu of deflection plates, in order to take advantage of the high Q of such a structure. Further, the electron beam would enter and exit the cavity through a copper shielding tube which has a gap of calibrated length at just the central zone of the cavity, where the deflecting cavity electric field is strongest. The gap's length is to be "tuned" to the electron velocity so as to avoid self canceling effects of the oscillating cavity electric field on the net electron deflection.

Conveniently, the Linac has a 10 watt reference line for the 1284 MHz CCL bucket signal, a portion of which one might envision feeding into the proposed cavity via an adjustable phase shifter. Let us go through a rough exercise to estimate the maximum deflection sweep that might result from dissipating one watt of power in a 3 cm $\times$ 16.52 cm $\times$ 16.52 cm square-faced copper cavity, whose fundamental resonant TE011 mode is 1284 Mhz. The electrons, having traversed the H^- beam, are still traveling very nearly in their original z-direction (albeit with a small vertical, or y-component to their momenta). They enter the copper shielding tube at the center of the nearest (to the H^- beam) 3 cm $\times$ 16.52 cm face of the cavity, whose 3 cm edge is oriented to be horizontal (in the x-direction) and whose 16.52 cm edge is oriented to be vertical (in the y-direction). This internal copper shielding tube leads through the cavity in the z-direction, allowing the electrons to exit the cavity through the center of the opposite 3 cm $\times$ 16.52 cm face, and this tube has a 2.28 cm gap which is symmetric about the cavity's center. Ignoring the effect of the shielding tube, the fundamental TE011 mode within the cavity has the non-zero electromagnetic field components,

$$
\begin{aligned}
E_x(x,y,z,t) &= E_0 \sin(\pi y/l)\sin(\pi z/l)\sin(2\pi f(t-t_0)),\\
B_y(x,y,z,t) &= (1/\sqrt{2})E_0 \sin(\pi y/l)\cos(\pi z/l)\cos(2\pi f(t-t_0)),\\
B_z(x,y,z,t) &= -(1/\sqrt{2})E_0 \cos(\pi y/l)\sin(\pi z/l)\cos(2\pi f(t-t_0)),
\end{aligned}
$$

where l is the length 16.52 cm and f is the frequency 1284 MHz. We here take note of the relation $l = c/(\sqrt{2}f)$. The interior of the cavity extends from 0 to l in y and z, and from 0 to 3 cm in x. The maximum magnitude E_0 of the electric field may be related to the power P dissipated by the surface currents which the magnetic fields stimulate on the cavity inner walls, as we shall indicate below. In the shielding tube gap region close to the center of the cavity, one can approximate the non-vanishing electromagnetic fields as simply,

$$E_x(x,y,z,t) = E_0 \sin(2\pi f(t-t_0)),$$

The horizontal (x-direction) deflection of an electron which passes through the gap with constant z-velocity $c\beta_z$ is governed by the simple Lorentz force equation,

$$dp_x/dt = -eE_0 \sin(2\pi f(t - t_0)),$$

with initial condition (at the beginning of the gap) $p_x(t = 0) = 0$. We wish to solve for $p_x(t = l_g/(c\beta_z))$, the x-momentum at the end of the gap, where l_g is the gap length of 2.28 cm. This is the change in horizontal momentum Δp_x which the electron experiences upon traversing the gap. Of course, it depends on the phase $2\pi f t_0$ of the electric field at time $t = 0$ when the electron enters the gap. We obtain,

$$\begin{aligned}\Delta p_x(t_0) &= \frac{eE_0}{2\pi f}\left[\cos\left(2\pi f\left(t_0 - \frac{l_g}{c\beta_z}\right)\right) - \cos(2\pi f t_0)\right] \\ &= \frac{eE_0}{\pi f}\sin\left(\frac{\pi}{\sqrt{2}\beta_z}\left(\frac{l_g}{l}\right)\right)\sin\left(2\pi f t_0 - \frac{\pi}{\sqrt{2}\beta_z}\left(\frac{l_g}{l}\right)\right).\end{aligned}$$

To maximize the deflection sweep, then, we need to choose the gap length to satisfy $l_g = \beta_z l/\sqrt{2}$, which the l_g of 2.28 cm does for our 10 keV electrons and our $l = 16.52$ cm cavity side.

With this choice of l_g, the horizontal deflection angle $\Delta\theta(t_0)$, which equals $\Delta p_x(t_0)/p_z$ (where $p_z = m_e\gamma_z c\beta_z$), comes out to be,

$$\Delta\theta(t_0) = -\frac{eE_0}{\pi f m_e \gamma_z c\beta_z}\cos(2\pi f t_0).$$

For this expression for $\Delta\theta(t_0)$ to be useful, we now need to relate E_0 to the power P dissipated on the cavity inner walls by surface currents. These are driven by the magnetic fields at the the cavity wall inner surfaces according to the relation,

$$\mathbf{J}_s = \frac{c}{4\pi}(\mathbf{n} \times \mathbf{B}_s),$$

where $\mathbf{B}_s$ is the magnetic field value at a cavity inner surface, $\mathbf{n}$ is the unit normal to that surface, and the surface current density $\mathbf{J}_s$ has dimensions of current per unit length. Thus the average power P dissipated on the inner wall surfaces is the *time average* of,

$$R\int_{\text{walls}} |\mathbf{J}_s|^2\, dS = \frac{Rc^2}{(4\pi)^2}\int_{\text{walls}} |\mathbf{B}_{s,\text{tang}}|^2\, dS.$$

Here R is the wall resistance, which is given (in ohms, where one ohm= $(30c)^{-1}$ in the units we are using) by $(\sigma\delta_s)^{-1}$, where σ is the conductivity of the cavity surface material (copper) in inverse ohms per unit length, and δ_s is the skin depth for the frequency f,

namely $(\pi f \mu \sigma)^{-\frac{1}{2}}$. Thus, we may write $R = \mathcal{R} f^{\frac{1}{2}}$, where $\mathcal{R} \equiv (\pi\mu/\sigma)^{\frac{1}{2}}$ and, for copper, has the value 2.62×10^{-7} ohms $s^{\frac{1}{2}}$.

With our above expressions for the components of the **B** field in the cavity, we can thus calculate the power P dissipated in the cavity walls. We obtain,

$$P = \frac{1}{2}\left(\frac{E_0 c^2}{8\pi f}\right)^2 \mathcal{R} f^{\frac{1}{2}}(1 + (2w_x/l)),$$

where w_x is the cavity's x-dimension of 3 cm. We now solve this for the maximum electric field magnitude E_0 in the cavity,

$$E_0 = \frac{8\pi\sqrt{2} f}{c^2}\left(\frac{P}{\mathcal{R} f^{\frac{1}{2}}(1 + (2w_x/l))}\right)^{\frac{1}{2}}.$$

If we thus dissipate a P of one watt in our cavity, E_0 comes out to be 402 volts/cm. We can put this expression for E_0 into that obtained above for $\Delta\theta(t_0)$ to obtain,

$$\Delta\theta(t_0) = -\frac{8\sqrt{2}\, e}{m_e \gamma_z c^3 \beta_z}\left(\frac{P}{\mathcal{R} f^{\frac{1}{2}}(1 + (2w_x/l))}\right)^{\frac{1}{2}} \cos(2\pi f t_0).$$

Thus for one watt of dissipated power, we estimate a deflection sweep of 29 mrad. From the end of the shielding tube gap to the end of the cavity, the electrons must travel another 7.12 cm, at which point this deflection sweep produces a sweep displacement of 2 mm, which would be adequate for a typical CCD. These estimates are without doubt on the optimistic side, taking no account of the power lost on the surface of the small diameter shielding tube, and overestimating the cavity electric field strength in the gap region. However one has leeway to increase the power consumed by the cavity to a value greater than one watt, and also to place the CCD electron beam detector some distance downstream from the mouth of the cavity exit.

The Kimball Physics ERG-21 high performance electron gun would seem a very satisfactory source of electron beam for this "1.284 GHz oscilloscope built across the Linac beam" diagnostic. It offers an energy range of 5 keV to 50 keV as well as collimation as good as 20 μrad half angle with a beam spot of 20 μm or less, which is the resolution of the typical CCD. Its beam brightness at 10 keV can reach 0.5 mamp per mm^2. It can also produce electron beam pulses shorter than 1 μs, so as to overlap images of only closely similar bunches. (The Linac's pulse length is 6.6 μs.)

One conceivable concern about this approach for visualizing microbunch structure in the Linac is the possibility that imperfections in the cavity electromagnetic field could have a decollimating effect on the electron beam. Such imperfections could arise particularly

from the field distortions caused by the copper shielding tube outlets at the ends of the gap. A computer study of this could be useful, and ameliorative measures might include flaring and rounding off these outlets, as well as making provision for refocusing capability downstream of the cavity in the form of magnetic lenses.

It is of some incidental interest to also note the expression for the Q of our cavity mode,

$$Q = \frac{(2\pi)^2}{\sqrt{2}\,c}\left(\frac{(w_x/l)}{\mathcal{R}f^{\frac{1}{2}}(1+(2w_x/l))}\right).$$

For our situation, this Q comes out to 11,800.

REFERENCES

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