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Ion Probe for Beam Position and Profile Measurement

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Abstract

We describe a non-perturbing diagnostic to measure the position and profile of tightly bunched (μm-sized) beams. The probe consists of a finely-focused, low-energy ($\leq$30 keV) ion beam that is injected across the path of the beam to be measured. The deflections of the ions are measured with a gated microchannel plate (MCP) detector and recorded with a video camera and frame grabber. By appropriately selecting the ion species and energy, the probe can be used with beams having a wide range of charge density. We will describe two operating regimes. The first holds for very short duration bunches, with the deflection scaling simply as the bunch charge divided by the bunch radius. More generally, the deflection depends on bunch length and must be solved numerically. We are now building a probe, using a specially-designed ion gun, that will be tested at SLAC. We will present the theory of operation of the device, discuss various possible configurations, and describe the components we are incorporating in the initial version of the probe.

INTRODUCTION

The general form of the ion probe diagnostic that we are developing is shown in Fig. 1. This diagnostic uses a tightly focused ion stream that is injected across the beam tube in the path of the high-energy beam. The probe ions are deflected by the high-energy beam, and the direction and magnitude of the deflection are directly related to the spatial and temporal charge distribution of the accelerated beam. Easily-resolved deflections can be produced by microbunches with total charge on the order of a nCoul and pulse durations of a few psec. The geometry of Fig. 1 will be used throughout. The high-energy bunch to be diagnosed travels along the z axis. The probe ions are injected in the y direction, but displaced from the axis in the x direction by an amount x_0, the impact parameter. The bunch has a radius r_b and a duration τ_b, corresponding to a length $L_b = c\tau_b$. The ions are deflected through an angle θ by the electromagnetic fields of the bunch. For highly relativistic bunches, the deflection does not depend on bunch energy.

We have previously developed an electron probe (1) which has many of the desirable features required for this application. However, the electron probe is restricted to use with beams which are not too tightly focused, because the space-charge potential of a strongly-bunched beam reflects the probe electrons unless their energy is very high. A probe of positive ions promises to have important advantages over an electron probe, including 1) ability to penetrate dense electron

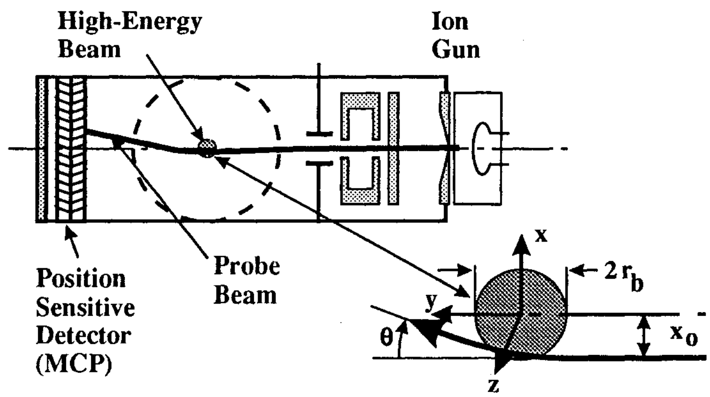

Figure 1. Geometry of the ion probe.

bunches, 2) less sensitivity to stray magnetic fields, 3) greater signal-to-noise ratio (via transit time isolation), 4) broader operating range (ability to adjust ion mass as well as energy), and 5) increased resolution. The trade-off is that a suitable ion gun is more complex than the electron gun.

We have analyzed this probe analytically and numerically. In either case, the fields of the bunch, as derived in Ref. 1, are used to calculate the ion deflections. We will present selected results of these calculations to illustrate the sensitivity and predicted operational characteristics of the probe.

IMPULSE MODEL

We begin by considering the probe behavior in the limit of a very short duration bunch, in which case the ion deflection can be considered to be an impulse. The situation is as illustrated in Fig. 2. On the timescale of the bunch, the ions of velocity v appear stationary, and the deflected ions are those that are within the interaction length L shown when the bunch passes. These ions arrive at the detector over a period of time given approximately by L/v. Thus, even for a psec bunch, the deflected ion pulse duration is typically a few nsec. The maximum deflection is acquired by the ions in the peak field, i.e., those at the edge of the bunch for a uniform bunch or those at r = 1.585 σ for a gaussian beam.

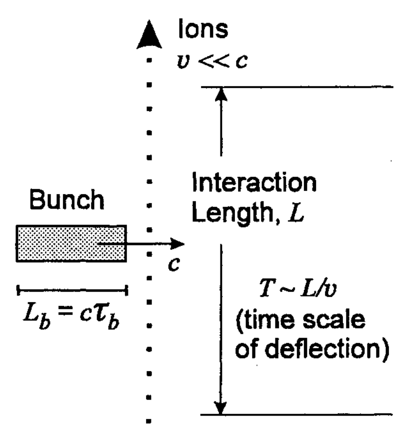

Figure 2. Diagram of interaction.

From the Lorentz force equation, we have for a uniform beam that the maximum deflection velocity is given by

$$\Delta v_{x_{\max}} = \frac{Ze}{Am_p} E_{x_{\max}} \Delta t \approx \frac{Ze}{Am_p} \frac{I_b}{2\pi r_b \varepsilon_0 c} \tau_b \ , \tag{1}$$

where Ze and Am_p are the charge and mass of the ion, and I_b is the current of the electron bunch. In Eq. 1 we have assumed that the impulse duration is simply the bunch duration. Expressing the ion velocity in terms of the ion energy $W = eV$, where V is the ion gun voltage, and using the bunch charge Q_b, we obtain the following theoretical relationship for the maximum deflection angle:

$$\theta_{\max} = 748^\circ \sqrt{\frac{|Z|}{AV_{[\mathrm{kV}]}} \frac{Q_{b[\mathrm{nCoul}]}}{r_{b[\mu\mathrm{m}]}}} . \tag{2}$$

Similarly, for a gaussian beam, the maximum deflection angle is

$$\theta_{\max} = 337^\circ \sqrt{\frac{|Z|}{AV_{[\mathrm{kV}]}} \frac{Q_{b[\mathrm{nCoul}]}}{\sigma_{[\mu\mathrm{m}]}}} . \tag{3}$$

Comparing these simple expressions with numerical calculations of the actual ion deflection, as shown in Fig. 3, shows that this simple model is valid over a wide range of parameters. In general, the model is valid so long as an ion does not move appreciably for the duration of the bunch; i.e., when $r_b/v >> \tau_b \Rightarrow r_b/L_b >> v/c$.

If this condition is not satisfied, the deflection depends on the bunch duration as well as the charge and radius. Figure 4 shows the numerically-calculated maximum deflection as a function of pulse duration for several sets of parameters. Clearly, as the ion velocity is increased (either by increasing the voltage or decreasing the mass), the impulse model begins to lose its validity. By properly choosing the operating regime, one can in effect select whether or not the probe is sensitive to bunch length.

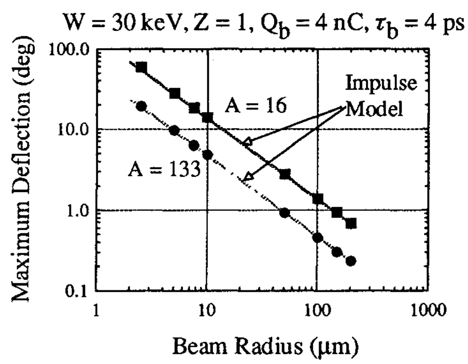

Figure 3. Test of impulse model. Points are from numerical calculations.

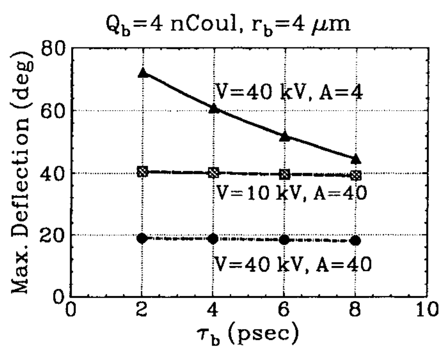

Figure 4. Dependence on bunch length.

MODES OF OPERATION

In normal operation, a small-diameter ion beam ($r_{ion} << r_b$) is scanned across the bunch path (assumed to be repetitive and reproducible), and the maximum deflection as a function of impact parameter x_0 is determined. For ions charged oppositely to the bunch, the deflection peaks at the location of peak field (not always true for identically-charged ions). Thus, the value of x_0 for maximum deflection determines the beam size, the value for no deflection corresponds to the bunch centroid, and the deflection amplitude provides a measure of the bunch charge (and possibly bunch length) and/or a more precise measure of bunch radius if Q_b is already known.

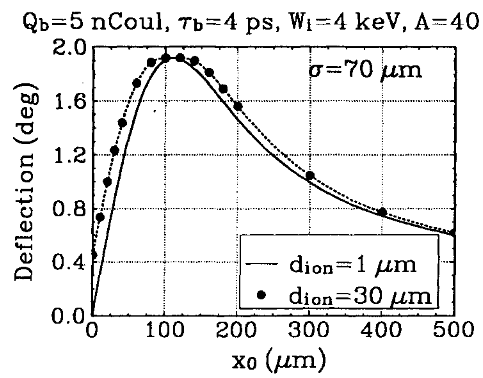

Figure 5. Deflection vs. impact parameter with two ion beam diameters.

A sample curve representative of the parameters of our planned SLAC experiment is shown in Fig. 5. Here, the effect of a finite ion beam size is also shown. The 30-μm beam results in a slight broadening of the deflection curve, but the location and magnitude of the peak deflection are unchanged and well defined.

It is possible to use an ion beam somewhat larger in diameter than the bunch, in which case the ions striking the detector can provide a measure of the maximum deflection angle from a single bunch. This operating mode is particularly important for μm or sub-μm bunches, because it is difficult to generate ion beams this small. An example of this mode is shown in Fig. 6, where we have assumed a 50-μm-diameter ion beam. The calculations use 500 ions equally distributed from $x = 0$ to $x = 25$ μm, and we show a histogram plot of the ion positions 1 cm beyond the intersection of the two beams. The width of the bins is 20 μm, which is a good approximation for

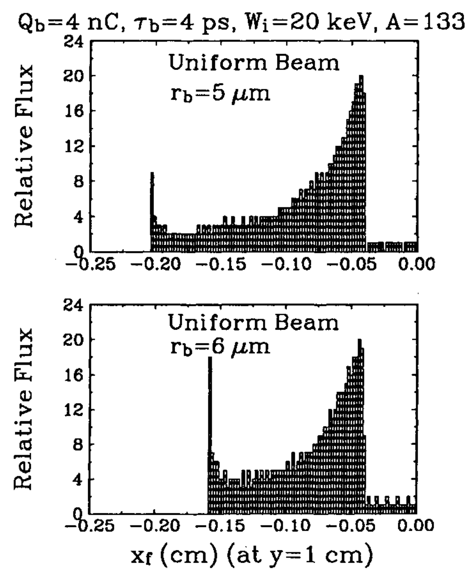

Figure 6. Histograms of ion deflection with a large-diameter ion beam.

the resolution of an MCP detector. As with the small-diameter beam, the largest deflection angle gives a good measure of bunch radius, but now the ions do not have to be scanned. (However, the ion density must be sufficiently large to ensure that a reasonable number of ions are in the peak field of the bunch). The large step that occurs in both plots at $x_f \sim -0.04$ cm is simply due to the finite size of the ion beam. It represents the deflection that occurs at $x_0 = 25\ \mu$m, which is about the same in both cases because the enclosed charge at that value of x_0 is the same. (If the calculation were performed over a much longer time interval, the points near the origin would also be much more numerous, because there would be many ions that do not interact strongly with the bunch.) The relative number of ions deflected through the various angles also gives an indication of bunch profile. For example, a gaussian bunch produces a flatter deflection vs. impact parameter curve, resulting in a weighting of the histogram toward larger deflections than in the case of the uniform beams shown here. However, this information may be difficult to extract from laboratory measurements.

It is also possible to monitor the ion energy rather than just the deflection angle to determine bunch parameters, because the electric field that causes the deflection also changes the ion velocity. Figure 7 illustrates the effect. The left graph shows the ion energy after the interaction with the bunch as a function of time for two different bunch radii ($t = 0$ is arbitrarily chosen here). The first ions to interact with the bunch have their energy decreased, because they are beyond the accelerator axis when the bunch arrives and are therefore pulled back toward the bunch. Ions injected later have not yet reached the accelerator axis when the bunch arrives, so they are accelerated. The right graph shows the maximum and minimum ion energy as a function of bunch radius. Typically, the net change in ion energy varies with bunch parameters in the same way as the maximum deflection angle does. Thus, a larger diameter bunch or lower bunch charge provides a smaller change in ion energy. Again, the ion beam can be larger than the bunch, but a sufficient number of ions must pass through the center of the bunch trajectory to ensure an accurate measurement (so a minimum ion density is required).

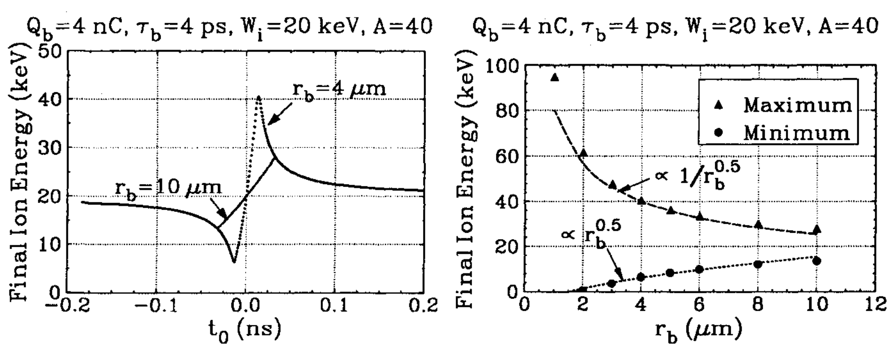

Figure 7. Ion energy variation during interaction with a bunch.

Note that for the parameters in the right hand graph, some ions are reflected when the bunch radius is decreased below 2 μm. The probe could be configured to monitor these reflected ions, which might actually be preferred for sub-μm bunches. By injecting the ions with a velocity component parallel to the accelerator axis and displacing the ion gun and the detector in z, the z coordinate of the reflected ions at the detector becomes a direct measure of reflected ion energy.

PROTOTYPE PROBE DESIGN

We are developing an ion probe to be tested at SLAC at the end of the two-mile accelerator. At this position, the bunch has a typical cross section of 50×100 μm, a length of 1 mm (3 psec), and up to 5 nCoul of charge. From the above results, an ion probe utilizing Ar^+ ions at $\lesssim$10 keV should produce easily observable deflections of tens of mrad. Such deflections allow us to place the detector 15 to 30 cm from the beam tube axis and have the deflected ions remain within the field of view of a 40-mm-diameter MCP. This spacing is sufficient to allow good transit time isolation via a gated detector (the ions arrive at the detector long after the bunch has passed). Gating not only minimizes the background signal, it decreases the spot brightness produced by undeflected ions. Ideally, the detector should be on only during the time that deflected ions are arriving, which is typically a few nsec. We are incorporating a strip-line gated MCP, provided by Lawrence Livermore National Laboratory (P. Bell), that can easily be gated on for 5 to 10 nsec.(2)

To test the performance of the detector in the radiation environment, we have installed a package consisting of the gated detector, a video camera, and an ion pump and ionization gauge next to the beam line at SLAC. Background noise does not appear to be a problem based on preliminary measurements with this apparatus. The assembly is being left in place and monitored periodically to determine the lifetime of the components.

The ion beam must satisfy a number of stringent requirements. Obviously, the ion beam divergence must be much less than the deflection angle to be measured. There must also be enough ions in the vicinity of the bunch as it passes to provide good statistics. This imposes a minimum current density requirement. Furthermore, the number of deflected ions reaching the detector must be large enough to overcome whatever noise is present. The current density condition is straightforward to analyze, resulting in a value of several mA/cm^2 for our parameters. To demonstrate this, we have performed a simple calculation using a 35-nA, 30-μm-diameter ion beam (5 mA/cm^2), with the ions initially equally spaced in an array. An expanded view of the ions that have undergone the largest deflection is shown in Fig. 8. Here, each point is an individual ion, and we are looking in the plane of the detector (xz plane, deflection direction is downward). Clearly, this current would be sufficient assuming a detector that can respond to individual ions (as the MCP can), provided that the background noise is small. By gating the detector and using transit time isolation as described above, we believe that this will be the case.

To generate an ion beam for this application, we are building an ion gun that uses a multicusp plasma source (from K.N. Leung at Lawrence Berkeley Lab) together with an optical system that we are developing from a design by R. Keller, also of LBL. The gun has a long focal length (~18 cm), so that the ion beam waist will be at the accelerator beam tube axis. This design will also allow the detector to be placed up to 30 cm from the accelerator axis. A scaled diagram of the entire configuration is shown in Fig. 9. The gun is predicted to provide a beam having a current density >50 mA/cm^2 and a divergence of several mrad (depending on the size of the aperture).

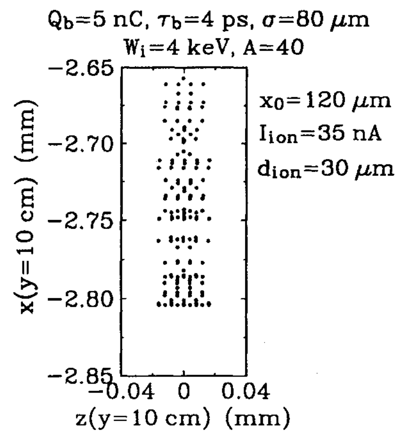

Figure 8. Deflected ions as seen by a detector 10 cm from the accelerator axis.

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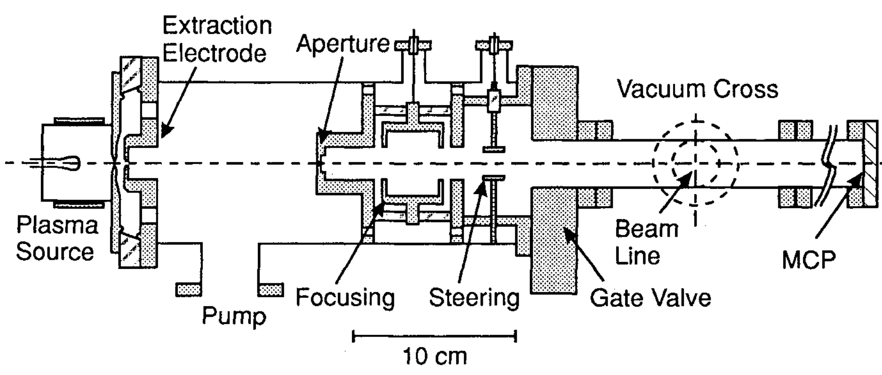

Figure 9. Schematic diagram of prototype ion probe (to scale).