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DEVELOPMENT AND TESTING OF AN ION PROBE FOR TIGHTLY-BUNCHED PARTICLE BEAMS

FINAL TECHNICAL REPORT

Mai Ngo
John Pasour

June 1996

Prepared for: U.S. Department of Energy
ER-16, Room G-351
Washington, D.C. 20585

Contract No. DE-FG03-92ER81297

Prepared by: Mission Research Corporation
8560 Cinderbed Road, Suite 700
Newington, VA 22122
703/339-6500

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1. INTRODUCTION

Many high-energy physics experiments require a high-quality and well-diagnosed charged-particle beam (CPB). Precise knowledge of beam size, position, and charge distribution is often crucial to the success of the experiment. It is also important in many applications that the diagnostic used to determine the beam parameters be nonintercepting and nonperturbing. This requirement rules out many diagnostics, such as wire scanners, thin foils which produce Cerenkov or transition radiation, and even some rf cavity diagnostics. Particularly difficult to diagnose are tightly-focused ($r_b \ll 1$ mm), short-duration (psec) beams, such as those in state-of-the-art or next-generation particle colliders. In this paper we describe an ion probe that is capable of penetrating the space-charge field of densely bunched CPBs without perturbation, thereby enabling the measurement of the microstructure of the bunch.

This diagnostic probe uses a finely-focused stream of ions to interact with the CPB. Related techniques have been discussed in the literature. In fact, the present work evolved from an electron deflection diagnostic for CPBs that we previously described [1]. A similar electron probe was tested even earlier at TRIUMF and in the Former Soviet Union [2,3]. Electron probes have also been used to measure plasma sheaths and potentials [4,5] and the neutralization of heavy ion beams [6]. Also, Mendel has used an ion beam (22 keV He^+) to probe rapidly varying fields in plasmas [7].

The general form of the ion probe diagnostic is shown in Fig. 1.1. The probe ions are injected across the beam tube and into the path of the high-energy CPB. The ions are deflected by the CPB, and the direction and magnitude of the deflection are directly related to the spatial and temporal charge distribution of the CPB. Easily-resolved deflections can be produced by microbunches having total charge on the order of a nCoul and pulse durations of a few psec. The deflected ions are monitored with a suitable detector, in this case a microchannel plate (MCP) capable of detecting single ions.

A probe of positive ions has important advantages over an electron probe, including 1) ability to penetrate dense electron bunches, 2) less sensitivity to stray electric or magnetic fields, 3)

Figure 1.1. Geometry of the ion probe.

greater signal-to-noise ratio (via transit time isolation), 4) broader operating range (ability to adjust ion mass as well as energy), and 5) simpler kinematics (large linear regime and non-relativistic ions), which greatly simplifies interpretation of the data. An 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. The trade-off is that a suitable ion gun is more complex than the electron gun.

The geometry of Fig. 1.1 will be used throughout this paper. The high-energy beam or 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 highly relativistic CPB 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 CPB. For highly relativistic beams, the deflection is independent of CPB energy.

We have analyzed this probe analytically and numerically, using the fields of the CPB, as derived in Ref. 1, to calculate the ion deflections. Based on this analysis, we have built and implemented an ion probe that has been placed at the end of the linear accelerator at SLAC. We will present the results of the analysis and the experimental results from the probe at SLAC.

2. ION PROBE PRINCIPLES

2.1 Theory

For optimum performance of the ion probe in determining various CPB parameters, the ion beam parameters must be tailored to those of the bunch to be diagnosed. For this reason as well as to unfold the experimental data from the probe, it is essential to have a good understanding of the scaling laws that govern the deflection.

The basic theory of the ion probe is quite simple, consisting of single-particle ion dynamics in the electromagnetic fields of a relativistic charged particle beam or bunch (CPB). Ion trajectories for arbitrary CPB parameters can be calculated numerically, as we will show below, but two limiting cases can be solved analytically.

2.1.1 Quasi-Steady-State Model

First, we present a specialization of the theory to the linear regime that illustrates the utility of the probe for direct profile measurements for long-duration CPBs, such as those from induction linear accelerators or Van de Graafs. This mode of operation with electron probes has also been analyzed by Shestak, et al., whose approach utilized a set of deflection plates after the interaction with the CPB. They showed how the profile of a long beam could be determined from the deflection plate voltage required to null the deflection produced by the CPB. The analysis presented here is also very similar to that of Tsyanov, et al. [8], who proposed the use of an electron probe of the type we previously described [1] as an emittance monitor for the now-defunct Superconducting Super Collider (SSC) proton beam.

From the Lorentz force equation, the change in the perpendicular velocity of a probe ion is simply

$$\Delta v_x = \int_{-\infty}^{\infty} \frac{ZeE_x}{M} dt, \quad (1)$$

where Ze and M are the charge and mass of the ion, respectively, and E_x is the electric field from the high-energy bunch, which is given by

$$E_x = \frac{\lambda}{2\pi\epsilon_0} \frac{x}{x^2 + y^2} ; \quad \lambda = \iint \rho(x', y') dx' dy'. \quad (2)$$

Here, λ is the linear charge density of the high-energy bunch and ρ is the transverse charge distribution. In the linear regime (small deflection angles), the ion velocity is essentially constant, so we can use $y = v_y t$. If we further assume that the transverse charge distribution is independent of time (at least during the time that the ion is in the vicinity of the bunch), we can write

$$\Delta v_x = \frac{Ze}{2\pi\epsilon_0 M} \int dx' \int dy' \rho(x', y') \int_{-\infty}^{\infty} \frac{x - x'}{(x - x')^2 + (v_y t - y')^2} dt. \quad (3)$$

The time integral can be immediately evaluated to give $\pi/v_y \operatorname{sgn}(x - x')$. Then noting that the deflection angle θ is simply $\Delta v_x/v_y$, we obtain

$$\theta(x) = \frac{Ze}{2\epsilon_0 M v_y^2} \int dx' \int dy' \rho(x', y') \text{sgn}(x - x'). \quad (4)$$

An important result can be obtained by differentiating the angular deflection with respect to offset, x_0 . Using the fact that $d/dx \text{sgn}(x - x') = 2\delta(x - x')$, we find

$$\frac{d\theta}{dx_0} = \frac{Ze}{\epsilon_0 M v_y^2} \int dy' \rho(x_0, y'). \quad (5)$$

The interesting feature here is that the integral on the right hand side of Eq. 5 is just the y-integrated bunch density profile. Thus, by scanning the probe beam across the bunch and differentiating the resulting curve of θ vs. x_0 , one can directly obtain the bunch charge profile in the x direction. This is the same information that is obtained with a conventional wire scanner diagnostic, but the ion probe does not perturb the beam. Furthermore, wire scanners are severely limited by breakage of the wires when used with tightly focused bunches. Accurate measurements, however, require using a sufficiently energetic or massive ion beam so that the approximation of operation in the linear regime is valid. Also, the bunch duration must be long enough to satisfy the assumption of time independence.

2.1.2 Impulse Model. For short-duration, highly-relativistic electron bunches, such as those produced by RF accelerators, the ion deflection is well approximated by an impulse. The situation is as illustrated in Fig. 2.1. On the time scale of the bunch, the ions of velocity v appear stationary, and the deflected ions are those that are within the interaction length L_i when the bunch passes. These ions arrive at the detector over a period of time given approximately by L_i/v . Thus, even for a psec bunch, the deflected ion pulse duration is typically ten nsec or more. The maximum deflection is acquired by the ions in the peak field, i.e., those at the edge of the bunch for a radially uniform bunch.

From the Lorentz force equation, we have for a uniform beam

$$\Delta v_{x_{\max}} = \frac{Ze}{Am_p} E_{x_{\max}} \Delta t \approx \frac{Ze}{Am_p} \frac{I_b}{2\pi r_b \epsilon_0 c} \tau_b, \quad (6)$$

where Am_p is the ion mass and I_b is the CPB peak current. In (6) we have used the fact that the peak field of a uniform beam occurs at the beam edge and have further assumed that the impulse duration is simply the bunch duration, which is true for highly relativistic bunches. This expression for the electric field is valid when $\gamma L_b \gg r_b$. Using $v_y = (2|Z|eV/Am_p)^{1/2}$, we obtain the following theoretical relationship for the maximum ion deflection angle (which obviously could only be expected to hold for $\theta_{\max} < 90^\circ$):

Figure 2.1 Diagram of interaction.

$$\theta_{\max} = 748^\circ \sqrt{\frac{|Z|}{AV_{[\text{kV}]}}} \frac{Q_b[\text{nCoul}]}{r_b[\mu\text{m}]} \quad (7)$$

One feature that can be seen immediately from (7) is that the deflection is proportional to the charge per bunch ($Q_b = I_b \tau_b$), independent of the bunch duration. The key requirement for the validity of this impulse approximation is that the ion be essentially stationary during the time that the bunch passes; i.e., when $r_b/v \gg \tau_b$ or

$$r_b/L_b \gg v/c. \quad (8)$$

Thus, for a given bunch duration, this regime can be accessed by employing lower energy or more massive ions.

For the more typical case of a gaussian-profile beam, the charge density varies with radius as

$$\rho(r) = \frac{Q/L}{2\pi\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \quad (9)$$

where Q/L is the charge per unit length of the bunch. The charge contained within a radius r is given then by $Q_i(r) = Q[1 - e^{-r^2/2\sigma^2}]$, and the radial field is a maximum at $r = 1.585 \sigma$. In this case, the maximum deflection angle becomes

$$\theta_{\max} = 337^\circ \sqrt{\frac{|Z|}{AV_{[\text{kV}]}}} \frac{Q_b[\text{nCoul}]}{\sigma[\mu\text{m}]} \quad (10)$$

As we will show, the impulse model is very accurate over a wide range of RF accelerator parameters. Thus, experimentally measuring the maximum deflection angle provides a direct measure of CPB radius, assuming the charge per bunch is independently known (as is usually the case).

2.1.3 Correction for Elliptical Beam. Most high-energy beams use quadrupole focusing, and the beam cross section is elliptical with dimensions that vary with axial position. The effect of the elliptical cross section on the electric field of the bunch and hence the ion deflection is shown in Fig. 2.2, which has been calculated assuming a fixed charge uniformly distributed within an elliptical boundary given by $x^2 + h^2y^2 = R^2$. The maximum value of E_x , which occurs at $x = R$, relative to the field for a circular cross section ($h = 1$) is plotted as a function of ellipticity h . As the bunch becomes elongated in the y direction ($h < 1$), E_x decreases quite rapidly.

Figure 2.2 Maximum electric field variation with ellipticity.

2.2 Numerical Calculations

To numerically compute ion trajectories, we used a modified version of our Runge-Kutta-based trajectory code [1]. The major modification was the introduction of variable time steps (depending on the proximity of the CPB to the ion). These numerical calculations illustrate the regions of validity of the simple models and show important details of the probe behavior.

First, we compare the simple expressions derived above with numerical calculations of the actual ion deflection. Figure 2.3 illustrates the use of the probe for radial profile measurements in the short-bunch (impulse) and quasi-steady-state regimes. A gaussian beam profile with $\sigma = 100 \mu\text{m}$ is assumed in each case, and the maximum deflection angle θ_m is plotted as a function of impact parameter x_0 along with the actual profile and $d\theta_m/dx_0$. For the long pulse $d\theta_m/dx_0$ gives a very accurate representation of the true profile. Even in the short-pulse regime, profile information is contained in the plot of $d\theta_m/dx_0$, but more complex numerical analysis is required to recover it.

The large range of validity of the impulse model is shown in Fig. 2.4, which shows the variation of θ_m with CPB radius for two different ion masses. Only for the smallest beam radii and largest deflections does the numerically-computed deflection begin to deviate slightly from that predicted by the simple impulse model. The fact that the deflection is so well predicted by such a simple model is a significant advantage in the real-time interpretation of experimentally-measured ion deflections.

When condition (8) is not satisfied, the deflection depends on the bunch duration as well as the charge and radius. Figure 2.5 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 deflection varies with bunch length and the impulse model loses its validity. Thus, by properly choosing the ion parameters, one can

Figure 2.3. Radial profile determination from variation in deflection angle with impact parameter for short-pulse and long-pulse CPBs.

Figure 2.4. Test of impulse model. Points are from numerical calculations.

Figure 2.5. Dependence on bunch length.

effectively select the operating regime and choose whether or not the probe is sensitive to bunch length.

To understand the nature of the detected signal from the ion probe, it is necessary to compute the time dependence of the deflected ions at the detector. This is made more complicated by the fact that the ions are accelerated and decelerated by the CPB as well as undergoing the angular deflection. Figure 2.6 shows results for several cases. The calculations assume an ideal, 4-keV, singly-charged argon ion beam with a current of 1.9 nA. Each 83.3 psec, an ion is injected in the y direction with an impact parameter of x_0 . The centroid of a gaussian electron bunch passes through the origin at $t = 0$, and the x coordinates of the ions are calculated in the plane of the detector, in this case at $y = 30$ cm. The plots show the x position of each individual deflected ion as a function of the time it reaches the detector. Not shown here is the continuous stream of undeflected ions at $x_{MCP} = 0$.

Several important features are apparent from these plots. At the time of maximum deflection, the ion spacing is increased, so that relatively few ions undergo the maximum deflection. As

Figure 2.6. Plots of the (x, t) coordinates of the ions reaching a detector located at $y = 30$ cm.

expected from the impulse model, the deflection patterns depend only on the ratio Q/σ of the bunch. The spreading in time of the deflected ions is larger for smaller impact parameters, because the maximum acceleration and deceleration of the ions occur when $x_0 = 0$.

The transit time isolation that can be achieved with this diagnostic allows very effective filtering of the background noise that accompanies the bunch. For this case, the detector can be gated on $2.165 \mu\text{sec}$ after the bunch passes. If the gate duration is small compared to the total time over which the deflected ions arrive at the detector (tens of nsec, typically), then the output signal consists of two spots, one corresponding to undeflected ions and the other to the deflected ions. If the gate pulse is longer than the deflected ion arrival time, the output is essentially a continuous streak that fills the line on the detector between the position of the undeflected and maximally deflected ions.

3. MODES OF OPERATION

In the normal configuration shown in Fig. 1.1, a small-diameter ion beam ($r_{\text{ion}} \ll r_b$) is scanned across the CPB 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 or ellipticity if Q_b is already known.

Variation of the maximum deflection angle with impact parameter is shown in Fig. 3.1 using the parameters of the probe we built and tested at SLAC. The effect of a finite ion beam size is also shown. The 30- μm ion 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 even 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. 3.2, where we have assumed a 50- μm -diameter ion beam. The calculations use 500 ions equally distributed from $x = 0$ to $x = 25 \mu\text{m}$, 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 the resolution of an MCP detector. As with the small-diameter ion 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 $x_f \sim -0.04 \text{ cm}$ is simply due to the finite size of the ion beam. It represents the deflection of ions at the edge

Figure 3.1. Maximum deflection vs. x_0 for two ion beam diameters.

Figure 3.2. Histograms of ion deflection with a large-diameter ion beam.

of the 50- μm -diameter beam, which is 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.

If the CPB is extremely well-focused and dense, a very high energy ion beam is required to operate in the normal mode. In such cases, monitoring the reflected ions using a configuration as shown in Fig. 3.3 is more appropriate. In this mode, ions are injected with a z velocity component. Although individual ion trajectories can be quite complex, the value of the z coordinate of the maximally deflected ions is the critical piece of data that corresponds to Q/r_b of the bunch. The ions that are reflected most strongly arrive at the detector with the smallest value of z_t . Another advantage of this approach is that the ion current requirement is reduced as α is increased.

A graph of the minimum value of z_t as a function of σ for a 3-nC bunch having a 4-psec duration is shown in Fig. 3.4. Here, we have computed the reflection of 20 and 40-keV protons injected at a 45° angle, and the value of z is given in the plane $y = -15$ cm. It is clear that the minimum z coordinate is a sensitive measure of bunch radius, even for sub-micron bunches. However, as the bunch radius becomes smaller, a larger ion current is required to ensure a high probability of interaction with the peak field of the bunch. This point will be addressed more quantitatively below.

It is also possible to monitor the ion energy rather than the position of the deflected ion to determine bunch parameters, because the electric field that causes the deflection also changes the ion velocity. Figure 3.5 illustrates the effect. The left graph shows the ion energy after the interaction with the bunch as a function of ion injection time for two different bunch radii ($t_0 = 0$ 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

Figure 3.3. Reflection mode.

Figure 3.4. Minimum value of z_t for protons reflected from a gaussian electron bunch.

radius. Over the range of parameters shown, the minimum and maximum ion energies vary very nearly as $r_b^{1/2}$ and $1/r_b^{1/2}$, respectively. Also, in this case some ions are reflected when $r_b < 2 \mu\text{m}$. 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 3.5. Ion energy variation during interaction with a bunch.

4. PROTOTYPE ION PROBE DESIGN

4.1 Ion Gun

Originally in the Phase II proposal we had tentatively chosen a commercial ion gun from VG Microtech. However, after carefully analyzing the specifications and holding numerous discussions with VG Microtech representatives, we were convinced that their ion gun can not satisfy our requirements. Most of the commercial ion guns are designed for applications such as sputtering, surface etching, material processing, machining, etc., so their beams are focused down to a small spot at the focal point and have relatively large beam divergence after the focal point. Essentially, the ion gun for our application must satisfy three requirements: 1) It must focus down to a small spot size ($\sim 50 \mu\text{m}$ in diameter) at the focal point. In our case, the focal point is at the intersection between the probe beam and the high-energy beam. 2) It must have a small beam divergence (less than the deflection of the probe beam) after the focal point. 3) The total output beam current must be adequate so that the deflection image on the microchannel plate is clear. For the above reasons, we devoted a great deal of effort to alternative approaches.

We contacted Dr. Ka-Ngo Leung of Lawrence Berkeley Laboratory (LBL), an expert on high-current ion sources, and Dr. Roderich Keller also of LBL, an expert in beam optics, for suggestions on ion sources. It became clear that there are some major advantages to fabricating an ion gun especially for this application. Both Drs. Leung and Keller convinced us that our requirements are achievable with a relatively simple system and we would gain a great deal of flexibility by designing the ion source as part of the full diagnostic package. Furthermore, the development of such a source might have other commercial applications, which we consider to be quite important given the emphasis of the SBIR program. Subsequently, we decided to build an ion source with the help of Drs. Leung and Keller. The ion gun consists of a plasma source and an ion optics system that extracts ions from the plasma and focuses them to a small spot.

4.1.1 Plasma Source

The plasma source was designed by Dr. K. N. Leung based on a multicusp source configuration. The plasma source chamber is a very compact cylinder with 4 cm diameter and 5 cm length. The chamber is surrounded by 16 columns of samarium cobalt permanent magnet to form the cusp field line distribution. The cathode of the plasma source is a 0.5-mm tungsten filament. A schematic diagram of the plasma source and its connection to the power supplies is shown in Fig. 4.1. The plasma source can operate either in dc mode with terminals 1 and 2 connected or in pulsed mode with the discharge voltage modulated with a transistor switch circuit

Figure 4.1 Schematic diagram of the plasma source.

as shown in the upper right hand corner of the figure. Since the plasma chamber is floated at about the extraction voltage, the transistor switch is triggered via a high voltage pulsed isolation transformer. The filament and arc discharge power supplies are also electrically floated at the extraction potential, the 110 V - 60 Hz inputs to these power supplies are provided via a high voltage transformer. The plasma chamber is evacuated to a base pressure of $\sim 10^{-5}$ Torr and water cooled at a rate of about 1 gallon/minute. In a typical operation, pulsed or dc, the gas pressure is set at a few mTorr, the discharge voltage is applied to the plasma chamber, and the filament current is slowly raised at a rate of roughly 2A/minute until a discharge is achieved (about 17 to 20 A). The discharge current can be monitored by the ammeter from the discharge power supply if operating in dc mode, or by a Rogowski coil if operating in pulsed mode. The gas pressure is automatically regulated by an electronic feedback system from Granville Phillips. The output from a pressure gauge monitoring the chamber pressure is fed to an automatic leak valve control system. This signal is constantly compared with a reference level to produce an error signal. The leak valve controller adjusts the gas flow rate such that the error signal is always zero. Thus, the gas pressure in the plasma source is adjusted by varying the reference level on the control system.

The open end of the plasma source is connected to the extraction optics system, where the ions are extracted to form a beam. The extraction optics system is described in the following section.

4.1.2 Optics System

The optics system was designed by Dr. R. Keller of LBL. Using the code IGUN by B. W. Hermannsfeldt and R. Becker, Dr. Keller performed a series of simulations to tailor the ion gun design to our specific requirements. The optics system is designed to produce the required beam brightness with a beam spot of $\leq 30 \mu\text{m}$ at the focal point. The beam divergence away from the focus is less than 5 mRad, which is much less than the ion deflection angles we anticipate. The optics system is also designed to operate up to 15 keV, with the ion current scaling as $V^{3/2}$.

The optics system consists of a series of apertures that forms a beam with a small angular divergence, an electrostatic focusing lens, and a pair of deflection plates to scan the ion beam. A detailed drawing of the optics system is shown in Fig. 4.2. The ion beam first passes through a 1 mm-diameter aperture of the extraction electrode and travels down the optics system. The ions emerging from the extraction aperture are comprised of a very cold central core together with a warmer halo. At the second aperture, only the core of the beam passes through the 1-mm aperture, eliminating the outside ions which, due to curvature of the extraction field and to space charge, travel with some radial velocity. The spacing between the first two apertures is about 7.5 mm. The

Figure 4.2. Detailed drawing of the extraction optics system.

beam continues to travel to the final aperture with an opening of only 0.45 mm. The drift spacing is about 12 cm. This long drift spacing allows the beam to expand and only a small fraction of the core of the beam is selected, where the associated radial velocity is small. This method achieves a beam with small divergence. The beam then passes through an electrostatic focusing lens, where it is focused down to a small spot. A pair of deflection plates at the end of the optics system is used for scanning. Since the ion beam needs to be scanned across the high-energy beam, which is only in one direction, there is no need to scan the ion beam in both directions.

The optics region of the system is typically evacuated to 10^{-6} Torr. The location of the pumping port and the first 1-mm aperture of the extraction electrode provides a differential pressure between the plasma chamber and this high-vacuum region where the ion beam intersects with the high-energy beam.

Figure 4.3 is a schematic diagram of the ion probe system including the plasma chamber and the optics system with the power supplies and the control systems connected, two gate valves, a four-way cross where the probe beam intersects the high-energy beam, and a microchannel plate. The two gate valves are to isolate our ion probe system completely from the SLAC beam line. The valves are electropneumatic and connected to an ionization gauge, so that when the pressure rises to a certain level the gate valves will close automatically. Figure 4.4 is a photograph of the ion probe system.

4.1.3 Experiment with the Ion Gun System

The ion gun was first fully assembled and tested at MRC prior to the actual beam tests at SLAC. The ion gun system was tested extensively to characterize and optimize the ion beam over its full operating range. The purpose of these tests was to fully categorize the gun performance and familiarize ourselves with its operation so that we could rapidly achieve the optimized beam parameters during testing at SLAC, where time is limited and access is nearly impossible.

Figure 4.5 shows the experimental set up. In this set up the total output ion current and the beam size were measured for two different gases: argon and helium. The ions were collected with a Faraday cup, which was positively biased to suppress any secondary emission. The ion current was then measured by measuring the voltage drop across the viewing resistor. The beam profile or the beam size at the focal point was measured by scanning a narrow slit (35 μm wide and 5 mm long) across the beam using a micrometer. The beam profile was determined by plotting the ion current passing through the slit as a function of the slit displacement. The slit was mounted in the 4-way cross that connects the probe to the SLAC beam line, so the beam size was measured at

Figure 4.3. Schematic diagram of the ion probe system.

Figure 4.4. Photograph of the ion probe system tested at MRC.

the intersection between the probe beam and the high-energy beam.

Figure 4.6 shows oscilloscope traces of the plasma in pulsed mode. The top trace is the transistor switch trigger pulse, the middle trace is the discharge current measured with a Rogowski coil, and the bottom trace is the output ion current measured with a Faraday cup. As can be seen, the discharge starts to develop as soon as the voltage is applied to the anode (chamber). The slow rise and fall times of the ion current pulse seen in the figure are due to integration from the cable capacitance. The pulse width of the discharge can be varied from $\sim 50 \mu\text{s}$ to $400 \mu\text{s}$ by adjusting the pulse width of the trigger pulse. For our ion probe application, we need only a few tens of nsec of stable ion current.

To ensure the high quality beam, the alignment of the ion gun was verified. Next, a fine wire of 0.5 mm diameter was scanned across the 0.45-mm output aperture (the last aperture). Ion current impinging on this wire (before the aperture) and ion current passing through the aperture (after the aperture) were measured as a function of displacement of the wire. The measurement was repeated twice. Figure 4.7 shows the results of this measurement. As can be seen, the current-before-aperture curves display a Gaussian distribution with a FWHM (full width half

Figure 4.5. Experimental set-up for ion current and beam size measurements.

maximum) of about 2.5 mm. If we assume the ion beam is Gaussian at this point, this measurement indicates that $\sigma \approx 1.05$ mm, which is obtained by numerically integrating the ion distribution over the wire cross section. The current-after-aperture curves have sharper wings because of the truncation of the aperture. From these results, the optics of the ion gun are well aligned since the minima of the current-after-aperture curves are aligned with the maxima of the current-before-aperture curves. It is worth pointing out that even though the beam before the aperture is quite large, only a very small fraction (0.45 mm) of the core of the beam is selected for the output beam. This is again to yield an ion beam with small angular divergence.

The plasma parameters, which include the filament current, the gas pressure, and the discharge voltage, were next optimized to form an ion beam as small as possible, but with adequate

Figure 4.6. Oscilloscope traces of the trigger pulse (top: 2 V/div), discharge current (middle: 50 mA/div), and ion current (bottom: 50 nA/div). Horizontal: 0.1 msec/div.

ion current. Because the plasma sheath is different for each extraction voltage, the plasma parameters need to be adjusted to produce a good quality, stable, and small divergence beam at each extraction voltage. For this optimization procedure, at each extraction voltage, the filament current, discharge voltage, and gas pressure were systematically varied. The total ion current and the beam size were then measured. The total current was measured with a Faraday cup and the beam size was measured by scanning a 35- μm slit across the beam at the four-way cross. The beam size was determined at the FWHM points.

Figure 4.8 shows total current in nAmp and beam size in μm as function of filament current for extraction voltages of 2, 4, and 5 kV. It was noticed that the ion beam was optimized at gas pressure of about 6 to 10 mT. At too low of a pressure ($P < 6$ mTorr) the plasma was very unstable, and at too high of a pressure, higher filament current was required to start a discharge. It should also be mentioned that the filament has a very limited lifetime. Higher filament current shortens the lifetime of the filament, so the filament current was kept at a level that was just enough to produce a good plasma. For our operations, a filament lasted about 65 hours.

Figure 4.7. Beam current collected on the wire (open symbols) and current passing through aperture (solid symbols) as a function of wire positions.

There is also an upper limit on the discharge voltage. For argon gas, the discharge can produce doubly-ionized particles at a discharge voltage higher than 27.6 V. If our ion beam contains both singly and doubly ionized ions, then the deflection image will be a smear due to deflections from both singly and doubly ionized ions. For our application, singly ionized ions are desired, since it would be easier to analyze the data. Therefore, the discharge voltage was kept as close to 27 V as possible. In this optimization process, it was found that the discharge was not started at discharge voltages less than 25 V. From 26 V to 30 V the discharge was not very stable and difficult to control. The discharge was optimized at a discharge voltage of about 31 to 33 V. From Fig. 4.8 there is a general trend for all extraction voltages. The total ion current decreases markedly as the filament current increases, and the beam size follows the total current very well. The small beam size is associated with low total ion current. This can be explained by the space charge effect. For all three extraction voltages shown in Fig. 4.8, the minimum ion beam size is about 50 μm at FWHM.

Figure 4.8. Total beam current and beam size vs. filament current at different extraction voltages.

The space charge effect can also be seen from Fig. 4.9. This plot shows optimum focusing voltage as a function of output ion current at a fixed extraction voltage of 3 kV with the plasma parameters varied systematically to adjust the ion current. As the ion current increases, the space charge becomes more significant, so a higher focusing voltage is required to focus the ion beam.

Figure 4.9. Focusing voltage vs. ion current with extraction voltage = 3 kV.

The ion beam profile was next carefully measured for three extraction voltages, 4, 5 and 6 kV, with fixed plasma parameters as shown in Fig. 4.10. Although as mentioned above, the plasma parameters need to be optimized for each extraction voltage, however, the experimental data shown in Fig. 4.8 indicate the optimum beam size was achieved at a filament current of about 17.5 A, and at a pressure of ~ 10 mTorr. The width of the curves in Fig. 4.10 are about 50 to 60 μm at FWHM for the extraction voltages tested. Assuming a Gaussian beam, this corresponds to $\sigma \approx 18$ to 23 μm , which is adequate for our application.

The maximum ion current was measured at different extraction voltages. At each extraction voltage the filament current, the gas pressure and the focusing voltage were adjusted to

Figure 4.10. Beam current through a 35- μm slit vs. slit position for Ar gas in pulsed operation.

achieve maximum ion current. The discharge voltage was kept constant for this measurement. Figure 4.11 shows maximum ion current as a function of extraction voltage. As can be seen, the ion current variation is very close to $I \propto V^{3/2}$.

To avoid doubly ionized ions completely, helium gas was next studied. In order to produce doubly ionized ions with He, a discharge voltage $> 54\text{ V}$ is needed. The power supply that we are using for the discharge voltage is limited to 41 V . Thus, with He gas it is always ensured that only singly ionized ions are obtained. However, since the ion deflection varies as $1/\sqrt{(A V)}$ where A is the atomic weight and V is the energy of the ion, a much higher ion energy is required to keep the deflection within a 4-cm diameter of the microchannel plate. Figure 4.12 shows the ion beam profile of He ions measured with a 250- μm slit. For each extraction voltage, the plasma parameters are also shown. The measurement was made at the center of the four-way cross, where the ion probe beam will intersect with the high-energy beam. It was found that with He, a higher gas pressure is required to produce a stable discharge, consequently, higher filament current is also required. From this data, it is difficult to determine the beam diameter, because the

Figure 4.11. Maximum ion current vs. extraction voltage for Ar gas in pulsed operation.

slit width was larger than the beam. For example, a gaussian beam with $\sigma \leq 50 \mu\text{m}$ would produce a FWHM of $250 \mu\text{m}$. However, the smaller the beam, the flatter the peak of the plotted data. Thus, it seems true that just as with Argon gas, higher ion current is accompanied by larger beam size. For instance, at an extraction voltage of 10 kV , a smaller beam (flatter peak) was formed at a lower ion current (solid diamonds), whereas a relatively larger beam was formed at a higher ion current (empty diamonds). Similar behavior was observed at an extraction voltage of 8.9 kV . For our application, a smaller spot size with adequate beam current is preferable to higher beam current with larger spot size. From the results shown in Fig. 4.12, lower ion current and smaller spot size are also associated with lower filament current. This low filament current requirement is to our advantage, since it will prolong the lifetime of the filament.

Figure 4.12. Beam profile for Helium gas in pulsed operation for several extraction voltages.

4.2 Microchannel Plate

We select a microchannel plate (MCP) detector for our ion probe system because of its high sensitivity and good spatial resolution. However, before the MCP could be used effectively in our program, several issues had to be investigated carefully. The major issue was the signal-to-noise ratio (SNR). Because the MCP is sensitive to both charged particles and x rays, care must be taken to isolate the detector from the large radiation pulse that typically accompanies a high-energy beam. The simple approach is to move the detector as far away from the beam as possible, but we were obviously limited by the ion beam divergence as well as the deflection angles that we expected. As we found during our development of the electron deflection diagnostic, gating the MCP so that the high voltage across the plate is only applied during the time of interest can

dramatically improve the SNR. For the electron beam diagnostic, we built a dual krystron gate circuit that had a 500-nsec duration, but to use the MCP in a high-energy accelerator environment, the gate duration had to be shortened to a few tens of nsec, corresponding to the duration of the deflected ions' arrival.

In order to deliver a fast-rising, narrow pulse to the MCP, the MCP must be well matched to the pulse generator. We have found that the large capacitance of the 40-mm diameter MCP causes a significant amount of reflection when driven by a charged-transmission-line circuit. To reduce the capacitance of the MCP, instead of using the whole diameter of the MCP, only a thin, gold-plated strip in the center of the MCP is used, thus forming a transmission line configuration. For our application, since the deflection of the probe ion is only in one direction, a strip only a few millimeters wide is needed. Such a technique has been used successfully at Lawrence Livermore National Laboratory (LLNL) for diagnosing pellet implosion at the NOVA laser facility. They have gated a strip-line-MCP-configuration as short as a few tens of psec.

The impedance of the MCP strip line is approximated by the following expression (assuming a 50% open area of the plate):

$$Z_{MCP} = \frac{L}{0.5w(1 + \sqrt{\epsilon_r})} \sqrt{\frac{\mu_o}{\epsilon_o}}$$

where L is the thickness of the MCP, w is the width of the strip, ϵ_r is the dielectric constant of the MCP material, and μ_o and ϵ_o are the permeability and permittivity of free space, respectively. For a typical MCP with a 0.5-mm thickness and $\epsilon_r \sim 8.5$, the impedance of the MCP is $\sim 15 \Omega$ or 6.5Ω when the width of the strip is 6.5 mm or 15 mm, respectively.

Early in the program we contacted Mr. Perry Bell at LLNL, who has extensive experience in the use of ultra-fast gated MCP detectors. Because of a mutual interest, we entered into a collaborative agreement with LLNL, which is interested in the performance or the degradation of the MCP in a high radiation environment. Through a Small Business Initiative Program at LLNL, we received a complete MCP system from LLNL. The system consists of a 40-mm diameter MCP with a 12 mm strip-line gating, a fast (< 10 nsec) gate pulser, video camera and frame grabber, power supplies, vac-ion pump, and cables. Figure 4.13 shows a schematic diagram of the strip-line MCP configuration that we borrowed from LLNL. Using a resistive-capacitive coupling circuit as shown, the strip-line MCP can be operated in dc mode, pulsed mode, or pulsed mode with an additional dc bias for increased gain.

As mentioned above, we were quite concerned about the signal-to-noise ratio from the detector in the harsh accelerator environment, as well as degradation due to radiation damage. Because of the difficulty in making modifications to the diagnostic after it is installed in the high-energy accelerator facility, it was extremely important to ascertain that noise or lifetime problems would not preclude satisfactory operation of the device. With the MCP system from LLNL, we

Figure 4.13. Schematic diagram of the strip-line microchannel plate.

went out to SLAC and installed the system next to the high-energy beam line when SLAC was down temporarily. Figure 4.14 is a photograph of the MCP system installed at SLAC. This is the same location where we ultimately installed our ion probe system. The entire MCP system was assembled in a metal box as shown in Fig. 4.15.

Figure 4.14. Photograph of the MCP system installed next to the SLAC beam line.

Figure 4.15. Schematic diagram of the MCP system.

Preliminary measurements were made with the MCP system as SLAC turned on the high-energy beam. To ensure the proper operation of the MCP system, the ion gauge, which measured the system pressure, was turned on and ions from the background gas striking the MCP were monitored by the video camera. Figure 4.16 shows an image of the strip-line MCP illuminated by the ions from the background gas. In this measurement, the phosphor voltage was 3.5 kV, and the strip-line MCP was dc biased at 850 V. Figure 4.17 shows the image of the MCP when the high-energy beam was on, but the ionization gauge was off.

At the beginning, the SLAC beam was operated at 30 Hz and $\sim 10^{10}$ electrons/bunch ($\sim 1/4$ the normal level). No background noise from the high-energy beam was observed when the MCP was dc biased at the same voltage that was used to obtain Fig. 4.16. Even when the MCP was dc biased at the maximum voltage of 1000 V, no signal was observed on the MCP. The maximum voltage that can be applied to the strip-line MCP is determined by the breakdown voltage. For this MCP, the breakdown voltage is ≥ 1000 V.

For the next several months after the installation, the background noise level measurements were repeated by a SLAC technician. No change was noted in the operation of the MCP with bunches as high as 2×10^{10} electrons. These results showed that background noise generated from x rays at the high-energy accelerator should not be a problem at the levels of gain that could be achieved with the MCP. However, after about 4 months, the ions from the background gas were no longer observed. At this time we could not get access to the MCP system to determine exactly what was damaged. We had to wait for the next down time at SLAC to remove the MCP system from the accelerator tunnel.

The MCP system was removed from the SLAC accelerator facility 8 months after it was first installed. The MCP module was then taken to LLNL to evaluate its performance and deterioration. We are pleased to find that after 8 months in a harsh environment at SLAC, there was no degradation in performance of the MCP, no loss in sensitivity, and no signs of damage. The only component that was obviously damaged was the camera lens, which was discolored. Although we have not tested the video camera, we suspect it is also damaged. This is based upon conversations with SLAC personnel, who have been using video cameras in the same environment and also because we could no longer see the ions. A special hardened camera, a charge-injection-device (CID) camera has been shown to tolerate up to 10^6 Rad total dose before showing any signs of performance deterioration, whereas a regular charge-coupled-device (CCD) camera can only take up to 10^3 Rad. However, the price for a CID camera is $\sim \$5k$ from CID Technology Inc., which is about 15 times more expensive than a CCD camera. Also, a radiation hardened version of a camera lens with the total dose capability of greater than 10^6 Rad from Fujinon is about $\$4k$. For these reasons and based upon the fact that the camera in the first unit lasted for several months, we decided to use a regular CCD camera and lens and mount it as far away from the high-energy

Figure 4.16. Image of the strip-line MCP with ion gauge on, Phosphor voltage: 3.5 kV, DC bias: 850V.

Figure 4.17. Image of the strip-line MCP with ion gauge off, SLAC beam: 10^{10} electrons/bunch. Phosphor voltage: 3.5 kV, DC bias: 850 V.

beam tube as possible. Additional protection was provided by adding lead around the camera. A detailed description regarding the camera issue will be discussed later.

Subsequently, we took the MCP module to our laboratory to test the sensitivity of the MCP to our ion beam, and its operation relative to the rest of the ion probe system.

4.3 Ion Probe Configuration

A simplified schematic diagram of the ion probe system is shown in Fig. 4.18. The plasma chamber output flange is mated to the input end of the optics system. The ion probe beam intersects the high-energy beam at a four-way cross, which can be inserted directly in the SLAC beam line. On both sides of the cross are electropneumatic gate valves, which are interlocked using an ionization gauge that monitors the pressure in the optics region of the probe. The gate valves will be closed automatically when the pressure rises to a certain level, and they can be opened only when the pressure is below a certain level. For our case, the gate valves can only be opened when $P < 1 \times 10^{-5}$ Torr, and they close when $P \geq 3 \times 10^{-5}$ Torr. These pressure levels were set by SLAC to ensure the integrity of their vacuum system. These gate valves, which isolate our ion probe system totally from the SLAC vacuum system, are only open when we are present to conduct the experiment.

The MCP is mounted on the vacuum cross after the gate valve, opposite from the ion gun. The MCP is also mounted on a Conflat flange. The other arm of the vacuum cross is connected to one of the two pumping paths of the vacuum system. The other pumping path goes to the ion gun section directly, as shown in the figure. This pumping configuration provides both the differential pumping to the plasma chamber and the optics system regions, and also the pumping to the MCP region when the two gate valves are closed.

With all the vacuum hardware as shown, the ion beam will be focused at the center of the first four-way cross, where it will intersect with the high-energy beam, then travel 32.7 cm to the MCP. With the 4-cm MCP, this 32.7-cm working distance allows ion deflections up to $\pm 3.5^\circ$ to be measured. To minimize noise and potential damage of the MCP in the high radiation environment, it is desirable that the detector be placed as far from the beam tube axis as possible. Of course, the distance is limited by the expansion of the probe beam. The deflection angle must be kept large compared to the beam expansion angle.

The vacuum pump is a turbomolecular drag pump backed by a diaphragm pump from Balzers. This pumping station provides a totally oil-free system, which is one of the main requirements from SLAC. This pump has a 60 l/sec pumping speed and can pump a volume up to 30 liters. To protect the electronics of the pumping station from the high x rays radiation, the vacuum pump is remotely controlled via a set of 100-ft cables by its electronics and

Figure 4.18. Schematic diagram of the ion probe system.

power supplies, which are located in the control room. The pumping station is located about 150 cm below the high energy beam tube.

The output image from the MCP is monitored using a video camera coupled to a frame grabber and computer. The MCP package that we received from LLNL also includes a frame grabber board. This is a Macintosh-based basic frame grabber board from Neotech. Although we have to transfer the captured image to another software to perform any image processing, we found this frame grabber to be adequate for our application.

4.4 Probe calibration

The MCP and gate pulser were tested to make sure the MCP has enough sensitivity to detect our ion beam. Obviously, we can not generate psec-duration electron bunches in our laboratory to fully test the diagnostic. However, we can generate fast pulses to deflect the ions on a few tens of nsec time scale to verify the soundness of our probe system. Figure 4.19 shows the schematic set-up for the probe calibration. The ion probe system is as described in the

Figure 4.19. Experimental set-up for testing the ion probe system with a parallel-plate transmission line.

previous section, but with the unnecessary vacuum hardware removed. At the center of the four-way cross is a parallel-plate transmission line that can be pulsed to provide a known deflection of the ion beam. The angular deflection, θ , of an ion passing through the parallel-plate transmission line is given by:

$$\Delta v_x = \frac{Ze}{Am_p} E_x \Delta t \quad v_y = \sqrt{\frac{2ZeV_{ion}}{Am_p}}$$

and

$$\theta = \frac{\Delta v_x}{v_y} = E_x \Delta t \sqrt{\frac{Ze}{2Am_p V_{ion}}}$$

where E_x is the electric field across the strip line, Δt is the pulse duration of the pulse applied to the strip line, V_{ion} is the energy of the ion beam, and Ze and Am_p are the charge and mass of the ion, respectively. Of course, the above equation is only valid if the transit time of an ion across the parallel-plate transmission line is longer than Δt .

Figure 4.20 shows the top and side views of the 50- Ω parallel-plate transmission line design. The parallel plates are made out of the PC (printed circuit) board material, with a conductive strip evaporated on it. The length and the width of the PC board are 4 cm and 1.1 cm, respectively. For a 50- Ω air-spaced transmission line the width to gap ratio is about 4.5. For our parallel-plate transmission line the width of the conductive strip is 4.5 mm. Four 1-mm blocks of dielectric material were used as spacers at the four corners of the parallel plates. The parallel-plate transmission line was then assembled together with 5-minute epoxy. The top and bottom plates are connected to 50- Ω 1/4" rigid coaxial cables as shown from the side view of the figure. The parallel-plate transmission line was calibrated with one end of the coaxial cable connected to a 50- Ω pulse generator and the other end terminated into a 50- Ω resistor. Very little reflection was measured at both the generator and the terminator ends, indicating the parallel-plate transmission line is well matched to a 50- Ω system.

Figure 4.20. Design of the 50- Ω parallel-plate transmission line.

Figure 4.21 shows the output pulse of the pulse generator, that drives the parallel-plate transmission line. The pulse duration can be varied from 10 nsec to about 60 nsec. The amplitude

Figure 4.21.
Parallel-plate transmission line gate pulse.
Vertical: 5 V/div. Horizontal: 10 nsec/div.

Figure 4.22.
Microchannel plate gate pulse.
Vertical: 500 V/div. Horizontal: 2 nsec/div.

is fixed at about 37 V. Figure 4.22 is the gate pulse applied to the MCP. This signal was measured immediately at the output port of the gate pulse generator terminated into 50 Ω . The gate pulse has sub-nsec rise time, and about two nsec at the flat top. Because the impedance of the MCP strip line is 12.5 Ω , the output pulse is fed into four equal length 50- Ω transmission lines, which serve as an impedance matching section. Thus, the actual voltage across the strip line of the MCP is about 1/4 of what shown in Fig. 4.22.

Since the MCP strip line is only activated with the application of the few nsec gate pulse, precise timing of the parallel-plate transmission line pulse and the MCP gate pulse is required to detect ions. The time for an ion at a certain energy to travel from the parallel plate transmission line to the MCP was calculated. This time was then used to set the delay to trigger the MCP gate pulse generator. Relative timing between the ion beam pulse, parallel-plate transmission line pulse, and MCP gate pulse is shown in Fig. 4.23. Notice that even though the ion beam pulse duration is only ~ 200 μ sec, when compared to the parallel plate transmission line pulse and the MCP gate pulse, it can be considered as being on indefinitely.

Figure 4.24 shows an output deflection image on the MCP captured by the frame grabber. This deflection was obtained with an Ar ion energy of 3.8 kV, voltage on the parallel-plate transmission line was 37 V, and the pulse duration was 40 nsec. The horizontal stripes through the spots result from the fact that only one field of the interlaced video frame is active during the gate pulse. The image shows both deflected beam and nondeflected beam. Ideally, there should be no undeflected ions at the MCP when it is gated on. Presumably, the undeflected beam spot results from secondary electrons produced by undeflected ions striking the MCP some 20-40 nsec before it is gated on. Some of these electrons have not yet recombined and are thus accelerated through the MCP when it is gated. The ion probe was then tested for several different ion beam energies. The measured deflections agree very well with the calculated values.

Figure 4.23. Relative timing for discharge current pulse, parallel-plate transmission line, and MCP gating pulse.

$$V_{\text{ext.}} = 3.8 \text{ kV}, V_{\text{SL}} = 37 \text{ V}, \Delta t = 40 \text{ nsec}$$

Figure 4.24. Image of ion deflection by an electric field from the parallel-plate transmission line.

5. ION PROBE AT SLAC

5.1 Experimental Set-up

After the ion gun was fully characterized and we had determined that the ion probe system works as expected, we shipped the whole system to SLAC for installation. Once at SLAC, we assembled the ion probe system in an off-line laboratory and performed some basic tests prior to the actual installation to ensure that nothing was damaged during shipment and to demonstrate the operation of the system, particularly its vacuum integrity, to SLAC personnel. Everything checked out as expected and we received final approval to install the system on the beam line. Figure 5.1 shows the schematic diagram of the ion probe system installed at SLAC. In this figure the SLAC beam tube is in-and-out of the page at the four-way cross between the two gate valves. The big tube in the middle of the figure is part of the SLAC alignment system and also provides mechanical support for the beam tube above. Our ion probe system is mounted entirely on our support system. This support system provides adjustments in all three axes and tilts in all three directions. This allows the flexibility needed to mate our ion probe system to the SLAC beam line. The support system is mounted on a standard SLAC "belly band", which is mounted directly on the big tube. The center of the high-energy beam tube is about 66 inches from the floor. To help protect the vacuum pump station from radiation, the vacuum pump is placed on the floor. Although this increases the volume of the vacuum system, the 2.5-inch-diameter straight tube from the pump to the probe system does not significantly slow down the pumping process.

As mentioned before, we were very concerned about the video camera being subjected to intense radiation. Originally, we mounted the video camera directly at the MCP, on the ion gun axis, at approximately the same location used in the earlier test of the MCP. After some discussions with SLAC personnel, who told us that the radiation would be much worse than when we made our previous measurement because of an increase in beam energy, we decided to move the camera as far way from the beam tube as possible. The obvious choice was to place the camera on the floor. To do this, we mounted a 45° mirror right after the MCP and installed a long telephoto lens on the camera. To add extra protection, we put the camera and the lens in a steel frame, and placed 4 layers of 2" thick lead bricks around it as shown in the figure. With this set-up we were very confident that the camera would last long enough to complete our tests. Figure 4.2 shows several photographs taken after the ion probe system was installed at SLAC. Notice that these pictures were taken before we changed the location of the video camera.

Figure 5.1. Schematic diagram of the ion probe system installed at SLAC.

Figure 5.2. Photographs of the ion probe system installed at SLAC.

5.2 Results with SLAC Beam

5.2.1 Preliminary results with low current electron bunches

After SLAC operation resumed, we returned to SLAC and tested our ion probe diagnostic with actual electron bunches for the first time. At the beginning, the SLAC beam was not an individual bunch, but rather a train of bunches. The macro bunch duration was 200 nsec with each micro bunch about 5 psec long, and the separation between the micro bunches was 345 psec. The total charge of the macro bunch was about $5 - 8 \times 10^{11}$ electrons/bunch. Accompanying the macro bunches was a so-called witness bunch, a single bunch with a duration of 5 psec. This witness bunch was at a rep rate of 1 Hz, and the total charge was about 0.5×10^{10} electrons/bunch. Although the total charge of the macro bunch was very high, the charge for each individual micro bunch was not high enough to deflect the ions by any measurable displacement on the microchannel plate. It was calculated that for 3-kV helium ions, the lightest ion of the inert gas family, the ion deflection was on the order of a few 100's of μm . This was smaller than the diameter of the ion beam observed on the MCP. For this reason, we synchronized our ion probe diagnostic to the witness bunch to make the measurements.

To make the measurement of the SLAC beam, precise knowledge of the time the high-energy electron beam crosses the four-way cross of the diagnostic system is required. The synchronization of the ion probe diagnostic system to SLAC's beam was accomplished with the pre-trigger pulses provided by SLAC. These pre-trigger pulses are precisely timed to the witness bunch and can be adjusted relative to when the witness pulse crosses a specific location. These pre-trigger pulses were used to trigger the plasma source and the micro channel plate gate pulser separately. One pre-trigger pulse was set at 50 μsec prior to the electron bunch arrival at the four-way-cross to trigger the plasma source. This means with a 100- μsec duration of the ion beam, the electron bunch crosses the four-way cross at the middle of the ion beam pulse. To trigger the MCP gate pulse, additional delay, which took into account the traveling time of the ions from the center of the cross to the MCP, was added to the pre-trigger pulse. Propagation time in the cable (~ 150 ft) from the gate pulser unit to the MCP module was also taken into account.

To obtain the highest sensitivity from the ion probe, the lowest energy of the lightest ions should be used. In our case, the lowest energy of helium ions that could be produced with adequate ion beam quality was 1.5 kV. It was calculated that with 1.5-kV helium ions, a maximum deflection of about 3 mm is expected on the micro channel plate by a Gaussian high-energy beam with $\sigma = 200 \mu\text{m}$ and a total charge of 0.8 nC. Since we do not know the exact location of the high-energy beam relative to our ion beam, the ion beam was then scanned vertically in 100 μm steps. This procedure continued until the ion deflection was observed.

Figure 5.3.a shows the ion beam image on the MCP detected by the video camera and captured by the frame grabber board. Again, the alternate dark spaces between the bright strips result from the interlacing effect of the 30-frame/sec video camera. Since we are using a phosphor screen with a few millisecond persistence as a read-out device, the image is limited to one field of the interlaced scan. Figure 5.3.b shows an image of the ion beam deflected by the high-energy beam. In this picture, the high-energy beam is traveling vertically upward on the left, hence causing the ion beam to deflect from right to left, toward the high-energy beam.

Figure 5.3. Ion beam detected by the MCP (a), and deflection of the 1.5-kV ion beam (b).

5.2.2 Results with higher current electron bunches

With the SLAC beam tuned up to a higher current level with $n \sim 2$ to 3×10^{10} electrons in a single bunch, we went back to SLAC to make additional measurements. Since the bunch current is relatively higher than before, we can use Argon ions instead of helium to keep the deflection within the 4-cm microchannel plate. Figures 5.4.a and 5.4.b show typical deflections of the ion beam, which was on the right and on the left hand side of the electron bunches, respectively. In these figures, the electron bunch was traveling vertically upward. The directions of the deflection are as expected. The ion beam deflected from right to left (Fig. 5.4.a) as the ion beam was scanned from left to right and as it past the electron bunch the deflection changed direction and deflected from left to right (Fig. 5.4.b).

Figure 5.4. Typical deflections of the ion beam on the right (a), and on the left (b) hand side of the electron bunches.

Figure 5.5 shows the deflections of a 2.5-kV Ar ion beam at different sampling times. As the theoretical calculations predicted in Fig. 2.6, the ion deflections that reach the MCP span a few tens of nsec. Note that when these images were obtained, the video camera was damaged and several of the spots seen in these images result from bad pixels. In these images, the maximum deflection occurs at t_0 , where two distinct spots from the undeflected and deflected ions are seen. When the delay of the MCP gating pulse was adjusted from this t_0 to $t_0 \pm 5$ nsec the deflections seen on the MCP were smaller, although two distinct spots were still observed. When the delay was adjusted further the deflection was just a streak from the undeflected beam to the deflected beam, as seen in $t_0 \pm 10$ nsec images. Finally, when the delays were either too small or too large, as expected only the undeflected beam was seen, as in $t_0 \pm 30$ nsec.

To determine the dependence of the deflection on the impact parameter, the ion beam was scanned across the high-energy bunches, and the amplitude of the deflection was measured. Impact parameter is defined as the distance from the center of the electron bunch to the center of the ion beam. In our case since we do not know the exact location of the electron bunch, the impact parameter is just a relative parameter. Deflection as a function of impact parameter is shown in Fig. 5.6 for ion energies of 1.875 kV and 2.25 kV. In both cases, the deflection gradually increased as the ion beam was scanned from the left of the high-energy beam. Maximum deflection is produced when the ion bunch is at the peak field, and the deflection decreased to zero

Figure 5.5.

Deflections at different sampling times
 $HV=2.5kV$, $I(fil)=17.1A$, $V(dis)=34.3V$, $P=5mT$.

as the ion beam was scanned toward the center of the electron bunches. The exact same behavior was observed, but in opposite direction, as the ion beam was scanned from the center of the electron bunches toward the right. The deflections started to increase, reached the maximum at the peak field, and gradually decreased as the ion beam was scanned from the center of the electron bunches toward the left. As expected, lower energy ions produced larger deflections.

Ideally, if the diameter of the ion probe beam is much smaller than the electron bunches, the distance between where the maximum and the minimum deflections occur is a representation of the size of the electron bunches. When these measurements were made, the ion probe beam was much bigger than the electron bunches at the interaction region. Therefore, the distance between where the maximum and the minimum deflections occur is essentially the diameter of the ion probe beam.

Unfortunately, due to numerous problems with the SLAC accelerator, we were never able to repeat this scan with a more finely focused ion beam. Also, during the measurements we were able to make, the SLAC beam was not very stable. SLAC operators were continually adjusting parameters, so it was difficult to complete an extended scan with the SLAC beam parameters constant.

Figure 5.6. Deflection vs. Impact parameter for two ion probe beam energies.

5. CONCLUSIONS

The experimental results shown in Fig. 5.6 can be compared with theory, and to some extent with wire scanner data that was obtained simultaneously from monitors about 200 m upstream of the ion probe. The symmetry of the ion deflection data is quite good, with a peak deflection of about ± 4 mm with 1.875-keV Ar^+ ions. This corresponds to a deflection angle of 0.76° . For a bunch of 3×10^{10} electrons with a circular beam cross section, the impulse model (Eq. 10) predicts that $\sigma = 240 \mu\text{m}$. This is somewhat larger than the wire scanner measurements, which ranged from 40 to $90 \mu\text{m}$ in the vertical direction (x in our coordinate system) and 130 to $180 \mu\text{m}$ in the horizontal direction (y). Taking into account the elliptical nature of the beam, using Fig. 2.2, we can account for much, if not all, the apparent discrepancy. Data from four upstream wire scanners show elongation (vertical/horizontal) ranging from 0.22 to 0.67. This is the h factor, ellipticity, used in Fig. 2.2. Thus, we see that the reduction in E_x would range between 0.39 and 0.83. Thus, the prediction of σ_x would be reduced to a range of 95 to $200 \mu\text{m}$. This points out the need for simultaneous vertical and horizontal ion probe measurements for an elliptical beam. The ratio of the two measurements would be a direct measure of ellipticity.

The reasons for whatever discrepancy remains are unclear. Obviously, without having independent measurements at nearly the same location as the ion probe, it is very difficult to know even how large a discrepancy there really is. Potential sources of error are relatively few: the ion energy, mass, and charge are well-determined by the set-up, and the deflection pattern seems quite clear and well-defined. For the ion probe to over-estimate the electron bunch size, the ion energy would have to be larger than measured, the ion mass greater, or the charge smaller. None of these scenarios is plausible. If anything, one might argue that the ion energy could be smaller (due to losses in the transmission line) or the charge larger (multiply-charged ions), but in our extensive tests prior to collection of the data, no such anomalies were observed. Another possibility is that the maximum deflection of the ions might not be observed on the MCP. This is more plausible, but the well-defined deflected beam spot that varied as predicted as the timing was varied argues against this explanation. The other potential source of error is the charge in the electron bunch. If there were only 1 to 1.5×10^{10} electrons in the bunch, the predicted σ would be 2 to 3 times smaller.

There are two fundamental limitations that will undoubtedly come into play as the bunch size is reduced. First, the ion density n_i must be increased to ensure a reasonable number of ions interact with the maximum field of the bunch. Second, when the CPB field becomes sufficiently intense, additional electrons will be stripped from the ions as they interact with the CPB. From a practical standpoint, the only sure way to avoid this latter problem is to inject fully stripped ions, resulting in a limiting value of A/Z of ~ 2 . Thus, protons or possibly deuterons would be the ions of choice, and higher energies would be required to maintain a constant scattering coefficient, $[Z/(AV)]^{1/2}$.

To analyze the ion density condition, we note that to have an average of 1 ion in the peak field of the CPB, $n_i \geq 1/V_M$, where V_M is the interaction volume over which the field is maximum. It can be shown that the value of E_x for a gaussian beam is greater than 97% of the peak field over a cross sectional area in the xy plane of $0.4 \sigma^2$. If we assume the ion beam is radially uniform

over its diameter, D_i , we have $\mathcal{V}_M = 0.4 \sigma^2 D_i (1 + \Delta y / 0.8\sigma)$. Here, Δy is the ion motion in the y direction during the transit time of the CPB bunch and 0.8σ is the extent of the region of $\geq 97\%$ peak field in the y direction. Then the required current density is simply

$$J_i \geq \frac{Zev_i}{0.4\sigma^2 D_i \left(1 + \frac{v_i}{c} \frac{L_b}{0.8\sigma}\right)} \quad (11)$$

As an example, for a CPB with $\sigma = 1 \mu\text{m}$ and $L_b = 1 \text{ mm}$ and a 40-keV, 30- μm -diameter proton beam, we find $J_i \geq 0.29 \text{ A/cm}^2$, corresponding to a total ion current of $2.1 \mu\text{A}$. Shrinking the bunch to $\sigma = 0.1 \mu\text{m}$ while maintaining the same bunch length would require ten times the ion current, because the second term inside the parentheses in the denominator of Eq. 11 is $\gg 1$. Of course, these values could be reduced by monitoring the interaction with a large number of bunches using sampling techniques, but single-bunch diagnosis clearly is limited by available ion source technology.

Another potential issue is the sensitivity of an ion probe diagnostic to stray magnetic fields. From the Lorentz force equation, the contribution to v_x from a magnetic field B_z is $\Delta v_x = ZeB_z v_y t / M$, where t is the duration of the interaction with the field. The x displacement due to the magnetic field is then found to be

$$\Delta x = \sqrt{\frac{Ze}{8Am_p V}} B_z L_y^2. \quad (12)$$

Here, L_y is the distance the ion travels in the field. In practical units, this displacement is

$$\Delta x[\mu\text{m}] = 1.094 \sqrt{\frac{Z}{AV[\text{keV}]}} B_z[\text{G}] L_y^2[\text{cm}]. \quad (13)$$

For a worst case scenario, we could assume that the total travel distance is 30 cm and that a uniform z -directed magnetic field extends over this entire distance. In that case, a 25-keV proton would be displaced by $2.0 \mu\text{m}$ in a 10-mG field. Several factors could reduce the deleterious impact of the stray magnetic field, however. First, the effects of a dc magnetic field can easily be calibrated out, so that it is really only the time-varying field that must be reduced to a very low level. Second, the critical region of the ion's path is between the gun and the bunch being diagnosed, which is usually only a few cm at most, because this path completely determines the impact parameter of the interaction. Once the deflection occurs, the total ion displacement over a distance of 20–30 cm is very large ($\sim$ centimeters), so an error of even 10–20 μm is not significant. Finally, heavier ions or higher ion energy obviously reduce the sensitivity to stray fields. Thus, if we take a more realistic scenario of a 20-keV Ar^+ ion with a travel distance of 4 cm from the gun to the beam tube axis, a 1.6-G stray field would be required to deflect the ion by $1 \mu\text{m}$ over the 4-cm distance to the bunch. Thus, in most cases, the problem of errors induced by a stray magnetic field should not be too difficult to overcome. This is an important advantage over the electron probe. Of course, the sensitivity of the ion probe is also correspondingly less, but as we have seen, the sensitivity is more than adequate for tightly bunched beams.

One other aspect of the ion probe that may be questioned is the perturbation of the high-energy bunch by the ion beam. The current of the ion beam is so small that the electromagnetic field of the beam itself is negligible, leaving particle collisions as the major source of perturbation. If we assume a very tightly focused electron bunch of 10 nCoul with $r_b = 1 \mu\text{m}$ and $L_b = 1 \text{ mm}$, the electron density is $n \sim 2 \times 10^{19} \text{ cm}^{-3}$. The probability of any single ion having an impact parameter within a radius r_c of at least one electron in the bunch is $n\pi r_c^2 L_b$. Thus, the probability of an ion coming within 10 classical electron radii ($3 \times 10^{-12} \text{ cm}$) of at least one electron is $\sim 5 \times 10^{-5}$. Because the ion current required to diagnose a psec-duration bunch (without sampling or averaging) is on the order of tens to hundreds of nA, in which case fewer than 100 ions will actually pass through any single bunch of this small size. Thus, the probability of a significant perturbation of the bunch is extremely small and can be neglected.

In summary, we have developed and demonstrated a new diagnostic for tightly bunched charged particle beams. This non-perturbing ion probe is capable of measuring beam position and profile to a high degree of accuracy. The experimental results obtained with the prototype version of the probe that we fielded at SLAC have shown the ion probe diagnostic to be feasible, reliable, and well understood by the theory and models described in Sec. 2. During experiments at SLAC, no fundamental problems were discovered that negatively impacted the probe. Of course, at the location in which the probe was installed, the minimum size of the electron bunch was ~ 50 to $100 \mu\text{m}$, so questions regarding the ultimate limit for the ion probe still remain. Also, the numerous accelerator problems that were encountered during our test sequences prevented us from making as detailed comparisons with theory and with other SLAC diagnostics as we had hoped.

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