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FLUORESCENCE-BASED VIDEO PROFILE BEAM DIAGNOSTICS:
THEORY AND EXPERIENCE

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FLUORESCENCE-BASED VIDEO PROFILE BEAM DIAGNOSTICS: THEORY AND EXPERIENCE*

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ABSTRACT

Inelastic collisions between accelerated particles and residual gas in the accelerator vessel can cause the residual gas to fluoresce. The gas fluorescence intensity is proportional to the current density of the particle beam. This process provides the foundation for a video diagnostics system to measure the profile and position of accelerated particle beams. This, in fact, has proven to be a useful diagnostic at several installations¹⁻⁵. This paper describes the light production process resulting from beam - residual gas interactions and gives formulas for estimating the beam radiance for various conditions. Ground Test Accelerator (GTA) radiance calculations will be used as an example. In addition, measurement experiences with the GTA video diagnostics system will be discussed.

INTRODUCTION

A diagnostic that measures both the horizontal and vertical beam profiles and centroid positions of a high-current H^- particle beam is needed to monitor the input match point of the DTL. A small amount of nitrogen is injected into the beam viewing region to increase light production. H^- ions collide with the nitrogen causing the nitrogen to fluoresce, primarily at wavelengths near 400 nm with a relaxation time of approximately 60 ns⁶. The video approach was selected because of its non intrusive nature and relatively small longitudinal dimension (2.0 cm). The system consists of a set of optics used to relay the beam image to an intensified CCD camera, a piezoelectric valve (used to inject gas into the vacuum for increased light output), a control system and electronics to interface between the control system, valve and camera. The control system controls the data acquisition and analysis as well as the camera, intensifier and gas valve.

FLUORESCENCE MECHANISMS

As accelerated particles (H^- , proton, electron, etc.) pass through residual gas in a vacuum, collisions between the gas molecules and the accelerated particles have various effects. If the accelerated particle is heavier than an electron, (proton, mu or pi meson, etc.) collisions with a residual gas nuclei result in small energy transfers from the accelerated particle to the nucleus (elastic collision) but does result in scattering of the incident particle because of the nuclei's greater charge. A collision between the particle and a bound electron results in very little scattering, but can take up appreciable amounts of energy from the incident particle. Thus, the loss of energy from the incident particle occurs almost entirely because of the collisions with electrons. If the

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accelerated particle is an electron, collisions with atomic electrons cause both energy loss and scattering. Therefore, electrons tend to diffuse after traveling only a short distance.

The transfer of energy from the accelerated particles to the residual gas molecule can ionize the gas molecule or cause its electrons to become excited. Photons generated when excited electrons fall back to their lower energy levels can be used to measure beam profile and position of the accelerated particle beam.

ENERGY LOSS

In this paper we are particularly interested in light production which result from interactions between protons and H^- atoms with background gas in a vacuum. In order to estimate the light production resulting from these interactions, one must determine the energy loss, dE , caused by inelastic collisions in a given volume then determine the percentage of energy lost which is converted to visible light. The assumption that all energy loss occurs because of collisions with bound electrons will be made. It is also assumed that accelerated H^- particles and accelerated protons (same beam energy) produce an equivalent number of photons per collision.

The Bethe-Bloch energy loss equation for protons as given in reference 7 is

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right] \quad [1]$$

where the product $4\pi N_A r_e^2 m_e c^2$ equals $0.3071 \text{ MeV cm}^2 \text{ g}^{-1}$, βc is the velocity of the accelerated particle with charge $z e$, atomic number Z and atomic weight A ; m_e and r_e are the electron mass and the classical radius of the electron. The ionization constant I is approximated by

$$I = Z^{0.9} eV, \quad [2]$$

$$\gamma = \left(1 - \frac{v^2}{c^2} \right)^{-1/2}, \quad [3]$$

and

$$\beta = \frac{v}{c}. \quad [4]$$

The last term in the brackets, $\delta/2$, is a correction for density effects and will not be included in any calculations in this paper.

In order to determine the energy lost per unit length (cm) one must multiply equation [1] by the density (g/cm^3) of the background gas.

Alternatively, for many materials one can look up dE/dx in energy loss tables⁸.

It must be noted that some electrons will be ejected from the target nuclei and in turn collide with other gas molecules. Such collisions may produce light which could broaden the apparent beam size.

PHOTON INTENSITY

One can compare energy loss for a set of given parameters calculated by using equation [1] to that determined by a range-energy chart or table⁸. The energy loss for a single proton at several beam energies is shown in Table 1. As can be seen, the two methods agree with each other to within a few percent. Equation [1] gives a convenient method for calculating dE/dx and is in good agreement with the range-energy tables⁸. It must be noted that for lower beam energies (below approximately 1 MeV) the equations and tables become less accurate. A discussion on the limitations of equation [1] and the range-energy loss tables are given in the references [7] and [8] respectively.

Beam Energy	dE/dx Tables	dE/dx eq. [1]
2 MeV	141.7 MeV cm ² g ⁻¹	139.2 MeV cm ² g ⁻¹
30 MeV	16.5 MeV cm ² g ⁻¹	16.41 MeV cm ² g ⁻¹
100 MeV	6.43 MeV cm ² g ⁻¹	6.40 MeV cm ² g ⁻¹

Table I. Energy loss calculated using equation [1] and using the energy loss tables given in reference [8]. The beam parameters are those given in Chamberlin's paper.

Chamberlin⁶ gives measured light radiance of 9.1 $\mu\text{W}/(\text{sr cm}^2)$ for a 100 keV proton beam with a current density of 100 mA/cm² passing through a vacuum of 10^{-5} torr. He assumes a wavelength of 400 nm and gives an uncertainty of a factor of two for the measurement. A temperature of 300° K is assumed. The energy loss dE/dx was calculated for Chamberlin's parameters both by using equation [1] and by extrapolating from a range-energy chart⁸. The calculations showed that approximately 4% of the energy lost is converted to visible light if one uses equation [1] and 8% if one uses the range-energy chart. In this paper we will use the range energy chart and assume that 8% of the energy loss is converted to visible energy (photons). The wavelength of all photons produced is assumed to be 400 nm to facilitate calculations. In reality the spectrum is quite broad and must be measured in order to determine the appropriate "average" wavelength.

Knowing dE/dx (MeV/cm) for a single particle and the accelerator current one can now estimate the total energy loss $(dE/dx)_t$ in J/(cm sec) to be

$$\left(\frac{dE}{dx}\right)_t = \frac{dE}{dx} \left(\frac{1 \times 10^6 \text{ eV}}{1 \text{ MeV}} \right) \left(\frac{1.602 \times 10^{-19} \text{ J}}{\text{eV}} \right) \left[i \left(\frac{\text{coul}}{\text{sec}} \right) \right] \left[6.24 \times 10^{18} \left(\frac{\text{particle}}{\text{coul}} \right) \right]. \quad [5]$$

The number of photons, N_{ph} produced becomes

$$N_{ph} = \left(\frac{dE}{dx} \right)_t \frac{lf}{h\nu} \quad [6]$$

where $(dE/dx)_l$ is in J/cm, l is the beam length of interest in cm, f is the fraction of energy converted to photons, h is Planck's constant and ν is the frequency of the photons in Hz. The radiance^a L ($\text{Wcm}^{-2} \text{sr}^{-1}$) is given by

$$L = \left(\frac{dE}{dx} \right)_l \frac{fB_L}{4\pi A_{\text{view}}} \quad [7]$$

where A_{view} is the area of the beam being viewed and is defined as the beam length viewed (B_L) multiplied by the beam diameter (B_D).

If one makes the approximation that the beam is a flat lambertian source which radiates into 4π sr, the irradiance E_L on the lens (see Figure 1) is given by⁹

$$E_L = L \int_0^{\theta_{1/2}} \int_0^{2\pi} \cos \theta \sin \theta \, d\phi \, d\theta \quad [8]$$

where $\theta_{1/2}$ is one half the field of view angle. Integrating, gives

$$E_L = \pi L \sin^2 \theta_{1/2}. \quad [9]$$

Assuming that all the radiant energy passing through the lens system is captured by the detector, the irradiance on the detector (E_D) is

$$E_D = \frac{E_L T}{M} \quad [10]$$

where T is the lens transmission and M is the magnification of the lens system.

Figure 1. Light radiating from beam induced fluorescence captured by the lens.

EXAMPLE CALCULATION

GTA parameters: Beam current (i) = 30 mA, Beam energy = 2.5 MeV, Beam width = 6 mm (assumed to be uniform), Vacuum pressure assuming injection of $N_2 = 1 \times 10^{-5}$ torr, Gas temperature = 300° C, Beam length viewed = 1 cm, Beam pulse width = 300×10^{-6} sec, lens aperture = 2 cm, beam center to lens distance = 10 cm, lens system magnification (M) = 0.5, lens transmission = 80%.

^a Radiance in radiometric units is equivalent to luminance in photometric units.

Using the range energy chart⁸ $dE/dx = 1.8 \times 10^{-9}$ (MeV cm⁻¹) for a single particle. The total energy loss $(dE/dx)_t$ (assuming a CW beam) is given by equation 5.

$$\left(\frac{dE}{dx}\right)_t = 5.4 \times 10^{-5} J / (cm \text{ sec}).$$

and the beam luminance^b (L) for a single macropulse^c is

$$L = \left(\frac{dE}{dx}\right)_t \frac{fB_L}{4\pi A_{view}} \left(\frac{3 \times 10^{-4} \text{ sec}}{16 \times 10^{-3} \text{ sec}}\right) \left(\frac{300 \text{ lumens}}{1 \text{ Watt}}\right) \left(\frac{1 \times 10^4 \text{ cm}^2}{m^2}\right) = .032 \left(\frac{\text{lumens}}{m^2 \text{ sr}}\right)$$

$$\theta = \arctan\left(\frac{1 \text{ cm}}{10 \text{ cm}}\right) = .0997 \text{ rad}$$

Using equation 10 gives an irradiance (E_D) on the detector of 1.6×10^{-3} lux.

The intensified camera that was selected has a threshold sensitivity of 1×10^{-5} lux.

GTA VIDEO DIAGNOSTICS SYSTEM DESCRIPTION

The optical system in each plane (x and y) consists of two lenses inside the vacuum vessel that relay the image to a third motorized lens which is attached to an intensified CCD camera. The camera is located outside the vacuum vessel in a light-tight box (Figure 2). A piezo-electric valve is used to inject a small portion of gas (N₂) from reservoir near the vacuum vessel into the beam viewing region to increase the light intensity.

The first lens is located 10.5 cm from the beam axis and captures the maximum amount of light, given the physical constraints at the location of the lens system. The second lens transmits all the light that passes through the first lens and forms an image of the beam between the second lens and the camera lens. The majority of light is then captured by the camera lens and re-imaged on the intensifier. An extension tube is placed between the lens and the camera to properly focus the image on the intensifier. All the lenses have broad band AR (anti-reflection) coatings for maximum transmission. The total transmission of the optical system is estimated to be approximately 80-90%. The scale factor of the system is 73 microns per digitized pixel in X and 83 microns per digitized pixel in Y. There are 512 digitized pixels per line and 240 lines per image. The resolution of the video system was measured to be 4.1 line pairs per mm.

^b For a typical CCD camera the conversion factor between radiometric and photometric units is approximately 300 lumens per Watt at a wavelength of 400 nm. This is dependent on the camera's wavelength response characteristics.

^c The integration time for a typical CCD camera is approximately 16 ms per frame. The timing system is set up such only one frame contains data. Therefore, the duty factor of the beam irradiance on the camera is the beam length over the integration time.

Figure 2. VPM hardware configuration.

While the vacuum vessel is open, lenses 1 and 2 are individually moved along the optic axis to optimize the image clarity. The zoom, focus, and iris settings for the motorized lens can be controlled remotely at any time. The integration time (gate width) and the intensifier gain of the camera can also be controlled remotely. The optical gain of the camera is 20 k. The signal-to-noise ratio in a typical data set is approximately 60:1 for a gate width of 300 μ s, 25 mA of beam current and an estimated gas pressure of 1×10^{-5} Torr (after injecting gas) in the VPM (video profile monitor) region during data acquisition.

ELECTRONICS

The electronics consists of several subsystems (see Figure 3) which handle separate functions.

One subsystem consists of a piezoelectric valve driver which opens the valve for a specified duration, usually 3 ms. As a precautionary measure, this subsystem also includes electronics which limit the time the valve remains open. The fact that the pulses to the valve are so short causes the valve to have a tendency to stick closed. If the valve has been idle for a long time it usually requires several consecutive pulses to get the valve to work properly.

A second subsystem allows the camera gate and gain to be controlled remotely, either manually or under computer control. The lens controllers allow the lens functions (i.e., zoom, focus, etc.) to be controlled remotely, either manually or under computer control. A timing module housed in the VME crate controls all timing functions. This timing card is also the driver for reference LEDs which are used to calibrate the system. All digitization is done in the video VME crate¹⁰.

Figure 3. Video profile diagnostic block diagram.

CONTROLS

The VPM control system incorporates the GTA control system to perform the basic hardware functions of setting the focus, zoom, and iris positions on the motorized lens. It also controls the intensifier gain and gate for the camera and the nitrogen flow through the piezoelectric valve.

Data is acquired and stored as an 8-bit image having dimensions of 512 by 240 pixels. Real-time plotting of a single row or column of data as well as its full-width half-maximum width is available. A description of the control system is given in reference 10.

DATA ACQUISITION AND ANALYSIS

VPM data were taken at several settings of the field strength of the last two quads on the IMS. Emittance runs were taken in conjunction with the VPM data to characterize the validity of the VPM data. The data was compared to width and position information obtained using a slit and collector. Because the slit is several centimeters downstream of the VPM, the slit and collector data was traced back to the VPM location using TRACE 3D and REANE. TRACE 3D is an interactive beam-dynamics code that calculates the envelopes of a bunched beam through a user-defined transport system. REANE is an analysis code used to analyze slit and collector data. It can take a

measured phase-space distribution, propagate it using a user-defined transport matrix and give theoretical beam distributions at the desired location. In both cases the resulting analysis provided beam widths at the VPM location. REANE provided position information as well.

The initial results of the on-line data analysis produced VPM beam widths larger than widths obtained using the slit and collector method. Subsequently the video profile images were transferred to a Macintosh for analyses using Spyglass-Transform¹¹ and Sigma Plot¹². Several lines (approximately 15) are averaged together to reduce random noise in the data. The averaged waveform was then fit to a sum of two equations, one to fit the primary signal and one to fit a broad background:

$$f = a_1 \frac{1}{s_1 \sqrt{2\pi}} e^{-\frac{(x-m_1)^2}{2s_1^2}} + a_2 \frac{1}{s_2 \sqrt{2\pi}} e^{-\frac{(x-m_2)^2}{2s_2^2}} + b \quad [11]$$

where, a_1, m_1 and s_1 (a_2, m_2 and s_2) are the amplitude multiplier, the mean and standard deviation of the signal (background) and b is the dc offset. The dc offset in the background is due to dark current in the CCD array, luminous background and digitizer noise. This same equation fits data taken from an image of the reference LED's. This implies that the tails in the data are a systematic effect and was originally assumed to be photons in the intensifier leaking into adjacent pixels. Upon further investigation it was shown that an image is indeed broadened by the intensifier but not enough to account for the broadened tails seen in the data. Another possible contribution to the broadening effect might be stripped electrons which cause additional gas fluorescence. Further investigation is needed to determine the cause of the broadening effect.

Fig. 4. Raw VPM data plot with fitted curve superimposed.

Figure 4 shows raw VPM data with its fitted curve superimposed. Width and position information are then extracted from the data using eq. (11). One Gaussian represents the data; the other represents the broadening effect.

Figure 5 shows the beam width and position obtained with the VPM compared with the slit and collector data analyzed with REANE. The VPM data was analyzed using the above mentioned routine.

The above analysis routine has been implemented for on-line data analysis, with the exception that the background and data centroids are forced to be at the same locations. Allowing the centroids to be non-coincident does not contribute significantly to any changes in determining the width or location of the beam.

Fig. 5. Vertical beam widths and centroid location measured using the slit and collector apparatus and the VPM for several IMS output quad settings.

FURTHER INVESTIGATIONS

It is clear that much can be learned in order to better understand this diagnostic technique. For example, it is not clear what causes the tails in the acquired wave forms. One source may be loose electrons causing the beam to fluoresce. If this is the case, then one could place electrostatic plates in the vicinity of the profile measurement and look for changes in the shape of the tails. Another possibility for the cause of the broadening effect might be that there are metastable states in the background gas molecules. Any photons produced when the electrons fall to their lower state may be emitted after the molecule has drifted out of the beam region.

It would also be useful to measure the relative intensities of the various wavelengths of light produced when a proton beam passes through various gases (air, N_2 , O_2 and H_2) while keeping the vacuum pressure constant.

CONCLUSIONS

The VPM diagnostic as implemented at Los Alamos has proven to be a useful diagnostic which will benefit GTA and with modifications can be used on other accelerators. Results show that both position and width information agree quite well with other diagnostics (slit and collector).

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