OPTICAL BEAM SENSORS FOR RFQ1-1250*

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Abstract

The optical beam sensor system for the RFQ1-1250 direct injection line uses a pair of RETICON™ line scan cameras to view the light generated by the interactions of the beam with the residual gas. This non-intercepting sensor provides an on-line determination of beam profiles and position. This paper describes the cameras and their applications as well as some of the software features. The camera software has recently been modified to allow on-line display as well as archiving of data for later analysis. This on-line feature is used during operation to optimize the ion source beam match.

Introduction

The direct injector [1] on the RFQ1-1250 cw radiofrequency quadrupole accelerator [2] comprises a 50 keV electron-cyclotron-resonance (ECR) single-aperture proton source [3] and a short, 1 m long, low-energy beam transport (LEBT) system. Total design beam power in the LEBT is ≈ 6 kW (120 mA @ 50 kV) and average beam power intensity varies over a large range. About three-quarters of the LEBT consists of a drift space from the source to a RFQ matching solenoid, where the power intensity ranges from ≈ 100 kW/cm^2 at the source extraction column to ≈ 100 W/cm^2 at the solenoid (the same type of variation applies in reverse at the focus to the RFQ). Over most of the LEBT, intercepting beam diagnostic devices are not practical as they cannot be sufficiently cooled to prevent melting.

Beam interactions with the background gas in the LEBT result in light emissions, which are useful indicators of transverse beam profile and position. Windows in the LEBT vacuum chamber allow the beam-imaging/camera systems and the associated electronics to be placed outside the chamber, thus providing an easily accessible, non-interfering diagnostic, well suited for "on-line" operation.

RETICON™ photodiode line scan cameras [4] have been used for a number of years on RFQ1 to view transverse beam-light profiles. For the direct injection experiment, a pair of these cameras, interfaced with an IBM 286 computer, provided the operator with continuous on-line profile and position measurements of the beam from the ion source. Figure 1 shows a photograph of the system components.

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Fig. 1 RETICON™ camera, extension tubes, interface electronics and computer.

RETICON™ Camera and Optics

The EG&G Reticon LC1902 camera is a commercially available line scan camera marketed primarily for non-contact optical sensing of size, shape and position. Any object or pattern can be imaged, provided light levels are suitable and there is sufficient contrast against the background. The RFQ1 cameras contain a linear array of 256 discrete silicon photodiodes, on a 13 μm centre-to-centre spacing with an aperture width of 13 μm, connected to a CCD (charge-coupled device) shift register. The aluminum camera body is threaded to accept various lens mounting assemblies and is sufficiently rugged to be used in shock- and vibration-prone environments.

To operate the camera, an external clock and a line-transfer pulse are required. The line-transfer pulse triggers a scan of the array at the clock frequency. The video signals from odd and even pixels are transmitted as an alternating pulse train of 128 pulses (at half the clock frequency) on separate lines. The output pulse amplitudes are proportional to the light intensity on the corresponding diodes. The camera clock will accept any frequency from 20 kHz to 20 MHz (13 ms to 13 μs to read out the diode array).

The camera continuously exposes the diode array, and an array reset occurs at the end of each readout cycle. The maximum exposure time, however, is limited by dark current, which, at room temperature, saturates the diode output after about 500 ms. Nevertheless, one can make useful readings at signal levels as low as $\approx$ 10% of the dark current. Cooling the array can drastically reduce the dark current, but at the expense of increased cost and complexity. The cameras operate satisfactorily on RFQ1 at room temperature with a 20 kHz clock frequency.

For applications on the RFQ1 LEBT the cameras are used with 25 mm focal length lenses. At the minimum lens-to-object distance of $\approx$ 50 cm, a 6 cm object plane can be imaged with 0.25 mm resolution. To maximize light exposure the lowest f stop (focal length to aperture diameter ratio) setting of 1.8 is used. The resulting depth of field, assuming the acceptable blur spot to be the diode centre-to-centre spacing, is about 2 cm.

LEBT Light Emissions

Light emission in the LEBT results through interactions between the H^+, H_2^+ and H_3^+ beam particles and the low pressure ($\approx 5*10^{-5}$ torr) H_2 background gas. The visible light spectrum is characterized by the hydrogen Balmer emission lines. The cross sections for these emissions [5] are maximum in the 20 to 80 keV range, nicely bracketing the 50 keV LEBT beam energy.

Light from the beam in the LEBT is easily visible to the naked eye over the full 10 - 120 mA range of currents. The silicon diode, with a spectral response extending from 200 nm to 1100 nm and a peak response in the red to infrared (i.e., 650 nm to 850 nm), is well suited for detection of this light. However, the intensity is low and when viewed with a RETICON™ camera the peak signal levels are typically between 10% and 100% of the dark current. These signal levels are acceptable, providing the camera signal electronics have adequate resolution and stability.

Computer Control

The cameras are controlled from an IBM 286 computer. An electronics interface provides control and video signal conditioning for up to four cameras. The interface includes amplifiers and recombination circuitry to condition and combine the odd and even camera video signals prior to digitization. A master control circuit generates the gating and 20 kHz clock frequency signals to select and operate the cameras.

The required signal resolution is provided by a variable gain 12-bit (bi-polar) computer data acquisition board that digitizes the combined video signal. A data acquisition program on the computer collects and displays the digitized camera video signal in a position-versus-intensity table. The operator can select the camera(s) to be operated and adjust ADC gain and exposure time. Optionally, scans can be averaged to improve signal quality. A rolling average on the video signal removes any residual odd/even signal imbalance in the video signal.

For the direct injection experiment, the data acquisition program was modified to give a continuous "on-line" display of beam scans. Scan parameters were adjusted to give profile updates every few seconds.

Examples of Measurement Results

Two cameras provided horizontal and vertical views of the beam through plexiglass ports $\approx$ 35 cm from the ECR source. To provide the full range of required proton current (10 - 120 mA), different aperture radii and gap spacings were used on the three-electrode extraction column. Measurements on an ion source test stand showed that the ion source emittance was minimized when the source was operated to give a minimum divergence beam [6]. This ion source current is referred to as the "matched" current. The LEBT was designed for optimized beam injection to the RFQ at matched source current [1], although, for a given extraction geometry, source current was varied over a limited range by operating the source above or below matched current. On-line monitoring with the cameras, then, allowed the source operator to determine when the source was adjusted for minimum divergence (by minimizing the beam profile width) and to check for beam mis-steering and degradation of the beam profile.

Figure 2 shows the measured vertical profiles of beams at minimum divergence from a 5 mm diameter extraction aperture with 10 and 5 mm gaps. Most profiles were approximately Gaussian in shape and fitted-Gaussian curves are shown. The width parameter, σ_{rms}, is the Gaussian root-mean-square (rms) line width. The profile fits are reasonable, although some excess beam halo is indicated in both profiles. (Assuming a waist at the exit of the extraction column, rms divergences for these beams are estimated to be 11 and 16 mrad, for the 10 and 5 mm gaps, respectively, indicating an increase in divergence with decreasing gap spacing.) Given that the camera resolution is 0.25 mm, it is estimated that beam mis-steering can be measured to within 1 mrad.

The apparent noise in the measured profiles in Fig. 2 is caused primarily by the pixel-to-pixel variation in dark current and light sensitivity. The noise can be reduced by subtracting a background scan. For the profiles shown, where the peak signal intensity and dark current are about equal, a background

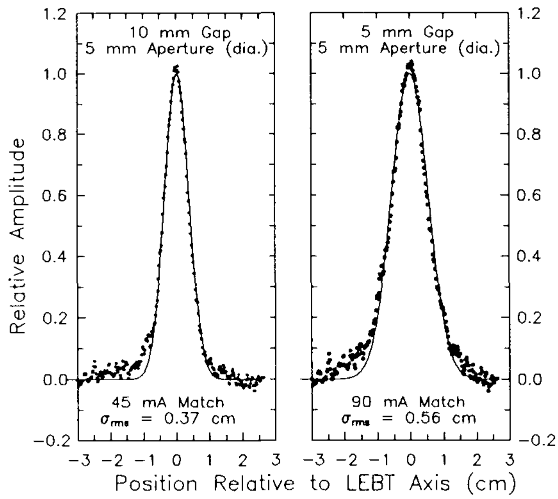

Fig. 2 Vertical profiles and fitted Gaussians for minimum divergence beams.

subtraction reduced the noise level by a factor of two. The manufacturer's specification of $\pm$ 10% variation in pixel-to-pixel light sensitivity is not apparent on our cameras.

Figure 3 shows a plot of the σ_{rms} from Gaussian fits to vertical and horizontal profiles for the 10 mm gap as the source current is varied. Based on measurement reproducibility, the uncertainty in σ_{rms} is estimated to be 0.25 mm, the same as the camera spatial resolution. As expected, the minima of the vertical and horizontal σ_{rms} plots are coincident; however, a non-circular beam is indicated at match. This was usual for the ECR source, and may be related to the transverse electric fields driving the plasma generator.

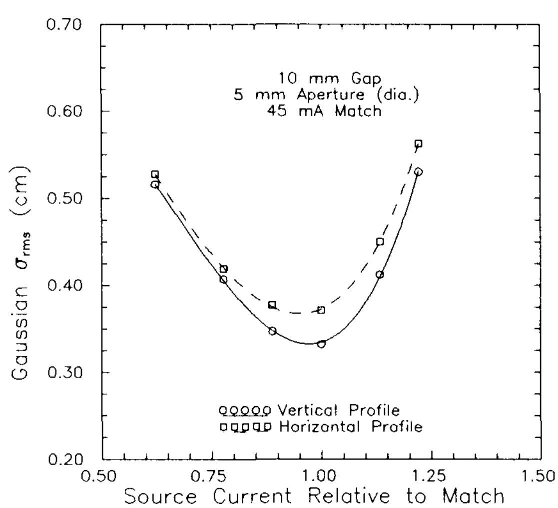

Fig. 3 Gaussian σ_{rms} values versus source current.

Concluding Remarks

The RETICON™ camera system has proven to be a useful on-line non-intercepting beam diagnostic on the RFQ1-1250 direct injection experiment. The cameras provide the primary means of determining when the ion source has been adjusted for the minimum divergence (and emittance), and are a practical tool for monitoring beam shape and position.

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