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DEVELOPMENTS IN NON-DESTRUCTIVE BEAM DIAGNOSTICS

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Summary

With the large average beam currents being achieved in accelerators and storage rings, there is an increasing need for non-destructive beam diagnostic devices. For continuous beams, position monitors of the capacitive pick-up type are replaced by resonant devices that respond to the transverse displacement of the beam centroid. Bunch length monitors of the SLAC type using resonant cavities operating in the TM_{010} mode can be used for continuous beams. The more detailed information derivable from beam profile scanners requires development of improved non-destructive devices. Profile monitors which scan the visible light produced by high current beams may be more reliable than ones using the residual ionization if the light intensity from gas molecules following non-ionizing collisions with beam particles gives a measure of the beam current density independent of the local electron density. The intense Balmer series lines from neutral hydrogen beams have been used successfully to measure beam profiles. At CRNL and at LASL, beam light profile monitors are being developed for high average current accelerators. Three or more projections will be recorded to allow tomographic reconstruction of the two-dimensional beam current density. Light detection is either by intensified Reticons or ISIT vidicons. The use of three or more beam light monitors on a beam transport line will also permit estimates of the transverse emittance to be made through the reconstruction technique.

Introduction

There is a demand for beam diagnostic devices that are non-destructive in two senses. Firstly, in high average current accelerators such as the Fusion Materials Irradiation Test Facility (FMIT) being built at Los Alamos and in the accelerator breeder prototype linacs being studied at Chalk River Nuclear Laboratories (CRNL), diagnostic devices must clearly not be destroyed by ion currents of 100 mA or more. Secondly, even at lower beam currents where the diagnostic device itself may survive, partial destruction of the beam itself will lead to intolerable activation levels in the structure and its surroundings and, in the case of storage rings, to a reduced beam lifetime. Beam diagnostics can be classified as either integral devices, which measure one of the moments of the beam, or differential ones which measure a distribution or a profile. Before discussing some specific new developments of the differential type I will enumerate a variety of typical non-destructive devices of both types that are in use.

Integral and Differential Diagnostic Devices

Non-destructive beam position monitors measure the first transverse moment or centroid of the beam. Typical of the non-destructive transverse beam position monitors used on pulsed accelerators and storage rings are variants[1,2] of the parallel plate monitor which detect beam centroid displacement by an unbalanced transient response of the two electrodes during the passage of individual micro- or macropulses. For continuous beams, narrow band[3] or resonant cavity[4,5] devices sample the induced rf field surrounding the beam.

In the longitudinal plane, capacitive phase probes[6] and resonant cavities[7] are used to measure the bunch phase in a non-destructive manner. Broad-band wall-current monitors[1] and a group of two or more harmonic resonant cavities[7] can be used to obtain bunch width information.

Differential beam density information is obtained from profile monitors of various kinds in the transverse and longitudinal planes. In the transverse plane, the distribution of residual gas ions[8] or electrons[9] collected on wire or strip electrodes in an electric field provides profile information with negligible perturbation of the beam. The fidelity of the response of these devices may be compromised by migration of low energy ions or electrons into the sweeping field region. This paper describes some new devices which make use of the visible light emitted following collisions of the beam particles with the residual gas molecules.

Finally, in the longitudinal plane, non-destructive methods have been developed to measure phase spread. Broad-band detectors, such as wall-current pick-ups[2] and capacitive probes[6] give transient responses from which useful phase profiles can be derived.

Beam-Induced Light Emission

The visible light from the vicinity of intense particle beams in air has long been a familiar phenomenon[10]. Can the beam light from the rarified gas within the accelerator or beam pipe be used as a non-destructive beam diagnostic? Since the light intensity decreases with decreasing gas pressure and, for proton energies above 100 keV, with increasing beam energy[11], the answer depends on several factors. The energy dependence will restrict the usefulness of beam light as a diagnostic to low energies, probably several tens of MeV. The pressure dependence may require locally increasing the gas pressure by differential pumping or momentarily by introducing a puff of gas. It should be emphasized that the use as a diagnostic of light resulting from beam-gas interactions is not restricted to high energy beams as is the case with synchrotron radiation[12].

A more important question, however, is related to the usefulness of the light signals, even if the intensity is adequately high. If the light emission results from a two-step process, for example, it may not be a reliable indicator of the differential beam current density. In the case of the Balmer emission lines in atomic hydrogen, which are very prominent in the light emitted when ions bombard molecular hydrogen gas[13,14], one might ask if the emission intensity depended both on the beam current density and on the free electron density. This question arises because the Balmer lines can result from the recombination of H^+ ions and electrons from the continuum. The experimental evidence[14] is that the Balmer line intensity varies linearly with both pressure and beam current. This behaviour was also found to be true for most of the emissions from nitrogen gas bombarded by protons[15]. The N_2 second positive system, however, varied quadratically with pressure, indicating a two-step process[15].

In the beam line near a proton ion source the background gas is predominantly hydrogen streaming from the

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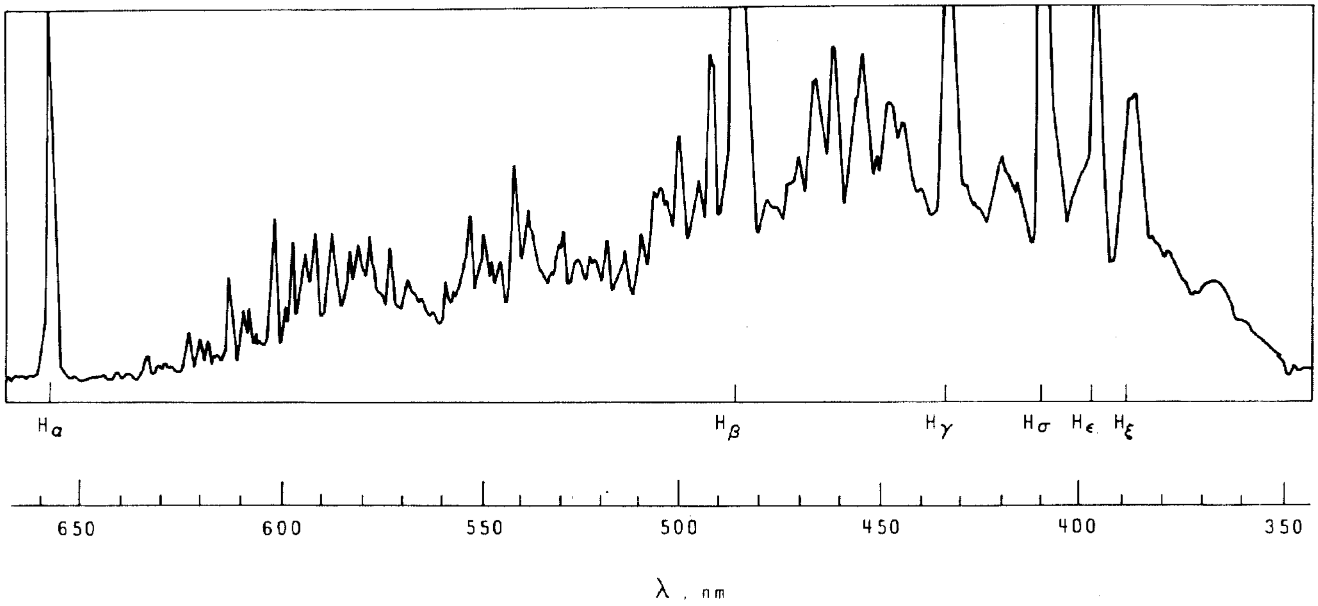

Fig. 1 Spectrum of light emitted from hydrogen gas at 10^{-4} Torr bombarded by 220 mA, 40 keV hydrogen ion beam in a CRNL ion source test stand.

ion source. Figure 1 shows a measurement made at the Chalk River Nuclear Laboratories of the spectrum of light emitted from the beam line gas at 10^{-4} Torr when bombarded by 220 mA of 40 keV unanalyzed hydrogen ions. The instrument was a 0.5 m Ebert Scanning Monochromator[16]. At the Los Alamos Scientific Laboratory it has been found that a 17 mA dc beam of protons passing through nitrogen gas at 2×10^{-5} Torr produces enough florescence to be observed by the unaided human eye[17]. Figure 2 shows part of the spectrum obtained at LASL for N_2. The prominent lines in the visible region are attributed to the first negative band of N_2^+ which have been shown by Hughes et al.[15] to be due to a single step process and therefore, one assumes, are reliable indicators of beam current density.

The Balmer series lines have also been used in optical diagnostics in high-power neutral beams. In a 32 keV, 6.3 A beam, Bonnal et al.[18], found that the optical profile, using the Balmer H_β line at 486 nm, matched an electrically measured profile except at the beam periphery where an excess of light emission was attributed to excitation of the residual gas by electrons flowing in to neutralize the beam.

One may conclude from the foregoing that beam-induced light emission from rarefied gases can be used as a reliable, non-destructive diagnostic of the spatial distribution of a beam. It remains to devise schemes for obtaining and handling the optical profile data.

Electro-Optical Systems for Beam Diagnostics

It has been shown[19-23] that the value of beam profile measurements can be enhanced if a sufficient number of profiles are recorded at different orientations so that a tomographic spatial reconstruction of the beam current density is possible. More importantly, if an appropriate set of projections is obtained, transverse or longitudinal emittance may be reconstructed. The new development discussed in this paper is the use of non-destructive optical profiles in the tomographic reconstruction of beam spatial distributions and, alternatively, of the phase space distributions.

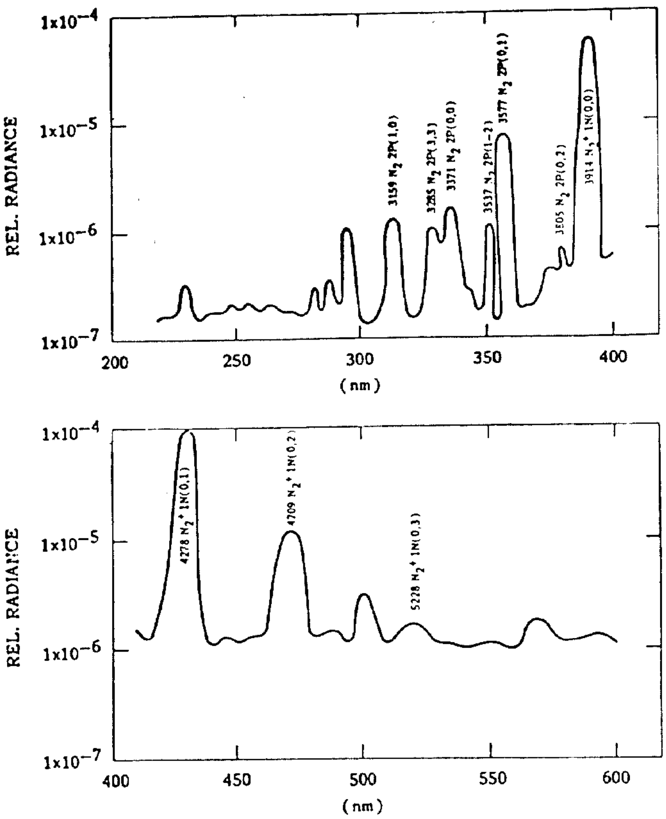

Fig. 2 Measured light spectrum from nitrogen gas at 2×10^{-5} Torr excited by 17 mA, 80 keV proton beam in a LASL ion source test stand.

Several requirements must be met for such a system to be practicable. First, as has been shown in the previous section, the light must be a reliable indicator of beam current density. Second, the intensity must be sufficiently great that reliable data can be recorded with the most sensitive electro-optical devices available commercially. Third, the electronic presentation of the data should include conversion from analogue to digital form for transmission to a computer for processing.

Two systems still in the development stage will be discussed, one at CRNL and the other at LASL[24]. Both systems record optical profiles at four angles 45° apart in a plane perpendicular to the beam axis. Economy and convenience dictate the use of mirrors in the optical system so that the four projections with angular spacing of 45° are brought into a common lens aperture with an angular spacing of about 3°. A constraint on the mirror arrangement is that the four path lengths be equal for the four magnifications to be equal. Figure 3 shows a schematic of the mirror and lens system employed at CRNL.

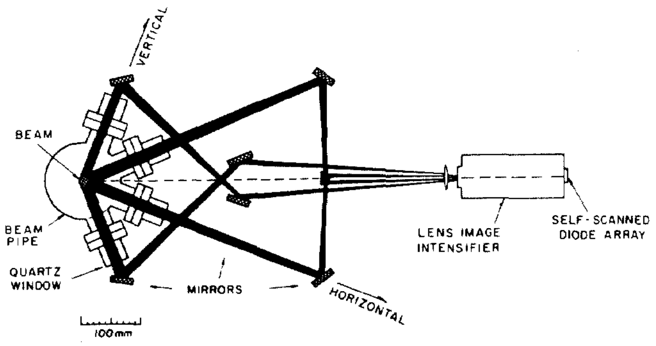

Fig. 3 Schematic diagram of an electro-optical system for beam analysis tomography.

One- and two-dimensional electro-optical imaging systems are available using commercial components. A very sensitive vidicon is the basic component in the two-dimensional TV display of beam images. Silicon intensified target (SIT) or doubly intensified silicon target (ISIT) vidicons have been selected for use in the low energy beam transport line for FMIT at LASL. ISIT vidicons have a sensitivity limited only by the quantum efficiency (about 10%) of the S20ER (S20 Extended Red) photo-cathode. A compact set of mirrors places the four beam projection images side-by-side in the video display. Electronic equipment is available for digitizing the video signal amplitudes for each picture element (pixel) in a single frame. Data from a number of horizontal sweeps in a single frame could be averaged if required.

The ISIT vidicon is basically a two-dimensional array of silicon photo-diodes preceded by a multi-stage image intensifier. One-dimensional systems of this type have been developed as focal plane detectors in astronomical spectrographs[25,26] and in optical multichannel analyzers[27]. A self-scanned photo-diode array with fiber-optic input face coupled to an image intensifier is a one-dimensional sensor of sensitivity comparable with an ISIT vidicon, the sensitivity again being determined by the S20ER photo-cathode.

A comparison of the characteristics of a typical ISIT vidicon and the intensified Reticon is given in Table 1. The fact that the sensitivities are equal is not surprising since in both cases it is determined by the properties of an S20 photo-cathode extended into the infrared (ER).

The Intensified Reticon (I-RET) system has been chosen for the CRNL beam light electro-optical system. If one chooses, say, 50 pixels for a single beam image with approximately 50 pixels in the gap between adjacent images, then a 512-element Reticon is an appropriate choice from the available models with 256, 512 and 1024 elements.

The electro-optical system[24] currently under development for the FMIT accelerator uses an SIT vidicon (RCA Model TC1030/H). In other applications with lower beam currents and/or high energies the sensitivity could be increased by using a ISIT tube. Preliminary tests using an 80 keV proton beam from an ion source extraction column have demonstrated spatial position accuracy of ± 0.1 mm and transverse emittance reconstruction using profiles from four viewing ports in a drift space[24].

The electro-optical system being tested at CRNL is shown in Figs. 3 and 4. Four projections 45° apart in one plane are brought out through quartz windows, directed by mirrors to a 50 mm focal length lens which produces real images, with a magnification of 1/16, of the four profiles side-by-side on the photo-cathode of an image intensifier. The intensifier, in turn, produces real intensified images with a magnification of unity on its output phosphor. The output of the 512 diode elements is presented serially as a video signal by the diode array control electronics.

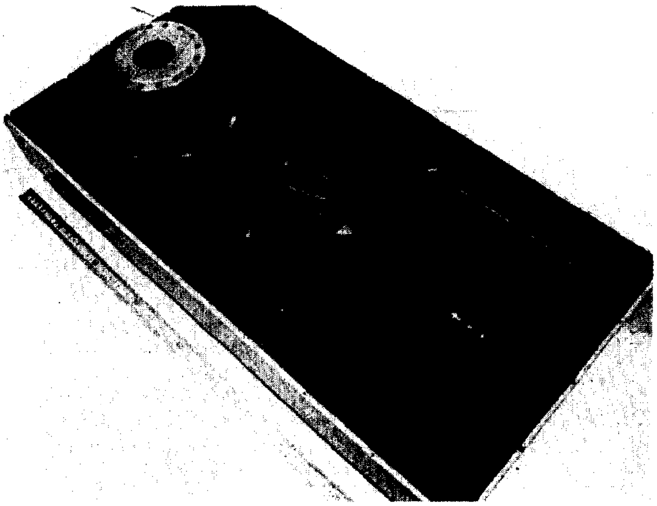

Fig. 4 Photograph of the electro-optical system of the CRNL beam analysis tomography system.

Initial tests of this system will be carried out on a 750 keV proton beam where it will be used for spatial reconstruction of the beam current density distribution. For the system to function as an on-line diagnostic with minimum time delay in computation, a specialized geometry has been devised for the MART (multiplicative algebraic reconstruction technique) algorithm[28], in preference to the more accurate but slower MENT (maximum entropy) algorithm[29]. This is shown schematically in Fig. 5. Each square pixel of a square grid is bisected by two diagonals to form four 45° isosceles triangles. Ray sums can be done in all four directions. The step size in the ± 45° directions must be $1/\sqrt{2}$ times the horizontal and vertical step size. The execution of this version of MART is about 10 times faster than MENT.

Table 1

Comparison of ISIT Vidicon with Intensified Reticon

	ISIT[*] Vidicon	Image Intensifier[†] with Reticon
Cathode Diameter	25 mm	23 mm
Photo-cathode		
Type	S20ER	S20ER
λ at Peak	500 nm	500 nm
Sensitivity	225 μA/ℓm	225 μA/ℓm
Quantum Efficiency at Peak	10%	10%
Phosphor	P-20	P-20 (Aluminized)
Resolution (MTF @ 50%)	11 ℓp/mm[**]	16 ℓp/mm[≠]
Imaging	2D	1D
Readout	Digitized Frame-Hold	Digitized Sample-and-Hold
Signal Averaging	Multiple horizontal scans in one frame	Successive scans

MTF: Modulation Transfer Function is the modulation depth vs spatial frequency of light and dark bar pairs.

[*] Thompson CSF TH 9473 with TH 9656 Nocticon.

[**] Corresponds to 300 lines on 25 mm cathode of TH 9656.

[†] Varo Model 1122-2 with Reticon RL512SF.

[≠] At output of image intensifier. Assumes no degradation on addition of Reticon with 40 elements per mm. With magnification of 16 this corresponds to resolution of 1 mm in beam.

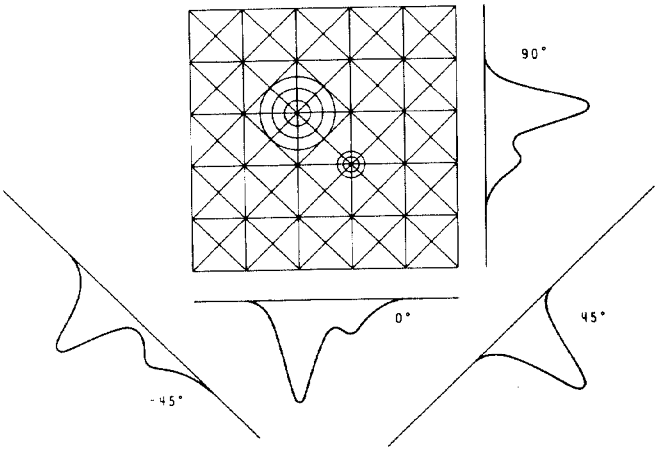

Fig. 5 Reconstruction grid specialized for four projections 45° apart.

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