Beam Diagnostics with Optical Means

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Abstract

We report the experimental results and calculations on beam diagnostics using an optical radiation by charged particles. Using TV-cameras with a Cadmicon image tube coupled with a digital image processing system based on CAMAC we have devised an accurate beam monitor. The experiments have been carried out at the proton synchrotron of the Institute for High Energy Physics, Russia.

1 INTRODUCTION

The goal of our work was to create the beam diagnostics using optical radiation for precise measurements of the beam parameters. There are a lot of problems connected with it. Notice that such works were carried out at other accelerator centers (CERN , SLAC, KEK et al.) [1,2,3,4].

This paper describes the system configuration, screens using luminescence and optical transition radiation (OTR), and their performances.

A new device for beam diagnostics using optical radiation, arising from charged particle interaction with the wire crossing the beam is proposed.

The results of calculations and experiments carried out in the 30 Mev – 3 TeV proton beams are also presented.

2 BEAM IMAGE PROCESSING SYSTEM

A schematic diagram of the system is given in fig. 1. It is made up of devices transforming the beam into a visible image, TV cameras, an image inputting and processing system based on CAMAC and a computer.

2.1 TV camera

A low cost TV camera works with a 12.8x9.6 mm Cadmicon image tube, which differs from a Vidicon in a more sensitive photoconductive target and high linearity. The exposure time of the TV camera is selected within the range of 20 ms – 5 s in a discrete step of 20 ms. The threshold sensitivity of the Cadmicon tube (signal/noise=1) is almost 2.4×10^{-7} J/m^2 (8×10^5 photons/mm^2) at $\lambda_{max} = 680$ nm. The linearity of the light-signal characteristics is within three orders. The dark currents and maximum output current are 1 nA and 1 μA, respectively.

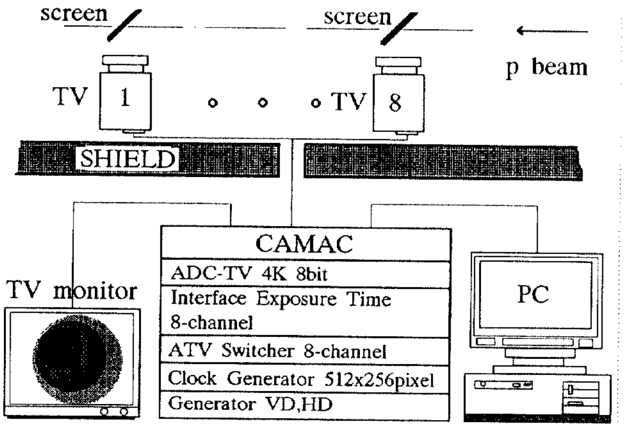

Figure 1: Schematic diagram of the system.

2.2 Measurement procedure

The system uses five CAMAC units, the controlled video amplifier with switcher for 8 cameras, the video digitizer clock interface, the digitizer 4Kx8 bit, the exposure time interface for 8 cameras, and the generator VD, HD. The maximum sampling density corresponds to 512 (horizontal) by 256 (vertical) points. Only a small part of the television picture is digitized. The window size, location, and density of points are controlled via CAMAC. The exposure time, the camera number are also controlled via CAMAC. The beam image is digitized, processed and then displayed on the color display.

The working algorithm of the system is presented in fig. 2. The beam image is measured together with the background produced by the dark currents, then the background was measured in the interval between beam pulses and then subtracted.

The exposure time in the vidicon target is the same in both cases. The radiation background produced by particles can be subtracted in the same way. Such a working procedure allows one to subtract the background, to collect all light and to synchronize the measuring system with the accelerator.

3 OPTICAL RADIATION

3.1 *Luminescence*

One of the most important features of the accelerator technology today is the production of intense particle beams. Such beams, with the intensity varying from 10^7 to 10^{14} particles, are produced in many experiments. A luminescence screen of zinc sulfide is a standard device in many medium-intensity beams. This screen is susceptible to radiation damage and when used in intense beams must be frequently replaced. The screens described below are radiant resistant and highly sensitive. Moreover these screens can be used with a digital television system as they have enough linearly light-signal characteristics.

The technique of manufacturing plates up to 1 mm thick and fibers 0.3 mm - 2.0 mm thick by Al_2O_3 single crystal activated by Cr or Ti has been elaborated. The intensity and decay time of the light emission from these screens depend on the activator. The experimental results are given in table 1. for the case using the TV camera with the Cadmicon tube, a 2.0 objective and 1.5 mm thick screens.

Ceramic $Al_2O_3Cr^{3+}$ was manufactured in Russia and has as high the sensitivity as AF995 [1]. $Al_2O_3Ti^{3+}$ screen has the maximum of the light emission spectrum of about 800 nm, the decay time of few μs. This screen may be used with any CCD camera.

The sensitivity of these screens was measured for the slow (0.8 s) and fast (few μs) extraction. Notice that the sensitivity is the same for these extractions as the TV camera was used with the exposure time more than 1 s.

Table 1

screen	activator %	threshold sensitivity proton/cm^2	light emission after 60ms %
Al_2O_3 single crystal	Cr, 0.018	$2 \cdot 10^6$	2
	Cr, 0.066	$1.7 \cdot 10^6$	8
	Cr, 1.16	$2.8 \cdot 10^6$	50
	Ti, 0.011	$1.9 \cdot 10^7$	—
	Ti, 0.047	$2.7 \cdot 10^7$	—
Al_2O_3 ceramic	Cr, 0.5	$4.5 \cdot 10^6$	—
Beo ceramic	—	$4.7 \cdot 10^8$	—
SiO_2	—	10^9	—

3.2 *Optical transition radiation*

OTR arises when a charged particle crosses the boundary separating two media with different dielectric constants (e.g. vacuum and metal). OTR was first theoretically predicted by Ginsburg and Frank in 1945 [5], then in 1973 Wartski [6] proposed to use OTR for the electron beam diagnostics.

OTR has both advantages and disadvantages. The important advantages of using OTR for charged beam diagnostics are a small amount of matter in the beam, linearity of light-signal characteristics, short decay time of the light emission. Its disadvantages are small light yield and inhomogeneous angular distribution.

The experiment was carried out in the slow and fast extracted 70 GeV proton beam with an intensity 5×10^{11} - 10^{13} and $\sigma = 0.3$ cm. Mylar film with aluminium coating 0.5 μm thick was used as the medium.

Estimates of using OTR for 70, 600, 3000 Gev proton beam diagnostics are given in table 2. For these estimates we assume that OTR is produced on the AL foil 1 μm. thick, an objective with F-number of 2 and the magnification of 10 (in this case light is collected within angles of ± 23 mrad)

Table 2

E(GeV)	70	600	3000
$\epsilon(\pi \cdot mm \cdot mrad)$	1	0.7	0.2
dI/dS (pr/cm^2)	1.4×10^9	1.9×10^8	1×10^8
dI/I	6.5×10^{-6}	6.5×10^{-6}	6.5×10^{-6}
dP/P	10^{-8}	10^{-9}	10^{-10}
$d\epsilon/\epsilon(\sigma = 1$ cm)	5.2×10^{-5}	1.4×10^{-6}	7×10^{-7}

ϵ - emittance, dI/dS - threshold sensitivity (signal/noise = 1), dI/I, dP/P, $d\epsilon/\epsilon$ - variations of the intensity, momentum, and emittance, respectively.

The threshold sensitivity of 1.4×10^9 protons/cm^2 for 70 Gev is the experimental date. Therefore it is possible to measure a 600 Gev proton beam with the intensity of about 10^9 protons/cm^2 (signal= 5 noise) both slowly and fast extracted.

4 TELEVISION WIRE SCANNER

The well-known device for the circulating beam diagnosis is the flying wire scanner (FWS) based on detecting high-energy secondary particles produced by the interaction of the proton beam with the wire [7].

TVWS is based on the TV-detection of the optical transition radiation produced on the medium-vacuum boundary by the interaction of the protons with the flying wire [8]. During the time of the wire crossing the beam the TV-camera accumulates optical radiation. Therefore the flying wire can be imagined as a fine stationary screen. The layout of the facility and the working algorithm are illustrated in fig. 3.

The signal current of the vidicon is determined by the expression

$$i = M \cdot J \cdot \frac{S_{tv} d}{T_c V} \int \frac{d^2 W}{d\Omega d\lambda} S_r(\lambda) d\lambda d\Omega$$

were M is the optical transfer quotient, S_{tv} is the scanned area of the vidicon, T_c is the TV camera scan period, $d^2W/d\Omega d\lambda$ is the spectral-angular density of OTR, d is the wire cross section, V is the wire speed, $S_r(\lambda)$ is the radiant sensitivity, J is the particle current density in the accelerator. In our calculations we consider the particle distribution follows to Gaussian. The results for different machines IHEP, CERN, FNAL, KhIPT are given in table 3.

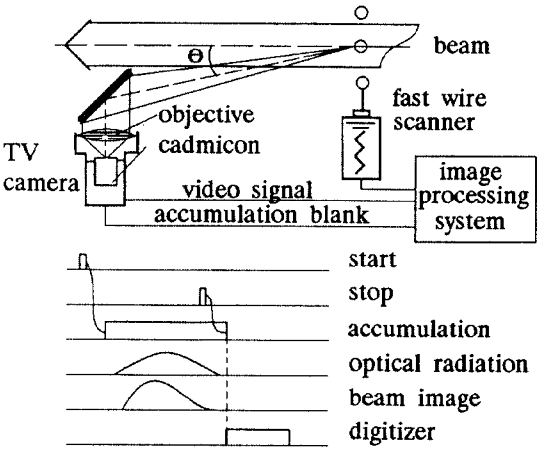

Figure 2: Layout of the experimental facility and the working algorithm of the system.

Table 3

	UNK	FNAL	SPS	KhIPT
Beam	p	p	p	e^-
γ	3200	853	289	3530
f, Hz	$1.4 \cdot 10^4$	$4.7 \cdot 10^4$	$4.4 \cdot 10^4$	100
σ_x, mm	1.0	0.3	1.1	1.0
σ_y, mm	5.0	0.3	1.1	1.0
I_{max}, part.	$2 \cdot 10^{14}$	$5 \cdot 10^{12}$	$2 \cdot 10^{13}$	$10 \mu A$
ΔT, °K	1433	1786	1709	98
i_T/i for:				
cadmicon	0.11	0.19	0.44	—
SIT	0.033	0.066	0.14	—
SIT*	$2 \cdot 10^{-3}$	$9 \cdot 10^{-3}$	0.018	—
I_{th}, part. for:				
cadmicon	$4 \cdot 10^{10}$	$1.3 \cdot 10^9$	$3 \cdot 10^9$	$4 \cdot 10^{-2} \mu A$
SIT	$2.2 \cdot 10^8$	$6.7 \cdot 10^6$	$1.6 \cdot 10^7$	$2 \cdot 10^{-4} \mu A$

I_{th} is the threshold sensitivity of the detectors(signal/noise = 1), ΔT is the wire heating temperature, i_T/i is the relative values of the heat emission to OTR. SIT is the high sensitivity tube. SIT* is the corrected SIT.

Notes: This data are given at $\theta = 70$mrad, carbon wire 25 μm thick, wire speed of 10 cm/s for KhIPT and 4.3 m/s for other machines.

5 EXPERIMENTS

Accurate beam measurements were used at IHEP to determine the parameters of lithium lens, target efficiency, bunched beam parameters and energy spread.

This system is able to measure the beam parameters for each pulse of the linac (or booster) beam operated at the repetition time period of 60 ms.

5.1 *Main ring*

For these measurements the TV camera was located so that the spatial resolution of the beam profile is to be 0.66 mm/step and 0.90 mm/step in the horizontal and vertical axes, respectively. For the window of 16×16 points and signal-to-noise ratio equal to 50 the errors (r.m.s) of the calculations are about 25 μm in the X-axis and 45 μm in the Y-axis for positions, 60 μm in the X-axis and 120 μm in the Y-axis for dimensions.

The $\sigma_x = 12.68$ mm and $\sigma_y = 8.17$ mm has been determined for 29 bunches with total intensity of 1.5×10^{13}, using the TV camera with the exposure time of 2 s. Evidently, increasing of the beam dimensions are basically due to the positions of each bunch.

5.2 *Linac*

The energy spectrum of a 30 MeV linac proton beam is determined by the magnetic analyzer of beams but instead of the Farade's cylinder BeO screen is used. The TV system views and processes the screen image. To measure the energy spectrum of pulses (repetition time period of 60 ms) one should use one working cycle of the linac. Notice the measurements with the Farade's cylinder require a lot of time and additional system to cool this facility.

The measured energy spectrum by the TV camera has the width 2.49 % at a level of 0.1 (by Farade's cylinder - 2.6 %). The difference in these energies spectrum for 30 bunches is found to be within 3 % (r.m.s.). In this configuration of the magnetic analyzer the expected resolution is 0.026 %.

The energy spectrum of the linac is determined RF parameters of the linac.

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