Abstract—The Fermilab Recycler ring will employ an electron cooler to store and cool 8.9-GeV antiprotons. The cooler will be based on a Pelletron electrostatic accelerator working in an energy-recovery regime. Several techniques for determining the characteristics of the beam dynamics are being investigated. Beam profiles have been measured as a function of the beam line optics at the energy of 3.5-MeV in the current range of $10^{-4}$-1A, with a pulse duration of 2µs. The profiles were measured using optical transition radiation produced at the interface of a 250µm aluminum foil and also from YAG crystal luminescence. In addition, beam profiles measured using multi-wire detectors were investigated. These three diagnostics will be used together to determine the profile dynamics of the beam. In this paper we report the results so far obtained using these techniques.

I. INTRODUCTION

In this paper we report on development and test of the electron beam diagnostics that was done at a bench of the prototype facility designed for electron cooling of the anti-proton beam. The facility was based on a 5-MV Pelletron accelerator operating in an energy recovery regime [1]. Investigations of the beam diagnostics were performed in a pulse mode. The accelerated 3.5 MeV electron beam had pulse duration of 2 µs with a 1 Hz repetition rates and the accelerated current was variable in the range of $10^{-4}$-1 A [2].

The beam diagnostics using transition radiation techniques, as well as the YAG-crystal as a luminescent detector and the multi-wires secondary emission monitors was performed to obtain the parameters of the electron beam at the bench to study the beam dynamics at the facility.

Experimental Set-Up

The location of the diagnostic test bench is shown in Fig.1; the layout of the bench is presented in Fig. 2. The system of the beam diagnostics includes a multi-wires monitor, a YAG crystal and a transition radiation monitor.

Fig. 1. Location of the test bench at the electron cooling facility

The multi-wires monitor was made from two planes of 48 tungsten mutually perpendicular wires. The wires in both planes (X and Y) were 25µm in diameter and were spaced 0.5mm apart. The signal from each wire was read independently, processed and displayed.

The YAG monitor was a 50mm square crystal with a thickness of 0.1mm. The crystal was inserted at an angle of 45 degrees to the incident beam.
Two types of transition radiation monitors positioned obliquely to the incident electron beam were tested in the set-up; initial measurements were done with a thin screen made from a 5µm nitrocellulose substrate having mirror coating with 1200Å of aluminum; this produces an ultra-flat pellicle surface with up to 1/100 reflection on central areas. Subsequent measurements were done with a 250µm aluminum foil with a reflectance noticeably less than that of the first screen. The YAG and transition radiation screen were orthogonal to each other in the six-way chamber (as shown) due to space constraints. As a result the devices could only be inserted into the beam when one or the other was removed. However the multi-wires monitor could be inserted independently during a measurement. The transition radiation and the light from the YAG-crystal was detected with a CCD camera located at the distance of ≈ 50 cm from the light sources and shielded by 5-cm lead bricks to suppress the bremsstrahlung. The focal length and the relative aperture of the objective were 50 mm and 1.4 respectively.

The beam sizes, position and profiles were measured as a function of the Pelletron gun current, which was varied by changing of the pulse voltage of the gun control electrode. These parameters were also measured as a function of the current of the focusing lens SPA05 which was mounted upstream of the beam, before the entrance to the test bench, Fig. 1. Results obtained using the optical monitors were compared with data from the multi-wires detector.

### Transition Radiation and YAG Image Processing

Images taken from the optical monitors were digitized and saved in an uncompressed format using application software that was developed using Lab View. Image analysis tools were used to combine techniques that compute statistics and measurements based on the gray-level intensities of the image pixels; linear (convolution) filters were then applied to remove unwanted background. The profile data were extracted from images, to establish color scale data and produce the beam profile or 3-D representation of the data. Calibration to real-scale coordinates was done by using a set of 125µm tungsten wires that were placed over the transition radiation screen to form a rectangular 10mm x 10mm grid. Beam profiles data were measured to study the beam optics parameters and also for optimization of the current density range by application of these monitors in the beam profile diagnostics with improved spatial resolution and using conventional CCD cameras.

### Transition Radiation Monitors

Predicted more than 50 years ago, transition radiation [3] is now widely used in many laboratories as a powerful method for diagnostics of beams of charged particles. The radiation is generated when a charged particle beam crosses the interface between two media of different dielectric constants; for beam profile diagnostics it is usually the radiation emitted from a vacuum-metal boundary. In practice a metal foil is inserted into the beam line at an oblique angle to the beam direction of motion. As a result transition radiation is emitted in both the forward and backward hemispheres. The method typically utilizes the optical part of the transition spectrum, so-called Optical Transition Radiation-OTR.

The OTR monitors have several excellent and unique features for beam diagnostics; they produce a wide emission spectrum including visible light with well defined directionality and polarization. In addition the simplicity of detection has lead to widespread use of the method. The surface nature of OTR also allows the use of very thin screens which reduces beam scattering and bremsstrahlung radiation. OTR detectors will be used in the Fermilab electron cooling facility to measure the real-time profile dynamics of the beam.

In case of relativistic electrons, the spectral density of the backward OTR with an ideal metal screen at oblique incidence to the surface can be expressed as [4], [5]

\[
\frac{d^2 W}{dΩ dω} = \mathcal{Z}(θ, ω) = \frac{e^2 β^2}{π^2 c^2} \frac{\sin^2 θ}{(1 - β^2 \cos^2 θ)},
\]

where \(e\) is the electron charge, \(c\) is velocity of the light, \(β\) is velocity of the electrons in units of \(c\) and \(θ\) is the angle between the wave vector of the radiation and the mirror-reflected electron velocity vector in the point of the incidence. The shape of the spectral density versus \(θ\) is shown in Fig. 3.

The intensity of the OTR is maximal at the angle of:

\[
θ ≈ (βγ)^{-1}.
\]

Note that for particle beams in the mid to low energy range the angular distribution of the OTR is not sharply peaked. As a result, the low value of the optical acceptance causes loss of light. Our optics provided an observation angle \(α ≈ 0.04\) radians. In this case the coefficient of collection of the OTR photons (relative number of detected photons) is estimated as:

\[
n_c(α) = \int_0^α \mathcal{Z}(θ, ω) \sin θ \cdot dθ \cdot \int_0^θ \mathcal{Z}(θ, ω) \sin θ \cdot dθ.
\]

This respective value is: \(n_c = 10^{-3}\).
Simple estimations show that for a beam spot size area of 100 x 100 pixels, and a beam current of 1 A with the pulse duration of 2 µs, the number of photons should be of $\sim 10^4$ photons/pixel per pulse. In this case the threshold current for detected profiles for the above conditions can be expected to be $\approx 0.1$ A. To decrease the minimal detected current and increase the sensitivity of the OTR diagnostics one could use a cooled CCD camera or an intensified CCD camera.

OTR diagnostics was used to study dependence of the beam profile on the SPA05 lens focusing and also on the voltage of the gun control electrode. Fig. 4 shows measured X-profiles as a function of the lens current for the pulsed beam current $\approx 1$ A. In all of profiles one can see marks of the scale; also one can see the shadow of the multi-wires monitor. Obtained space resolution of the OTR diagnostics is better than 0.1 mm.

Note that OTR monitors images have no saturation or limitation in dynamic range and yield of the photons is proportional to intensity of the monitored beam.

**YAG Scintillation Monitor**

YAG (Yttrium Aluminum Garnet) single crystal scintillators are now frequently used for charged particle beams and X-ray detection as well as for electron and X-ray imaging screens due to high resistance to radiation damage. The photon yield for the YAG crystals is $\approx 8 \times 10^3$ $\text{photons/MeV}$, so for the crystal which has a thickness of 0.1 mm, the yield should be $\approx 0.73 \times 10^3$ photons per passing electron. The light emitted from the crystal was collected under the same optical conditions as measurements made with the OTR monitor and the coefficient of collection of the photons had the value of $n_c \approx 3 \times 10^{-3}$. In this case the threshold current for the image of the beam spot with size of 100 x 100 pixels, and pulse duration of 2 µs can be estimated to be $\approx 1 \mu\text{A}$ in the pulse mode.

This high sensitivity of the scintillator is convenient for the investigations of low-current beams. Higher beam currents (above 1 mA) resulted in the saturation of the YAG crystal, Fig. 6. To avoid saturation in CCD camera we used neutral density optical attenuators.

Dependence of the beam profile on the beam current varied by the gun control electrode is presented in Fig. 5.
corresponding to 0.001 A/mm². The respective restored beam X-profile is shown in Fig. 8.

In both these figures one can see the shadow of the multi-wires monitor located at 330 mm upstream relatively to the disposition of the YAG monitor. The space resolution by the measurements with the YAG OTR monitors is approximately equal.

Multi-wires Beam Monitors.

Data from the X-Y monitor were used for measurements of the beam sizes and to study the beam optics in the test bench. The correlation between the spatial distribution of the beam density and the charge distribution as measured by the multi-wire in a given plane, is expressed by an integral equation having no singular solution in common case. However, in case of an axial-symmetric beam the integral equation has the form:

$$\lambda(x) = 2 \int_{0}^{R} n(r) \sqrt{r^2 - x^2} dr,$$

where $x$ is coordinate of the wire, $\lambda(x)$ is the measured charge distribution in the plane of multi-wires monitor, $n(r)$ is beam density distribution. In our case of weak dependence of the beam density on the radius, $n(r) = \text{constant}$ and the equation can be transformed to the following:

$$n(m) = \frac{n_{\text{max}}}{\sqrt{n_{\text{max}}^2 - (m - n_{\text{max}})^2}} \cdot \lambda(m),$$

where $m = 0, 1, \ldots, 2n_{\text{max}}$; $m$- number of wires charged by the passing beam, $n_{\text{max}}$ is the number of wires respective to the beam radius.

In Fig. 9 are shown the beam X-profiles restored from the charge distribution data of the multi-wires monitor. The profiles were restored for different fits, for 30 and 32 wires. For comparison in this figure is plotted the profile measured by OTR-monitor located at 330 mm downstream relatively the multi-wires monitor. Note that sensitivity of the multi-wires monitor to the beam current is comparable with this parameter of the OTR monitor, but the space resolution is in 5-10 times worse.

Conclusion

Beam diagnostics based on optical transition radiation monitors, YAG scintillator and multi-wires monitors has been developed and tested for use in the Fermilab Recycler electron cooling system. The OTR diagnostics provides real-time profiles with improved spatial resolution better than 100 µm in the current range of 0.1-1.0 A. The YAG monitor diagnostics provides approximately same resolution for currents less than 1 mA. The multi-wires secondary emission monitors provide space resolution approximately of 0.5 mm for the beam size measurements.
ACKNOWLEDGMENT

We wish to thank Arnold Germain Jr. for his technical contributions.

REFERENCES