OTR Measurements and Modeling of the Electron Beam Parameters at the E-cooling Facility

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Abstract. Parameters of the electron beam accelerated in the Pelletron, intended for the electron cooling of 8.9 GeV antiprotons in the Fermilab recycler storage ring, have been studied. The parameters were measured under the accelerating section using Optical Transition Radiation (OTR) monitor. The monitor employs highly-reflective 2 inch-diameter aluminum OTR-screen with a thickness of 5 μm and digital CCD camera. The measurements were done in a pulse-signal mode in the beam current range of 0.03-0.8 A and at pulse durations ranging from 1 μs to 4 μs. Processing of the measured results obtaining the differential beam profiles allows comparing the results with modeling of the DC beam dynamics from the Pelletron cathode to the OTR monitor. The modeling was done with ULTRASAM and BEAM programs. An adjustment of the magnetic fields in the lenses of the accelerating section was done in the simulations. The simulated electron beam parameters downstream of the accelerating section were in good agreement with processed measured in the pulse-signal mode data.

Keywords: Optical transition radiation, CCD camera, electron beam, accelerator, bremsstrahlung
COOL: 05

INTRODUCTION

Optical transition radiation monitors are being used to image the charge distributions of the 4.3 MeV pulse-signal electron beam employed to study the beam dynamics in the electron cooler at Fermilab. The transition radiation is produced by the charged particles as they traverse the boundary between media with different dielectric constants [1]. The OTR monitors have several advantages over more traditional imaging devices due to imaging of the 2-D beam distribution in a plane, linear response of OTR monitors to beam charge, good spatial resolution and wide possibility in data processing. Simplest way is using of the monitors with pulsed beam. Such mode of the Pelletron operation was based on the pulse-signal modulation of the blanking voltage at the electron gun [2] and was developed generally for the beam diagnostics. In this mode the gun optics noticeably varying during the pulse and makes the ordinary measured beam profiles inadequate to the results of the beam dynamics simulation in DC mode. Using developed processing we compensated effect of the beam modulation on the data of the OTR monitoring. Comparison of the processed beam profile dynamics with data of simulated DC beam trajectories show good agreement.

OTR Beam Profile Monitor Set-up

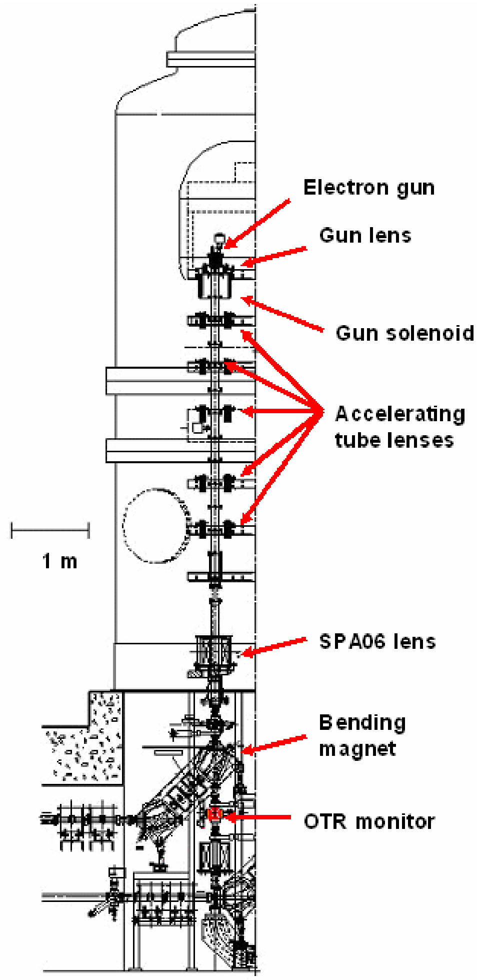

FIGURE 1. Layout of the experimental setup.

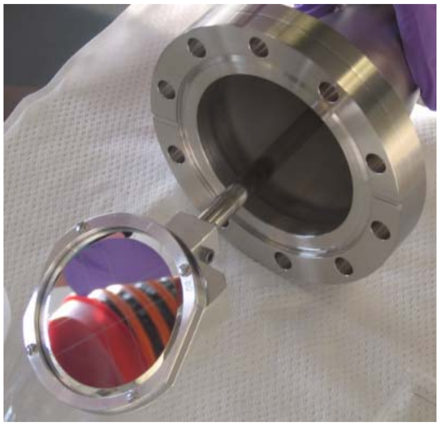

FIGURE 2. OTR screen mount.

The OTR beam profile monitor is mounted in standard 6-way cross downstream of the accelerating section of the cooling facility, FIG.1, and composed of the 2"-in diameter OTR screen made from a mirror-surface 5 μm aluminum foil tensioned with high flatness onto a ring frame movable with a stepper-motor actuator. Such thin foil is essential to reduce the background caused by beam scattering and bremsstrahlung. The linear drive provides insertion of the OTR screen with accuracy of 0.1 mm and the screen is inserted into the beam at an angle of 38.9 degrees to the beam direction. This corresponds to the angle $\theta \approx 1/\beta\gamma$ [3], where the intensity of the light has a maximum. This allows significantly increase the monitor sensitivity to operate with low beam current. Photo of the OTR screen mounted on the actuator is shown in FIG. 2.

The backward OTR passes through vacuum glass window to the digital CCD camera to image the beam. To transform images to real-world coordinates, four 75 μm tungsten wires are mounted over the radiation screens to form a rectangular 10mm x 10mm grid. The CCD camera has an objective with: focal length f =25 mm; relative aperture F =1.4. The distance between the OTR screen and the camera lens is of 320 mm. The CCD camera and associated optics are incased in a light tight housing to omit external sources of light.

The digital camera is connected to computer via IEEE 1394 fire-wire interfaces. A Labview based data acquisition and processing systems have been developed to obtain with real-time the beam spot images and to store them. The processing system provides the operator with tools for image analysis. The OTR diagnostic system employed at the cooler is designed to be routinely used to optimize the beam transport and to measure the transverse beam profiles and the respective beam sizes.

Data Acquisition

The images taken from the optical monitors are digitized in the CCD camera and saved in an uncompressed format. As a result external electronic and environmental noise sources have little effect on the image quality. In addition, the IEEE 1394 fire-wire interface allows control of the camera's gain and other features remotely. The images are then displayed and analyzed with application software that was developed using LabView and IMAQ vision utility tools. The program allows the user to display live (real-time) images of the beam and to simultaneously analyze either current (live) data or stored data from files. Two profiles taken with different pulse durations or optical settings can therefore be compared. This type of development differs from the standard application in that it incorporates image digitization, image display, as well as image analysis and system calibration in a real-time mode. These image analysis tools are used to combine techniques that compute statistics and measurements based on the gray-level intensities of the image pixels; linear (convolution) filters can be applied to remove unwanted background at any stage of the analysis if necessary.

Results of the Measurements

The system so far described has been used to measure the properties of the electron beam while the Pelletron was operating in a pulse-signal mode with the bending magnet turned off. This allows accelerated beam to be passed straight on to the OTR monitor. The residual field in the bending magnet was compensated with a coil mounted in the bending magnet. Images of beam pulses with durations of 1μs were subtracted from images obtained with 2μs pulse duration to suppress effect of variation of the gun optics caused by variation of the voltage on the control electrode during fronts of modulating pulses. The electron beam was carefully aligned with BPM monitors located upstream of the SPA06 lens and downstream of the OTR monitor before all measurements to avoid off-axis pass through the OTR-screen.

During the measurements we checked the response of the monitor versus beam current which was varied by changing the pulse voltage of the gun control electrode. FIG. 3 showing dependence of the integral of detected light in the beam spot versus the beam current demonstrates good linearity of the OTR monitor. Moreover we measured dependence of the monitor sensitivity versus position of the beam along both the X and Y axes of the screen at fixed beam current. Motion of the beam along the axes was done using correctors disposed inside the focusing SPA06 lens, FIG. 1.

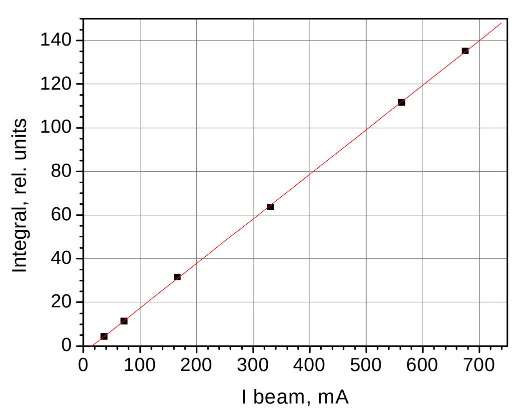

FIGURE 3. Beam spot integrals versus the beam current.

The measured dependence of the sensitivity on the beam position over the surface area of the screen is relatively week and allows using practically full area of the screen for the beam monitoring.

The beam profiles were measured as functions of the current of the lens SPA06 in the range of 6-22 A. FIG. 4 shows the variation of the profiles versus the lens current.

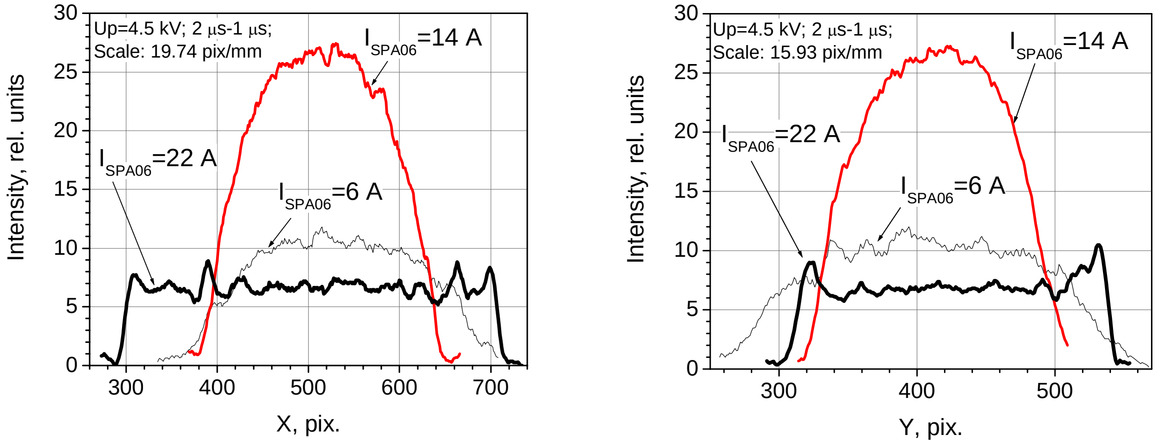

FIGURE 4. Beam profiles versus current in lens SPA06.

Simulation Results

The adjusted magnetic field distributions in the lenses of the accelerating section obtained using ULTRASAM program were used for simulation of the beam dynamics from the cathode to the OTR-monitor. The electron trajectories are shown with blue lines; border of electrodes and the equipotentials are shown with red lines; distributions of the electric and magnetic fields are plotted with green and gray lines respectively. In the right upper corner one can see the beam phase picture at the gun exit (Z=40 mm). In this picture with blue line plotted the beam current density, red and green lines shows the azimuthal and radial velocity distributions.

The electron beam envelopes versus SPA06 current for full beam current, 95% of the beam current and 25% of the beam current respectively, calculated using BEAM [6] program. Blue lines show the envelopes, green lines show distributions of the strength of the axial magnetic field. Measured rescaled (dots) and calculated (solid lines) beam profiles for the SPA06 current values of 6 A (blue color), 14 A (red color), and 22 A (green color). The rescaling was done to transform the elliptic coordinates to axial based on the measured horizontal and vertical sizes of the electron beam.

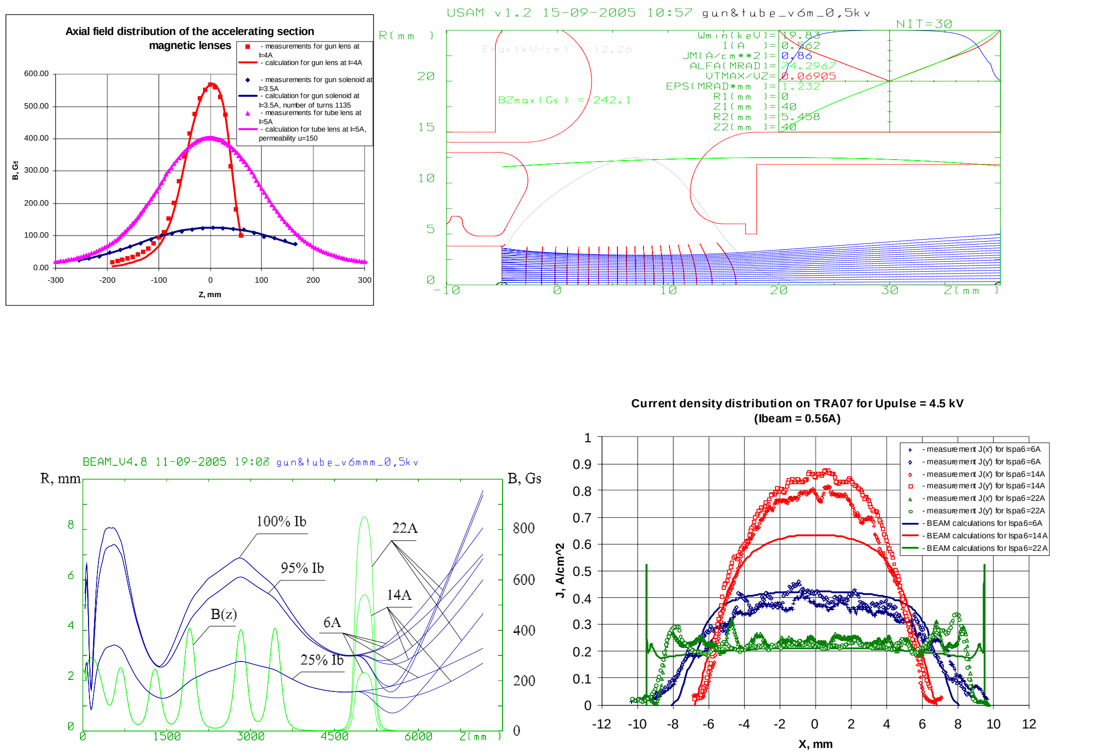

FIGURE 4. Axial field distribution of acceleration lenses (top left),Results of the gun simulation obtained with ULTRASAM program (top right), distributions of the strength of the axial magnetic field (bottom left) and measured (dots) and calculated (solid lines) profiles.

SUMMARY

OTR monitoring and data acquisition systems have been developed for analysis of beam dynamics with operation of the Pelletron in the pulse-signal mode. Using those systems measurements were done of the beam profiles downstream of the Pelletron accelerating section at the OTR screen location. Modeling of the beam dynamics in DC mode from the cathode to the OTR screen was done using ULTRASAM and BEAM programs. Measured results show good agreement with the modeling. This demonstrates that the developed systems operating in the pulse-signal mode provides results important for the beam dynamics analysis at the E-cooling facility.

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