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HIGH POWER BEAM PROFILE MONITOR WITH OPTICAL TRANSITION RADIATION

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Abstract

A simple monitor has been built to measure the profile of the high power beam (800 kW) delivered by the CEBAF accelerator at Jefferson Lab. The monitor uses the optical part of the forward transition radiation emitted from a thin carbon foil. The small beam size to be measured, about 100 µm, is challenging not only for the power density involved but also for the resolution the instrument must achieve. An important part of the beam instrumentation community believes the radiation being emitted into a cone of characteristic angle $1/\gamma$ is originated from a region of transverse dimension roughly $\lambda\gamma$; thus the apparent size of the source of transition radiation would become very large for highly relativistic particles. Our monitor measures 100 µm beam sizes that are much smaller than the 3.2 mm $\lambda\gamma$ limit; it confirms the statement of Rule and Fiorito that optical transition radiation can be used to image small beams at high energy. The present paper describes the instrument and its performance. We tested the foil in, up to 180 µA of CW beam without causing noticeable beam loss, even at 800 MeV, the lowest CEBAF energy.

1 SUMMARY

The CEBAF accelerator at Jefferson Lab delivers up to 200 µA of continuous electron beam in the 0.8 to 4 GeV energy range. The low emittance, 5×10^{-10} m–rad rms, constrains the beam to transverse dimensions smaller than 100 µm rms and may increase the power density to about 100 MW/mm^2.

Existing wire scanners measure profiles of only pulsed or low-current-CW beams to avoid melting their wire and also to prevent the beam loss monitors from triggering the machine protection system.

We present an operational prototype of a profile monitor that uses the optical part of the forward transition radiation emitted from a thin carbon foil when the beam passes through it. Previous studies [1, 2] indicated the heat the beam deposits on the foil should not damage it and also that the beam scattering through 0.25 µm of carbon should not deteriorate the beam characteristics down to 800 MeV. Here, we report on the successful operation of the instrument at 180 µA without damaging the foil and without any detectable beam loss in the range of CEBAF energy delivery.

An important issue for measuring small beam profiles is the resolution of the instrument. A relativistic particle beam yields a forward Optical Transition Radiation (OTR) with a peak intensity on a cone of characteristic angle $1/\gamma$. The thinking has been that there is an uncertainty $\approx \lambda\gamma$ in position of the OTR photon emission. Rule and Fiorito have challenged this concept [3]. We prove them to be right, after measuring a 100 µm rms size of a 3.2 GeV beam in the optical domain ($\lambda\gamma \approx 3.2$ mm).

In the near future, we are going to monitor the energy spread in the experimental beam lines with the same kind of profile monitor installed in a dispersive region. We mention a few improvements that will make these instruments better than the prototype from the operational point of view.

2 DESIGN CONSIDERATIONS

2.1 Forward versus Backward OTR

Transition radiation is generated on both sides of a conductive or dielectric foil when relativistic charged particles go through it, as shown in Figure 1. Backward OTR comes at specular angle, the foil behaving like a mirror [4]. The quantity of light is proportional to the reflection coefficient at the point of penetration. Very thin foils get wrinkles and local reflection defects. Using the thinnest foils is important to minimize beam scattering; therefore, we chose forward OTR to benefit from its advantages of not depending on either the beam's angle of incidence or the reflection coefficient.

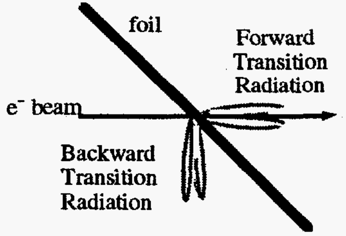

Figure 1: Direction of emission for backward and forward transition radiation.

2.2 Monitor

A simplified drawing of the monitor is shown in Figure 2. The electron beam passes near normal incidence through the 0.25 µm carbon foil. The foil is held on three sides of a square-hole support. The fourth side is open; in this way, one can insert or remove the foil without interrupting the beam delivery. A mirror sends the light outside the beam pipe through a vacuum optical window; the mirror and the foil support are mounted on a common assembly moved in or out of its operational position by a pneumatic actuator. The mirror has its edge 4 mm away from the beam trajectory when in working position. Two lenses focus the beam image on a Charge Injection Device (CID)

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camera specified up to 100 kRad of radiation dose. The video signal is sent to a monitor in the control room via the existing fiber optic network. It can also be switched to a video digitizer and processed to compute the beam size. The latter is still an off line process not yet available to the operators.

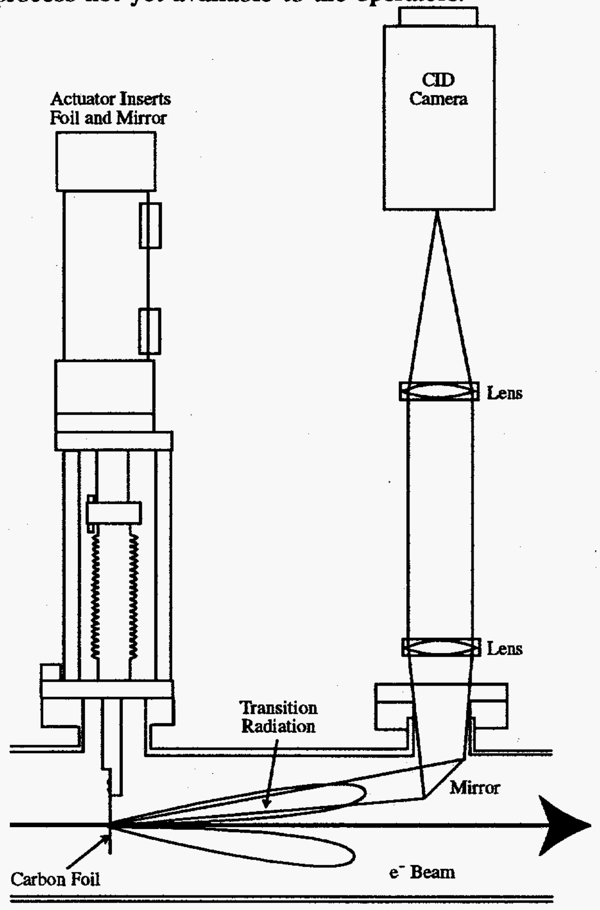

Figure 2: OTR profile monitor, top view.

2.3 *The Resolution Issue*

A low-emittance and high-energy linac like CEBAF is ideal to check whether the OTR phenomenon presents an intrinsic resolution limit of order $\lambda\gamma$. Figure 3 shows the vertical profile of a 3.345 GeV beam measured with the forward OTR monitor. With measurements at resolutions almost 40 times less than $\lambda\gamma$, it becomes clear that, as Rule and Fiorito stated a few years ago, there is no $\lambda\gamma$ limit and no uncertainty about the point of emission. The intrinsic resolution limit is that of the standard diffraction theory taking into account the specific distribution of the OTR (Figure 4) and the aperture shape. In our case, the first lens limits the vertical aperture, and the mirror the horizontal one. For the sake of simplicity, we considered only the first lens aperture : 50 mrad half-angle cone, 70 mrad off center in the horizontal plane. The numerical computation of the Fraunhoffer diffraction pattern along the horizontal axis (direction of aperture offset) and along the vertical one is shown in Figure 5. There is little difference with the Airy pattern $[J_1(x) / x]^2$ of an omnidirectional source of light. Looking at the directivity curves (Figure 4), we can see that the light distribution in the aperture does not change significantly above 100 MeV; thus, the resolution will not worsen at higher energy. An infinitely small beam would have an apparent FWHM value of the Airy variable x equal to 4.8. Thus, in the central part of the CID spectral response, at λ=500 nm, the resolution is that of a Gaussian beam 3.2 μm in rms size.

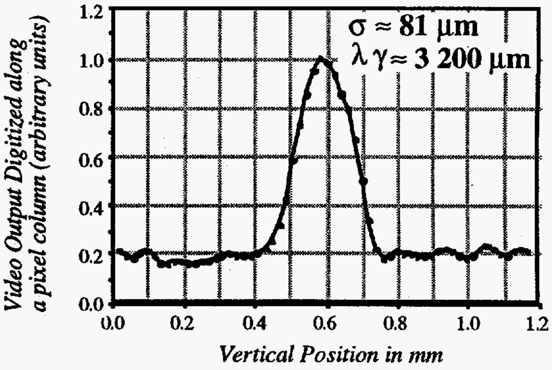

Figure 3: Vertical profile of a 3.245 GeV and 3 μA continuous beam.

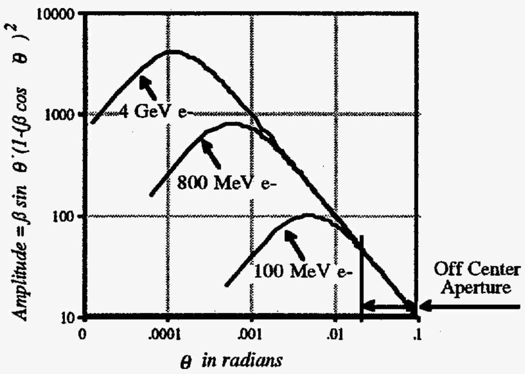

Figure 4: OTR Directivity versus spacial angle θ.

In practice, we do not need such a good resolution. We need to cover a field of 8 by 8 mm to calibrate the pixel size against the foil square holder. The pixel size and Modulation Transfer Function (MTF) of the camera contribute to a global resolution of about 50 μm rms.

3 OPERATIONAL CONSIDERATIONS

After a year of service, the CID camera failed once for reasons unrelated to radiation. Another failure occurred when the foil broke open after a vacuum opening and subsequent pumping in the vicinity of the monitor. The standard valve is now replaced by a restrictor valve that limits the pumping speed when recovering the vacuum after opening.

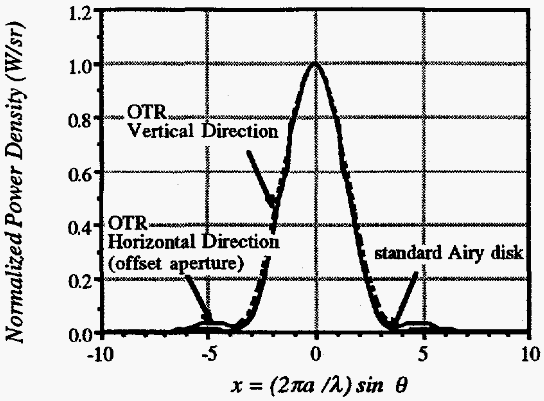

Figure 5: Diffraction patterns for standard Airy disk and for OTR through a 50 mrad half-angle aperture that is off-centered by 70 mrad. Both horizontal and vertical patterns are almost identical to the Airy disk.

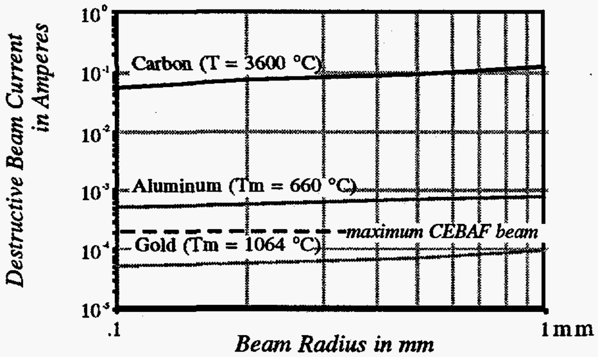

Figure 6: Computation of (destructive) beam currents that would bring Al and Au to their melting point and Carbon up to 3600 °C.

The instrument is only 50 m upstream of the experimental hall and has had no adverse influence on physics experiments. It can be inserted most of the time, even during end-station data acquisition. Two new instruments are going to be built for two of the experimental halls. A first improvement on these will consist of a better illumination of the foil support that will be implemented through a window opposite from the foil actuator. A second improvement will be to enhance the resolution down to 25 µm, adding a more powerful magnification to be switched after the calibration process. A third improvement pertains to measuring beam profiles at high currents: an automatic attenuator will prevent saturation of the camera. A simple software interlock will authorize the foil insertion only if the beam is centered well enough for not hitting the foil support or the mirror.

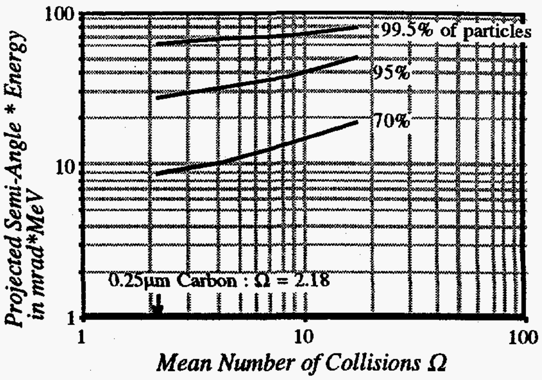

Figure 7: Plural beam scattering of highly relativistic electrons into thin materials. The number of collisions Ω is equal to $0.78\ \rho t[(Z+1)Z^{1/3}]/A$ where ρ is the density in g/cm^3, t the beam path length in the material in µm, Z the atomic number, and A the atomic weight.

4 CONCLUSION

The size of the OTR source is much smaller than $\lambda\gamma$. There should be no problem measuring a beam of a few µm at the present and future highest energy with a simple and low cost OTR profile monitor. A carbon foil 1/4 µm thick is used in daily operation to measure the CEBAF high-power-density beam up to 180 µA without affecting noticeably the beam or damaging the foil. Two new profile monitors are being built to measure the beam-energy spread in the experimental beam line during beam delivery.

5 ACKOWLEDGEMENTS

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