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Publication Date
1994-06-01

LBL-34973
UC-28

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Accelerator & Fusion Research Division

Presented at the 1994 European Particle Accelerator Conference, London, England, June 27–July 1, 1994, and to be published in the Proceedings

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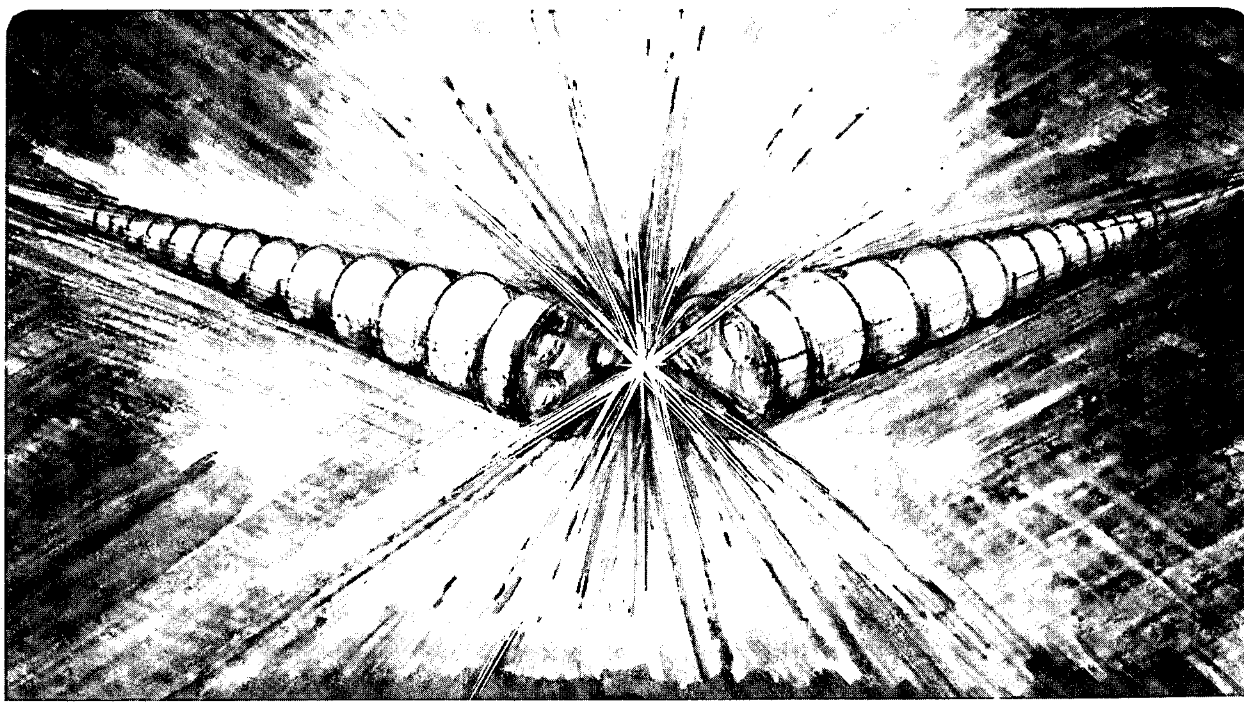

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL-34973

Characterization of the 50 MeV ALS Linac Beam with Optical Transition Radiation[1]

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Abstract

First experimental results of the optical transition radiation diagnostic at the Beam Test Facility (BTF) are presented. The BTF uses the 50 MeV Advanced Light Source (ALS) injector. Using sensitive CCD cameras single shot energies, spot sizes and divergences can be measured for the 1nC/bunch electron beam. The emittance was determined by analyzing optical transition radiation data for various currents of a quadrupole lens.

1. INTRODUCTION

Transition radiation was first predicted by Frank and Ginzburg [1] in 1945. It is produced when a charged particle crosses the boundary between two media with different dielectric constants. The radiation is emitted in a cone and contains information about the energy and divergence of the generating particles. In addition optical transition radiation (OTR) is prompt, radially polarized and the number of emitted photons is proportional to the number of producing particles making it a useful electron beam diagnostic as demonstrated by Wartski [2] and Rule [3].

2. RELATIVISTIC OTR BASICS

When a relativistic particle of charge *e* crosses an interface at normal incidence the intensity of the forward emitted radiation, in a frequency range $d\omega$ and solid angle $d\Omega$, is given by [2,4]:

$$\frac{d^2W}{d\omega d\Omega} = \frac{\mu_0 ce^2\beta^2}{4\pi^3}\frac{\sin^2\theta\cos^2\theta}{(1-\beta^2\cos^2\theta)^2} \times \left| \frac{(\varepsilon-1)\left[1-\beta^2-\beta\sqrt{\varepsilon-\sin^2\theta}\right]}{\left[\varepsilon\cos\theta+\sqrt{\varepsilon-\sin^2\theta}\right]\left[1-\beta\sqrt{\varepsilon-\sin^2\theta}\right]} \right|^2 \quad (1)$$

where θ is the angle with respect to the normal of the interface, ε is the dielectric constant of the medium, μ_0 is the vacuum permeability and β is the particle velocity normalized to the speed of light c. The formula for backward radiation can be obtained by replacing β with $-\beta$. The distribution is strongly peaked for $\theta=1/\gamma$ and typically yields 1 photon per 100 electrons. Here γ is the Lorentz factor. For extreme relativistic particles, a metallic foil and $\theta \ll \pi/2$, eqn. 1 can be simplified to:

$$\frac{d^2W}{d\omega d\Omega} = \frac{\eta_0 ce^2}{4\pi^3}\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2} \quad (2)$$

If the foil is rotated 45^0 the backward radiation is mirrored and the general formulae become difficult [4]. In the case of $\gamma=100$ the asymmetry arising from oblique incidence is of the order of one percent and its contribution is therefore neglected in our calculations.

To obtain the OTR radial distribution generated by an electron beam we convolve eqn. 2 with a gaussian profile for the angular divergence. The distribution of the photons produced by a beam of total charge Q is calculated numerically using:

$$\frac{dN(\theta,\alpha)}{d\Omega} = \frac{Q\mu_0 ce}{4\pi^3}\frac{1}{\hbar}\log\left(\frac{\lambda_{end}}{\lambda_{start}}\right) \times \int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}\alpha}e^{-\frac{1}{2}\left(\frac{\theta'}{\alpha}\right)^2}\frac{(\theta-\theta')^2}{\left(\gamma^{-2}+(\theta-\theta')^2\right)^2}d\theta' \quad (3)$$

where α is the standard deviation of the divergence angle, $\hbar$ is Planck's constant and $d\omega$ is integrated from λ_{start} to λ_{end}.

A rough estimate for the divergence can be obtained by calculating the ratio of the minimum (valley) and maximum (peak) of the radiation distribution, i.e. $dN(0,\alpha)/dN(\gamma^{-1},\alpha)$. Fig 1 shows the result of this calculation for γ between 90 and 110.

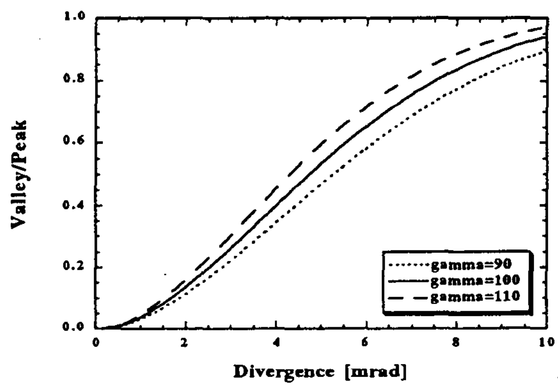

Fig 1: Valley/Peak characteristic for various γs.

3. THE EXPERIMENTAL SET UP

3.1 Beam Test Facility

The Beam Test Facility (BTF) uses the 50 MeV linac of the Advanced Light Source (ALS) and is operated under the auspices of the Center for Beam Physics. The parameters of the BTF electron beam are shown in table 1.

[1] This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Table 1: BTF Parameters

Energy:	50MeV
Charge:	1-1.5nC/bunch
Bunchlength:	10-15ps
Microbunch frequency:	125MHz
Macropulse frequency:	1Hz
Bunches/macropulse:	1-10

The BTF is designed for a variety of experiments. The first ones scheduled are a plasma lens experiment [5] and a femtosecond X-ray generation experiment [6]. One of the most important beam diagnostics is based on OTR.

3.2 OTR Diagnostic

A detailed diagram of the OTR experiment is shown in figure 2.

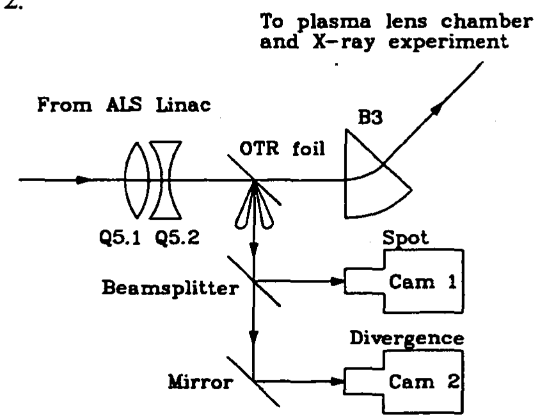

Fig 2: OTR Set up.

Backward emitted OTR is produced when the beam enters a 2μm nitrocellulose foil coated with 35-40nm aluminum. The radiation pattern is recorded simultaneously with two slow scan 16 bit 512x512 cooled CCD cameras. Both cameras use a 50mm f1.4 lens and have a sensitivity of 10 photons per count. One is focused on the foil to measure the spot size, one is focused at infinity to measure the radial distribution of the light. A polarizer is used to separate the contribution of the horizontal and vertical beam divergence to the radially polarized OTR light. Therefore α_x and α_y can be measured independently.

4. MEASUREMENTS AND RESULTS

We first show measurements of linearity of OTR with respect to beam charge. This is followed by a discussion of the data analysis procedure and the spotsize and beam divergence measurements as a function of quadrupole strength. We conclude by extracting a value for the horizontal and vertical emittance from these data.

4.1 Linearity

By varying the number of linac bunches in a macropulse (i.e. total charge) we have verified that the number of OTR photons is proportional to the number of electrons, up to 6 bunches (fig 3).

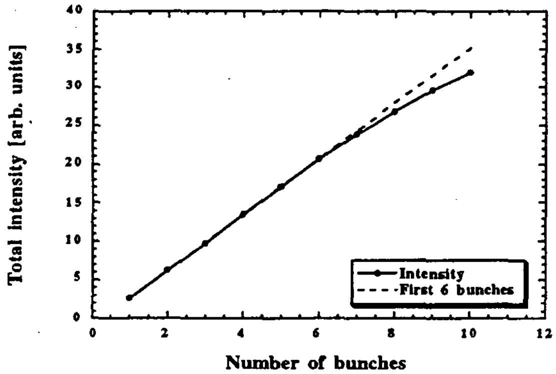

Fig 3: Recorded camera counts as function of number of bunches.

Simultaneous measurement of the charge per bunch with an integrating current transformer indicates that the deviation from linear for more than 6 bunches is caused by the limited energy acceptance of the BTF line in dispersive sections. Beamloading in the ALS linac causes an energy spread of about 1% per bunch, allowing only up to 6 bunches to be transported to the experiment without significant loss.

4.2 Data analysis

To analyze the data horizontal and vertical lineouts are taken through the center of the images. The standard deviation σ of the spot size is obtained by fitting a gaussian beam profile through the spot lineouts. Divergence angle α and energy are obtained by fitting eqn. 3 through the cone profiles. Sample data of a lineout through a radiation cone with fitted curve is shown in fig 4.

Beam divergences calculated using the simple valley over peak estimate are typically within 15% of the exact value.

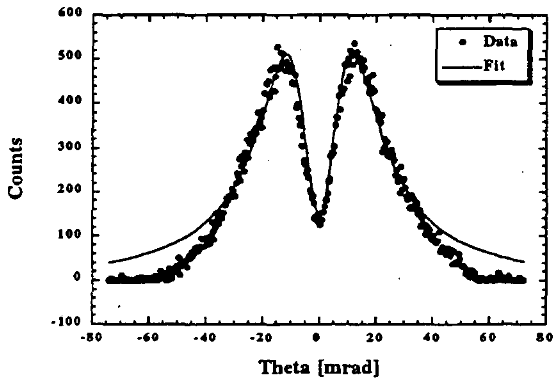

Fig 4: Sample cone lineout with fit. The difference between the data and the fit in the tails of the distribution is caused by a finite collection angle.

4.3 Quadrupole scan

During a quadrupole scan we fix the current of one of the quadrupole lenses Q5.1 or Q5.2 (see fig 2) while varying the current in the other one monotonically. The linac is set to run at 4 bunches per macropulse. Figs 5 and 6 show the rms spot size σ and rms divergence α, measured with a horizontal polarizer, as function of the current of Q5.1.

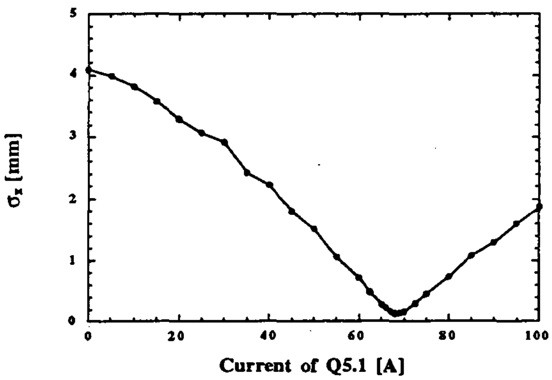

Fig 5: Rms horizontal spot size with Q5.2 fixed.

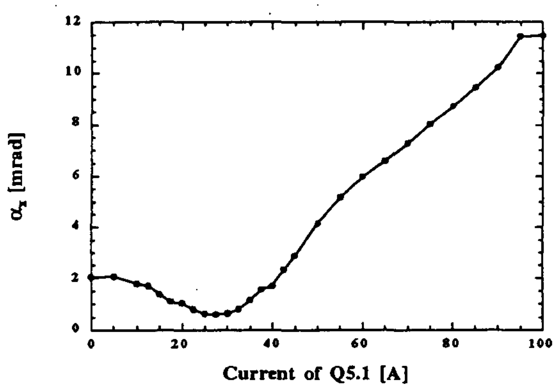

Fig 6: Beam's horizontal rms divergence with Q5.2 fixed.

With Q5.1 off, the beam has a small divergence. Increasing the strength of this quadrupole collimates the beam giving a minimum in the divergence, fig 6. Further increasing the strength focuses the beam and increases the divergence. When the focal point of the beam is at the position of the foil a minimum in the spot size is observed, fig 5. If we vary the current of Q5.1 we can pull σ_x and α_x through minima; using Q5.2 we obtain minima for σ_y and α_y. Simulation of the quad scan with the particle tracking code GPS [7] delivered qualitatively the same results showing the phase space ellipse to simultaneously rotate and stretch.

Gamma was found to be, as expected, independent of the quadrupole settings. The corresponding energy, calculated using $T=(\gamma-1)E_0$, indicated a beam energy of 50.0MeV. Gamma can be measured with an accuracy of about 1%.

4.4 Emittance

The measured values for spot size and divergence are projections of the phase space ellipse. Because the ellipse can be rotated, the area usually can not be calculated by multiplying these projections. When the ellipse is either horizontal or vertical we calculate the unnormalized rms emittance using $\varepsilon=\sigma\alpha$. Thus we obtain two values for the emittance per scan: when the spot size is minimal and when the divergence is minimal. The results for the two quad scans are displayed in table 2.

The emittance was also calculated independently by performing a non-linear χ^2 fit through the measured spot size σ vs. quadrupole strength (fig 5) and modelling this with TRACY [8,9]. TRACY uses the measured location of the different beamline components, measured magnetic lengths and strengths. The results are also shown in table 2.

Table 2: Emittance results

Polarizer	Horizontal	Vertical
σ minimum	ε_x=0.91 mm mrad	ε_y=0.45 mm mrad
α minimum	ε_x=1.70 mm mrad	ε_y=0.63 mm mrad
TRACY	ε_x=0.70 mm mrad	ε_y=0.59 mm mrad

Because the angular distribution of OTR is relatively insensitive to divergence angles smaller than 1 mrad (fig 1), the value of ε_x calculated at the minimum in divergence (0.6 mrad) is not very accurate. Both analysis methods give results larger than previously obtained values [9]. We are in the process of optimizing the linac performance and studying the sensitivity to dispersion in the beam line.

5. CONCLUSION

An OTR beam diagnostic has been built and tested in the BTF line. Using sensitive CCD cameras, single shot single bunch OTR light could easily be observed for a 1nC/bunch 50 MeV electron beam.

The light production has been shown to be linear with the total electron beam charge. Single shot spot size, divergence and energy measurements have been carried out as a function of the focussing strength in a quadrupole doublet. Estimates of the beam emittance using the divergence and spot sizes obtained from OTR and a conventional quadrupole scan are in good agreement.

A comparison of beam divergences calculated using the exact convolution integral and a simple valley over peak estimate indicates that the latter is accurate within 15%.

6. ACKNOWLEDGMENTS

We would like to thank S. Chattopadhyay and A.M. Sessler for their encouragement and support and M. Conde and R. Govil for their help with the experiment. We also greatly appreciate the assistance of the ALS operators, in particular T. Byrne and G. Ackerman.

7. REFERENCES

[1] I. Frank and V. Ginzburg, J. Phys. USSR, Vol 9, pp 353 (1945)
[2] L. Wartski et al. , J. Appl. Phys., Vol 46, pp 3644 (1975)
[3] D.W. Rule, Nucl. Inst. and Meth., Vol B24/25, pp 901 (1987)
[4] M.L. Ter-Mikaelian, *High-Energy electromagnetic processes in condensed media*, Interscience tracts on physics and astronomy, Wiley-interscience, NewYork (1972)
[5] W. Leemans et al., *"Plasma production for the 50MeV plasma lens experiment at LBL"*, these proceedings
[6] W. Leemans et al., *"Status of the LBL experiment on femtosecond X-ray generation through 90° Thomson scattering"*, these proceedings.
[7] General Particle Simulation, S.B. van der Geer, M.J. de Loos, J.F.G. van der Geer (1993)
[8] J. Bengtsson, E. Forest and H. Nishimura, unpublished
[9] J. Bengtsson, W. Leemans, T. Byrne, Proc. of the 1993 IEEE Particle Accelerator Conference, Vol. 1, pp 567 (1993)

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