

EMITTANCE MEASUREMENT OF THE DAFNE LINAC ELECTRON BEAM

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Introduction

The first measurements of the electron beam transverse emittances at the DAFNE-Linac exit have been performed with the quadrupole scan method. This technique gives in addition an assessment of the optical functions of the beam.

1. Transfer line layout and model

The transfer line layout downstream the Linac exit is shown in Figure 1. The monitor BPFTM01, used to measure the transverse beam sizes, is an aluminium screen emitting optical transition radiation (OTR) and positioned at a distance of 9.64 m from the Linac interface point. Three quadrupoles (QUATM01, QUATM02, QUATM03) and one steerer magnet (CHVTM01), positioned upstream of the screen, are used to set up the beam optics and the transport along the line.

The design specifications of the Linac in High Energy Electron mode are [1]:

$$\begin{aligned} \text{Emittance @ 510 MeV} &\leq 1 \cdot 10^{-6} \text{ m rad (geometric RMS)} \\ \text{Energy Spread} &= 0.5\% \quad (\text{FWHM}) \end{aligned} \quad (1)$$

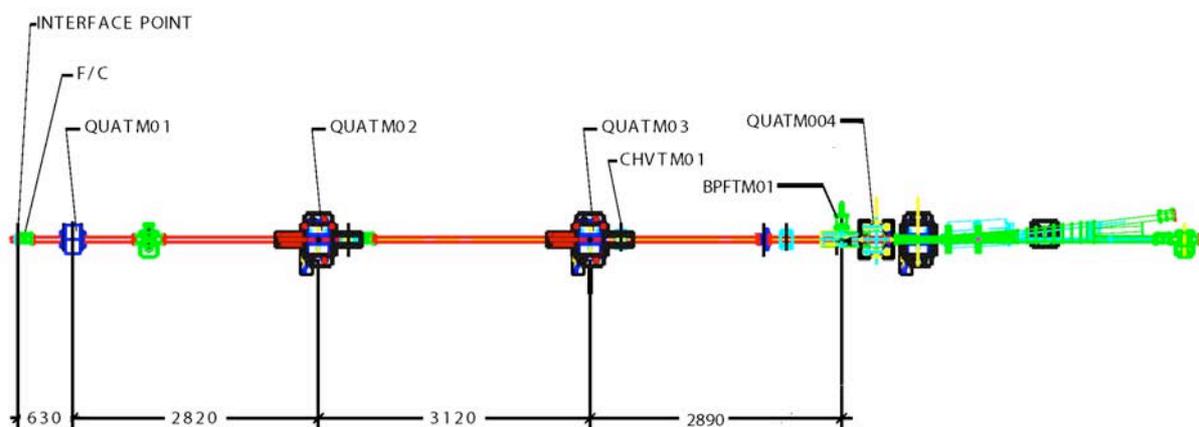


Figure 1: Layout of the transfer-line section where the measurement was performed, the distances are reported in mm.

The optics of the transfer line was modelled with MAD [2] and the starting optical functions were obtained from the last Linac FODO cell simulation discussed in a dedicated DAFNE Technical Note [3]. Two different sets of quadrupole currents have been calculated to be used respectively for horizontal and vertical emittance measurement.

2. Quadrupole scan technique

An invasive measurement of the beam emittance is performed by varying the field strength of a quadrupole located upstream from the screen. An extensive description of this method can be found in reference [4]. Briefly, the transfer matrix of interest is $M = SQ$, where S is the known transfer matrix between the quadrupole and the screen, and Q is the transfer matrix of the quadrupole:

$$Q = \begin{pmatrix} 1 & 0 \\ k = \pm \frac{1}{f} & 1 \end{pmatrix} \quad (2)$$

in the thin lens approximation for which the length of the quad is short compared to the focal length f . After multiplying the matrices S and Q , M turns out to be:

$$M = \begin{pmatrix} S_{11} + kS_{12} & S_{12} \\ S_{21} + kS_{22} & S_{22} \end{pmatrix} \quad (3)$$

Moreover M is related to the beam emittance matrix σ as $\sigma_{screen} = M \sigma_{quad} M^T$. Expanding the matrix product and equating the matrix elements on both sides, a quadratic expression for the beam size at the screen $\sigma_{screen11}$ is obtained in the quad field parameter k :

$$\begin{aligned} \sigma_{screen11} \equiv \langle x^2 \rangle &= A(k - B)^2 + C \\ &= Ak^2 - 2ABk + (C + AB^2) \end{aligned} \quad (4)$$

where A , B and C depend on the matrix elements S and σ_{quad} as described in the quoted reference.

Making use of this result the following procedure in the emittance measurement is carried out:

1. For each value of quadrupole strength k the image of the beam spot at the OTR screen is acquired;
2. Each image is analyzed to determine the beam size $\langle x^2 \rangle$ to be plotted as a function of the quadrupole strength k ;
3. The data points are fit with the parabola parameterized in Eq. (4) and A , B and C are determined.

Once the parameters A , B and C are known, the beam matrix σ_{quad} can be reconstructed and the beam emittance, calculated from the determinant of the beam matrix, comes out to be:

$$\varepsilon = \frac{\sqrt{AC}}{S_{12}^2} \quad (5)$$

while the phase space ellipse parameters β and α corresponding to the optical functions at the quadrupole location are given by:

$$\beta_{quad} = \sqrt{\frac{A}{C}} \quad (6)$$

$$\beta_{quad} = \sqrt{\frac{A}{C} \left(B + \frac{S_{11}}{S_{12}} \right)} \quad (7)$$

In our case $S_{11} = 1$ and S_{12} is the distance between the quadrupole center and the screen, 6.16 *m* for the vertical measurement with QUATM02 and 3.04 *m* for the horizontal one with QUATM03.

3. Experimental equipment

The experimental set-up used for the measurement is shown in fig 2. It consist of an OTR screen, a CCD camera with a 25 mm fixed focal lens, a NI frame grabber and a PC for the beam image acquisition. The plane of the screen is tilted with respect to the beam trajectory by 45°. The camera, a Philips LTC0335 monochrome has the CCIR standard, 512x582 video matrix, CCD area 4.8x3.6 *mm*² with a pixel dimension of 9.37x6.18 μm^2 . The analog output signal from the camera is fed into a NI frame grabber (578x760) and the conversion from pixel to real size dimension of the beam image size is defined by frame grabber digitalization (1 pixel = 45.78 μm^2). A synchronized trigger (trigger gun) is sent to a Stanford DG535 digital delay. This device provides a pulse (TTL standard) to drive the acquisition of the frame grabber.

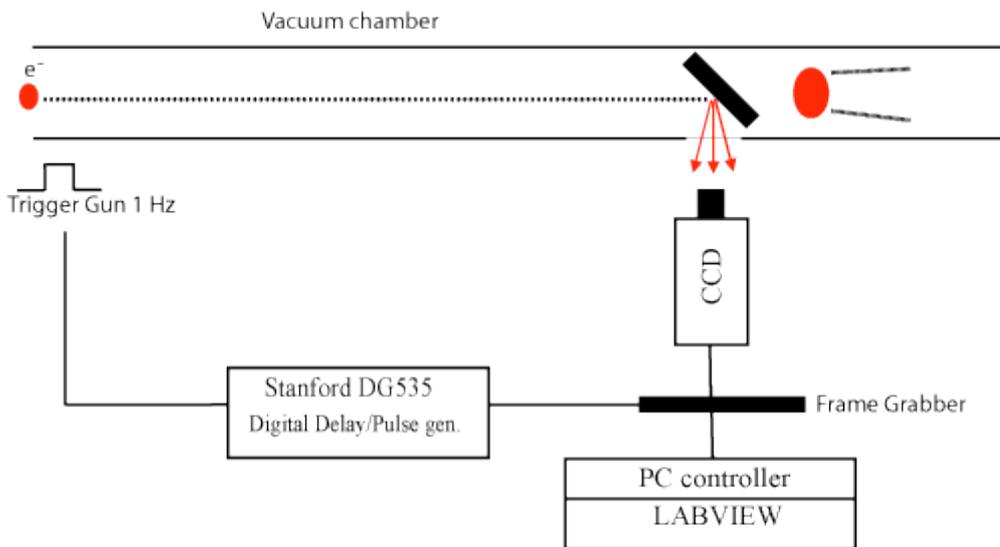


Figure 2: Block diagram of the acquisition system.

4. Quadrupole settings and data taking

The quadrupole currents have been calculated in order to produce a waist either of the horizontal or the vertical beam size near the OTR screen. Then the quadrupole scan is performed varying the current around the waist point in a range large enough to fit a parabola. The currents data sets for the last quadrupole of the Linac QLE0 and for QUATM01, QUATM02 and

QUATM03 are reported in Table I (ϵ_y and ϵ_x measurements). The steering dipole CHVTM01 was also adjusted at each step of the scan to center the beam spot on the screen.

The vertical emittance measurement was performed with an electron current from the Linac of 400 mA at the beam current monitor BCM4, while the horizontal emittance measurement with a current of 115 mA.

Table I – Quadrupole current settings.

Quadrupole	Current (A)	
	ϵ_y measurement	ϵ_x measurement
QLE0	12.0	12.0
QUATM01	20.0	34.0
QUATM02	-66.0	52.0 – 76.0
QUATM03	82.5 – 100.5	0.0

5. Data analysis

A new code has been developed for these measurements, to manage and analyze data in a simpler way. IACO (Image Analysis COde) is a Matlab and LabView based program that combines user friendly interfaces with compact and fast matrix manipulations. IACO has been used during these measurements to calculate beam parameters, as the centroid position and the r.m.s. size (σ_{RMS}).

Radiation from the OTR screen was captured by the CCD camera and images were analyzed. Obviously the parameter calculation depends on the image quality, while the image quality is strongly dependent from camera properties (such as pixel dimensions and distance from each other, electronic noise and pixel depth...); one can improve it by an accurate image treatment, so that post-processing becomes very important.

The program calculates the r.m.s. size of the beam to characterize its width rather than the standard deviation obtained by a Gaussian fit of the profile. This because in most cases the beam profile was not Gaussian and the theoretical distribution did not fit with the measured profile. In case of Gaussian beam the r.m.s. size and the sigma of the fit distribution give the same results.

However the disadvantage of taking the r.m.s. value is the weight of the tails in the calculation. In fact if one considers the formula for the r.m.s. values:

$$\sigma_{RMS}^i = \sqrt{\frac{1}{P_{tot}} \sum P_i (x_i - \bar{x})^2} \quad (8)$$

where P_{tot} is a normalization factor and P_i are the weights defined by the intensity on each point, what can be seen is that background noise or spikes distant from the centroid can lead to non negligible errors on the estimate of sigma, so that a very accurate filter is needed to make a precise selection of the collected signal.

The filter is based on an iterative procedure. The first step is to find initial values of parameters not so far from the final result; the distance between initial and final results determines the convergence time of the algorithm as described in the following.

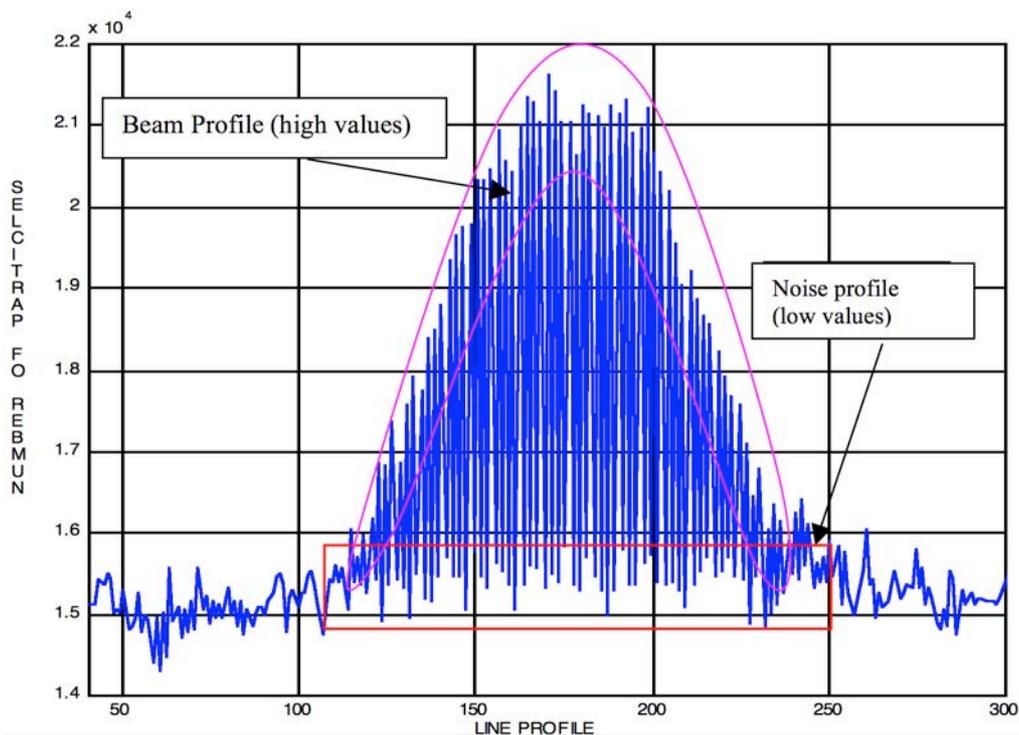


Figure 3: Example of measured signal for one image.

In our case we had an interlaced camera and the frame integration time is 33 ms (30 frames/s). Frame is divided in two fields (odd and even horizontal lines) and the camera uses half integration time to acquire single field. This time is much longer than the response time of OTR screen, so we had beam only on one field (even or odd) of the frame. This limits the resolution along y axis to half the resolution along x for every single pulse. On the other hand one can use the lines without signal to reconstruct noise also inside the beam itself. Doing this on every image, background noise subtraction pixel per pixel can be performed. The results of this procedure are good so they can be used to find initial values for centroid and sigma r.m.s. Once initial values are calculated, the filter comes back to initial image, and any pixel out from a region centered on the calculated centroid and with 8 sigma x and sigma y width is set to zero. Then the iterative procedure begins, in which external spikes are found with a “look around you” procedure, the parameters recalculated, and the region modified with that new numbers, and with 6 sigma width (instead of 8). The program stops when difference between values calculated in following iterations converges to pixel dimensions.

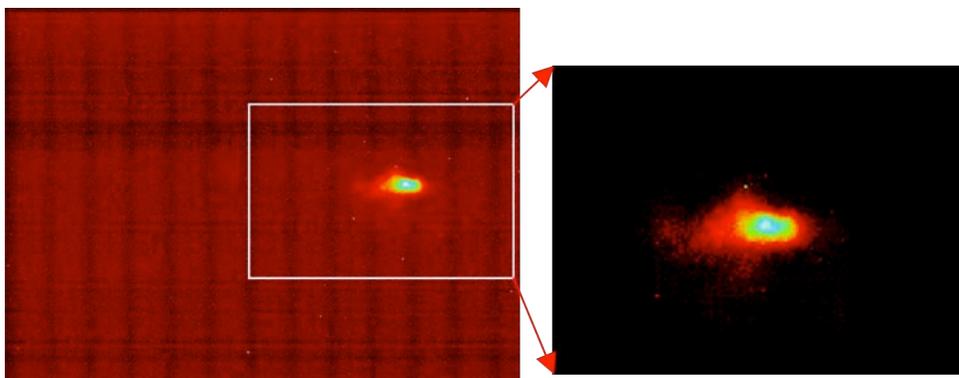


Figure 4: Example of image filter; on the left the measurement, on the right the same image after IACO filter; the program makes a selection of the region of interest, so the final image is smaller than the initial one.

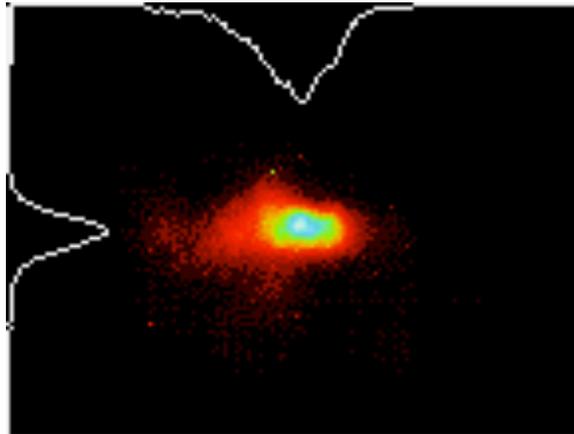


Figure 5: Final image with x and y profiles coming out from the sum over all columns and lines respectively. At the end of an iteration the program compares the values of the sigma and centroid with those obtained in the precedent step and exits the loop when the variations are negligible (less than $\frac{1}{2}$ pixel).

For each measurement several images were saved in a dedicated directory. The parameter values are averaged between all the images in the same directory, giving out the average centroid and r.m.s. size (x and y) for each directory with their errors.

Results

Figures 6 and 7 show the r.m.s. electron beam measured sizes plotted versus the quadrupole field strength, respectively for the vertical and horizontal scan. The measurements are fit with the parabola in Eq. (4) yielding results consistent with the emittance specifications [1] and in satisfactory agreement with the expected optical functions [3].

The vertical values are:

$$\begin{aligned}
 \epsilon_y^{rms} &= (1.2 \pm 0.3) \cdot 10^{-7} m \cdot rad; \\
 \beta_y^{QUA} &= 28 \pm 4 m; \\
 \beta_y^{OTR} &= 0.35 \pm 0.07 m; \\
 \alpha_y^{OTR} &= 0.2 \pm 0.4; \\
 \epsilon_y^n &= \gamma\beta\epsilon_y^{rms} = (1.2 \pm 0.3) \cdot 10^{-4} m \cdot rad;
 \end{aligned} \tag{9}$$

And the horizontal values:

$$\begin{aligned}
 \epsilon_x^{rms} &= (1.1 \pm 0.2) \cdot 10^{-7} m \cdot rad; \\
 \beta_x^{qua} &= 22 \pm 2 m; \\
 \beta_x^{OTR} &= 1.8 \pm 0.4 m; \\
 \alpha_x^{OTR} &= 0.5 \pm 0.4; \\
 \epsilon_x^n &= \gamma\beta\epsilon_x^{rms} = (1.1 \pm 0.2) \cdot 10^{-4} m \cdot rad;
 \end{aligned} \tag{10}$$

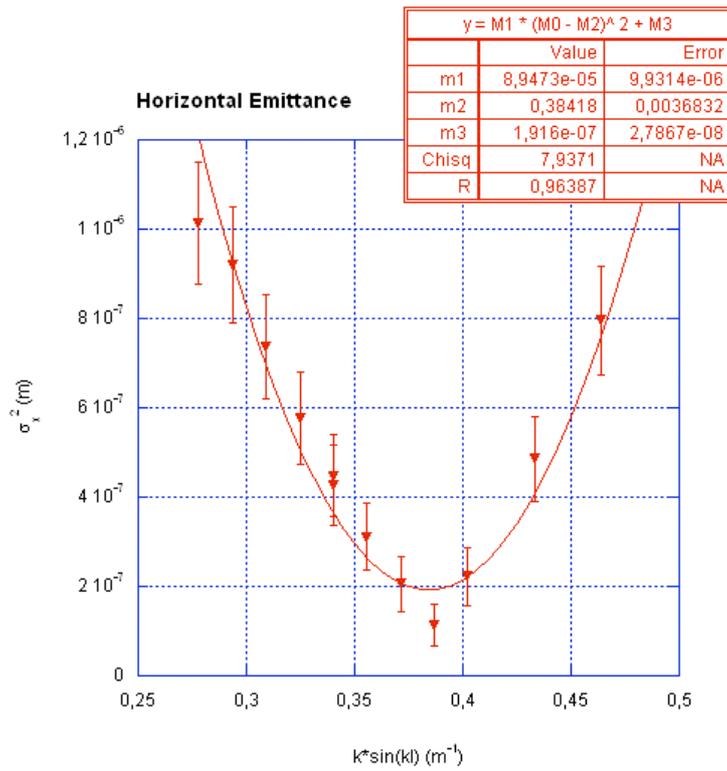


Figure 6 – The quadrupole scan fit for the vertical emittance measurement.

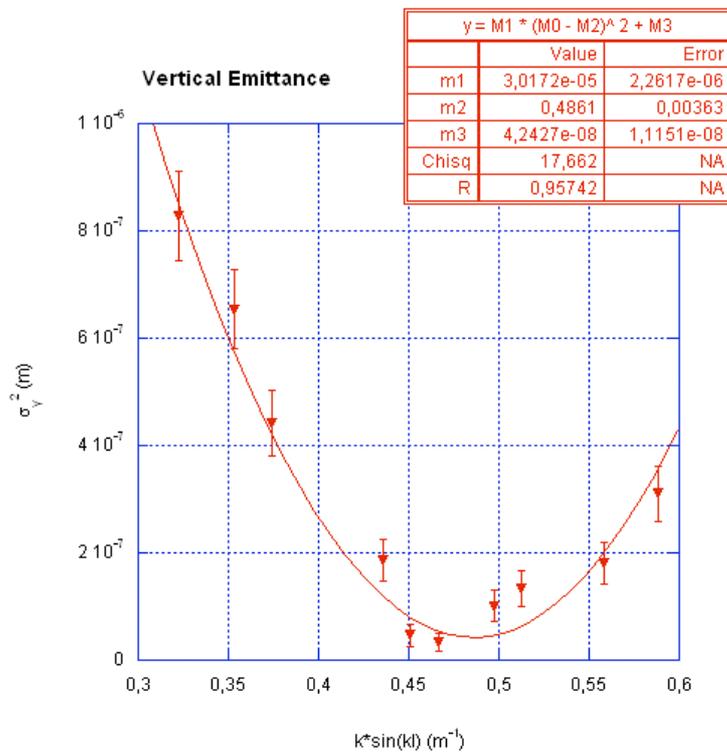


Figure 7 – The quadrupole scan fit for the horizontal emittance measurement.

Figures 8 and 9 show the betatron functions and the transverse beam sizes from the Linac exit to the OTR monitor BPFTM01 in a standard configuration calculated by matching the optical functions with the measured values at quadrupoles QUATM02 and QUATM03.

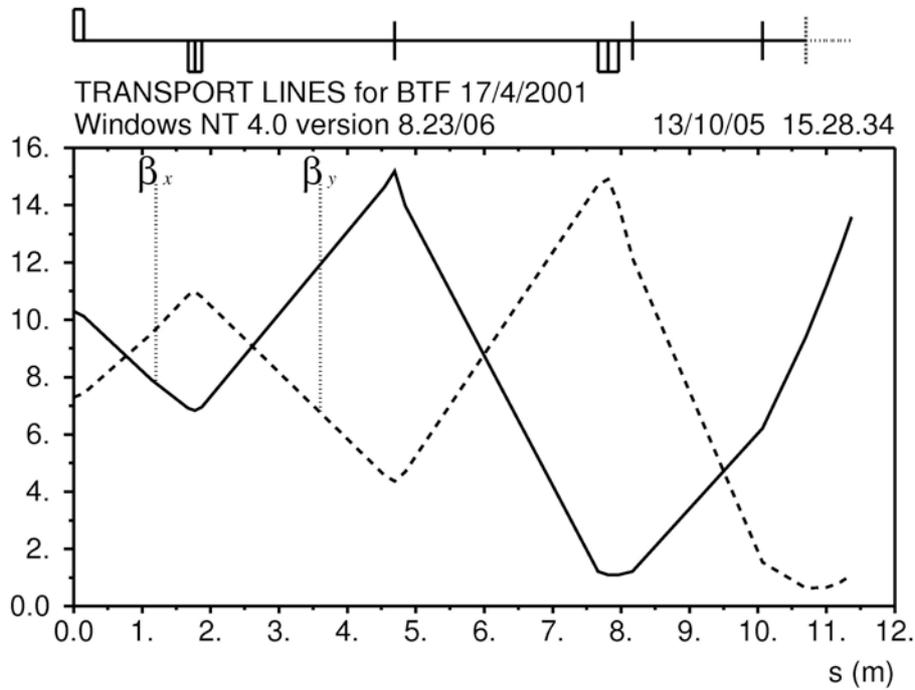


Figure 8 – The beta functions (meters) from the Linac exit to OTR screen.

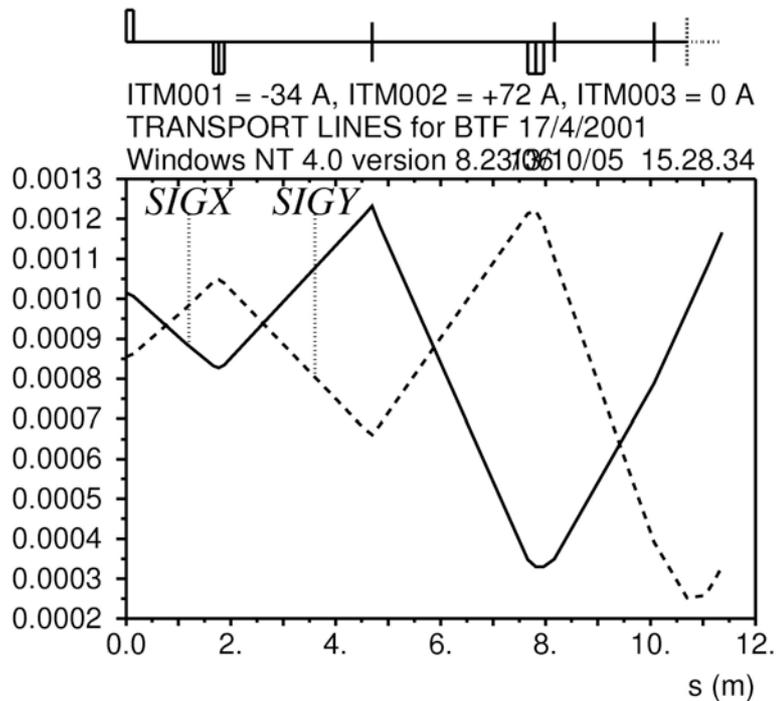


Figure 9 – The r.m.s. beam sizes (meters) from the Linac exit to OTR screen.

Acknowledgements

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References

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