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THE TESLA HIGH-POWER EXTRACTION LINE

E. Merker, I. Yazynin, IHEP-Protvino, Russia; O. Napoly, CEA/Saclay, France;
R. Brinkmann, N. Walker, DESY, Germany

Abstract

In the TESLA superconducting linear collider project, collisions occur at zero crossing angle. The option to rapidly dump the spent beams after the collision has been favoured recently to avoid the inconveniencies of large beam losses and beam line activation. For these reasons, the design of the beam and beamstrahlung extraction lines must be interplayed with those of the final focus optics and synchrotron radiation masking. We propose a system where the beam extraction is downward and where the beam and beamstrahlung power is dumped at 240 m from the IP. The power deposition along the beam lines and beam transmission to the dump are found to be acceptable.

1 INTRODUCTION

High energy (250 GeV) and intensity ($2.8{\cdot}10^{14}$ $\sec^{-1}$) of beams in the superconducting linear collider TESLA [1] require a careful design of extraction and transport of the spent beams and the beamstrahlung arising from the beam collisions at the interaction point (IP), to the dumps with small losses to avoid the activation of the surrounding equipment. The solution to this task is complicated because of the large increase in angular and momentum spread of the particles due the beam collisions at the IP and because the layout of the electron, positron and beamstrahlung extraction lines must be combined with the final focus optics of the incoming beam.

Emittances ε_x, ε_y [mrad]	$2.0{\cdot}10^{-11}$, $6.1{\cdot}10^{-14}$
Angular spreads θ^*_x , θ^*_y [μrad]	37 μrad , 12 μrad
Relative energy spread σ_δ	$3\ 10^{-4}$(e+)/$1.8\ 10^{-3}$(e–)

Table 1: TESLA 500 nominal beam parameters at the IP.

The design of the extraction system and beam line structure is driven by the following basic tasks: they must not influence the incoming beam; the relative beam losses from IP to dump should be nearly 0.1%; the part of the beam which cannot be transported to the dump should be intercepted

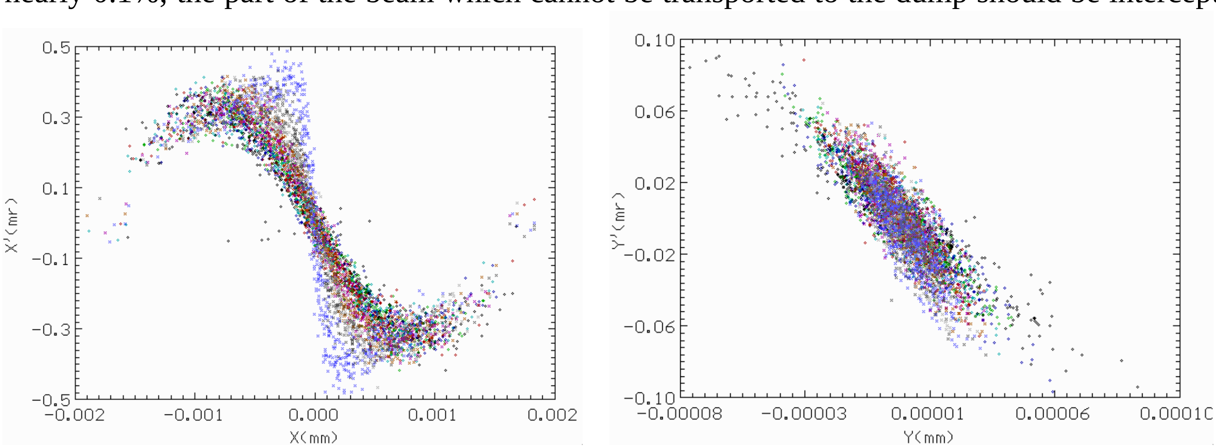

Figure 1: Beam horizontal (left) and vertical (right) phase space at the IP.

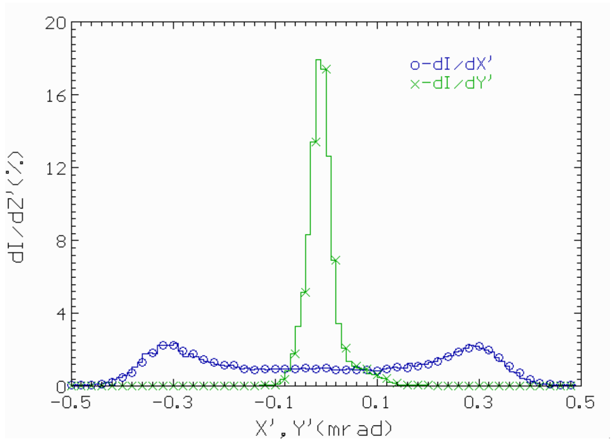

Figure 2: Angular beam distribution at the IP.

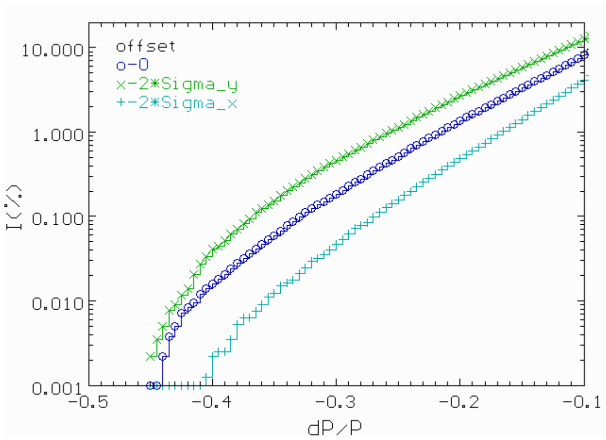

Figure 3: Beam distribution versus momentum

by a collimator specially installed for this purpose; the beam diameter on the dump in the case of collisions should be smaller than 0.8 m to fit in the dump window and, without collision, the spot size should be larger than 0.4 mm^2 for a small enough temperature rise of the dump water; the beam sizes in the sweeping kickers should not exceed the apertures of these magnets; the vertical inclination of the beam axis to the horizontal plane should be about 15 mrad at the dump. All these requirements must also be fulfilled in the case when beam position errors occur at the IP within a tolerable range. Indeed, the beam-beam effect gets larger for non-zero vertical beam offset.

The spent beam particles distribution in horizontal and vertical phase planes and their angular and energy distributions are shown in Figs.1-3. They are estimated from beam-beam simulations with GUINEA-PIG [2]. The effect of disruption and beamstrahlung can be inferred by comparing these distributions to the parameters of the nominal low emittance 250 GeV beam recalled in Table 1.

2 SPENT BEAM EXTRACTION

Beam Optics

The layout of the extraction system is shown in Fig.4 with the beam optics functions for 250 GeV energy. It contains the following main parts.

- The 20m long separator (ESEP1,ESEP2) consisting of electrostatic and magnetic deflectors combined in the same unit [3]. The bending of the beam by the magnetic field of the separator is compensated by its electric field for the incoming beam and added for the outgoing beam. The bending angle of the separator in the vertical plane is 0.8 mrad.
- The main spent beam deflection is executed by the 16 m long septum magnet (MSEP) with gradually increasing aperture. The total bending angle produced by the septum magnet is 2.1 mrad.
- To decrease the influence of the dispersion created by the extraction bends, it is reasonable to place the first focusing lens as close as possible to the IP. In order to preserve the necessary separation between the chambers of the incoming and outgoing beams, the first two lenses of the beam line are septum quadrupoles (QED,QEF): the two upper poles are replaced by a plate of magnetic material playing the role of a magnetic mirror. The first lens is then located 90 m downstream of the IP. Nevertheless because of the large energy spread of the spent beam, the apertures of these elements need to be too large. Therefore a collimator (MQED) is placed before the first lens to stop particles with the lowest momentum. Its aperture is chosen such that it intercepts nearly 0.1 % of the beam intensity and is defined by the beam distributions on the collimator surface, shown in Fig.5.

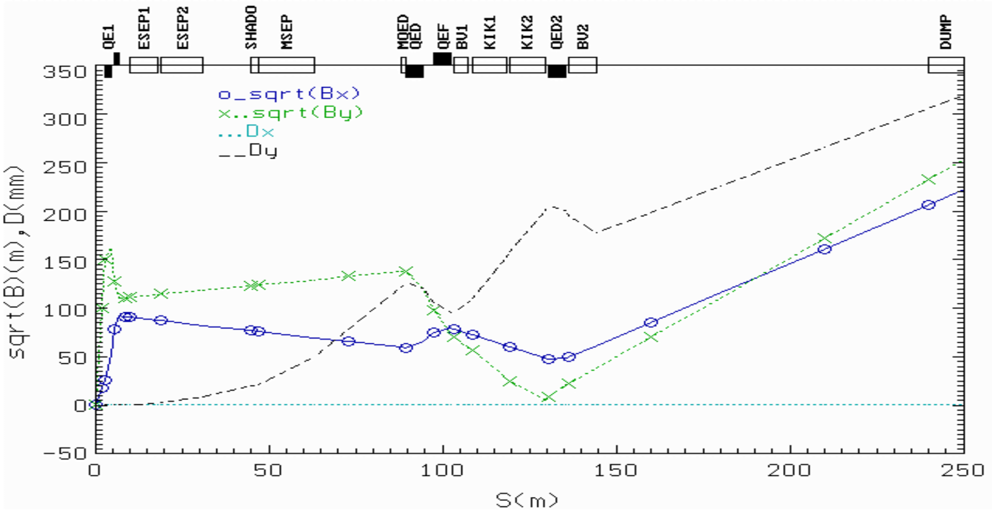

Figure 4: Layout of the beam extraction line

- On the other hand, during the accelerator commissioning phase the dump must sustain the power deposited by non-colliding low emittance beams. To avoid overheating of the dump, two 10 m long high-frequency kickers (KIK1,KIK2) are installed in the beam line, each providing beam sweeping along one of the transverse dimensions. As their fields are phase shifted by 90^0, the beam describes a circle on the dump. The kickers should provide a circle of 3 cm radius, large enough for the temperature rise in the dump water not to exceed an allowable limit of 80^0 C if the localized spot of the beam is $\sigma_x \times \sigma_y \sim 0.4 mm^2$ or larger [4].
- To get the necessary 15 mrad downward angle of the beam axis relative to the earth surface, vertical bending magnets (BV1,BV2) are installed.

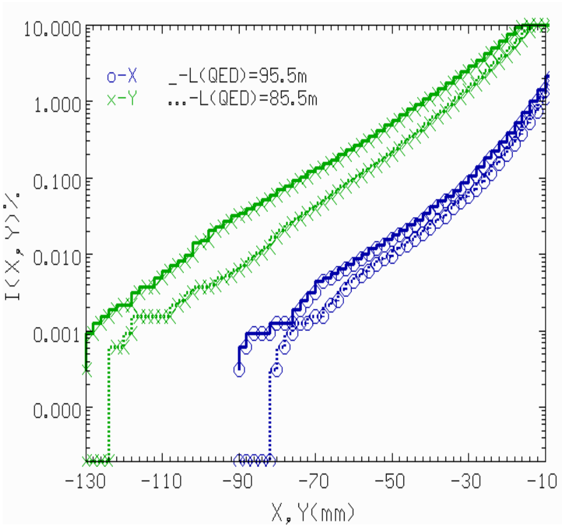

Figure 5: Beam distribution at the entrance of the QED quadrupole, for two different positions of this quadrupole.

The choice of the structure and of the beam line layout was made so that the spent beam losses are localized in the collimator and on the main dump, whereas the rest of the beam line is free from radiation and the apertures of the magnet remain technically feasible. A careful analysis of the beam cross-section along the channel depending on its structure and on magnet parameters was

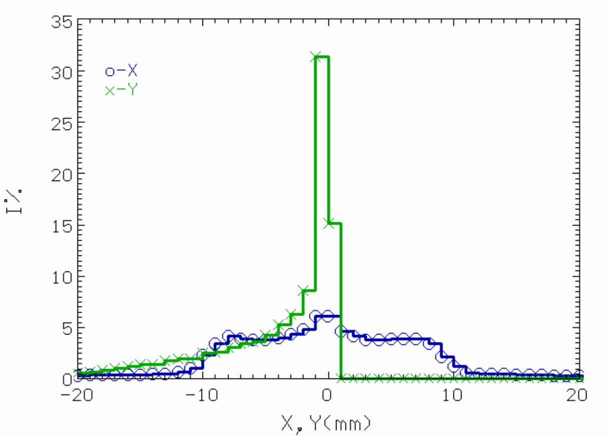

Figure 6: Disrupted beam profiles at the dump.

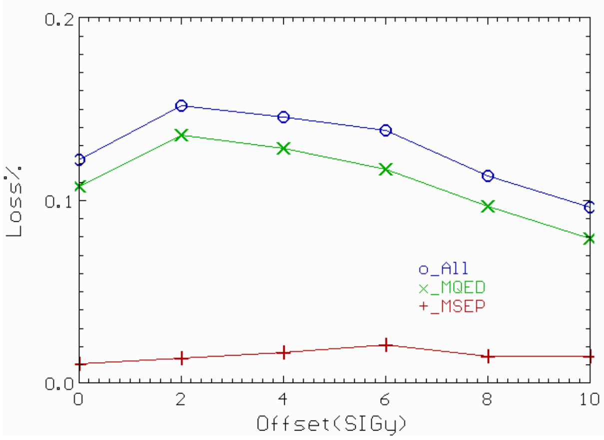

Figure 7: Losses versus vertical IP offset.

therefore needed. Because of the large momentum spread of the spent beams and their complex distribution on the transverse phase planes, this analysis is done more conveniently using a matrix tracking method for studying particle motion. The following variants were considered: without focusing elements, or with one, two and three lenses. Their comparison shows that in all variants, when there are particles with a large momentum deviation ($\Delta p/p_0 < -0.3$), the main influence on the beam size is coming from the products of the matrix element R12 with the angular deviation of particles rather than from the products of R11 with the coordinate deviations. The second important factor causing beam size increase in the vertical plane is the dispersion created by the bending magnets, mostly the dipoles BV1, BV2, which provide the required angle of the beam on the dump.

Variant	KIK1		KIK2		BV2		DUMP	
	ΔX Mm	ΔY Mm	ΔX mm	ΔY Mm	ΔX mm	ΔY mm	ΔX mm	ΔY mm
0 Lens	88	97	98	117	111	210	220	1620
1 Lens	169	60	242	58	340	60	1150	745
2 Lenses	124	64	98	110	71	130	550	503
3 Lenses	112	50	90	77	94	73	420	286

Table 2: Beam sizes (maximum displacements) in main line elements for variants of channel layout.

In table 2, the spent beam sizes in the most critical beam line elements are compared for the above mentioned variants of channel layout. All variants assume for the collimator jaw coordinates X = ±35 mm and Y = +10/–65 mm and, achieve nearly 99.9% beam transmission to the dump. From table 2 it is clear that with the 0-lens optics variant the beam is too large on the dump in vertical plane, while with one lens (QED) focusing in the vertical plane, the beam is too large in horizontal plane. With additional focusing in the horizontal plane (QEF), it is possible to get the beam sizes close to the required ones on the dump. Like QED, QEF must be then a quadrupole septum. Finally, the retained 3-lens optics with an additional vertically focusing quadrupole (QED2) provides some reserve for the beam electromagnetic cascade expansion in the dump, allows to narrow the apertures in main elements of the channel and, to reduce the gradient of the quadrupole QED.

The transverse beam profiles at the dump entrance are shown in Fig.6 for the 3-lens optics variant. As one can see from Fig.6 and table 2, the beam sizes on the dump satisfy the necessary requirements with a significant reserve, whereas the necessary apertures in all elements of channel can be met.

Beam Losses

The apertures of the electromagnetic elements and of the vacuum chamber should be chosen so that the beam losses must be as small as possible and concentrated at the collimator MQED. As shown by Fig.3, a vertical offset between the beams at the IP degrades the beam particle momentum deviation and therefore causes additional losses in the channel. In Fig.7 the dependence of the losses at the collimator MQED and at septum magnet MSEP and, of the total loss are represented as a function of the vertical IP offset : the maximum losses at the collimator occur at about $2\sigma_y$ offset. On the other hand, horizontal offsets at the IP do not cause additional losses. Table 3 gives the relative beam losses (at 0 and $2\sigma_y$ vertical offset) and the beam sizes in the main beam line elements and at the dump, as a function of different settings of collimator jaw apertures.

MQED		Total beam loss		KIK1		KIK2		BV2		DUMP	
$\pm X_c$	Y_{min}	dy=0	dy=2σ	ΔX	ΔY	ΔX	ΔY	ΔX	ΔY	ΔX	ΔY
mm	mm	%	%	mm	mm	mm	mm	mm	mm	mm	mm
15	–50	0.83	1.16	50	49	44	77	56	73	260	120
25	–60	0.25	0.35	82	50	78	77	80	73	360	240
35	–65	0.12	0.15	112	50	90	77	94	73	420	286
40	–70	0.08	0.10	128	50	100	77	97	73	500	325

Table 3: Transport efficiency and beam sizes (maximum displacements) in main channel elements.

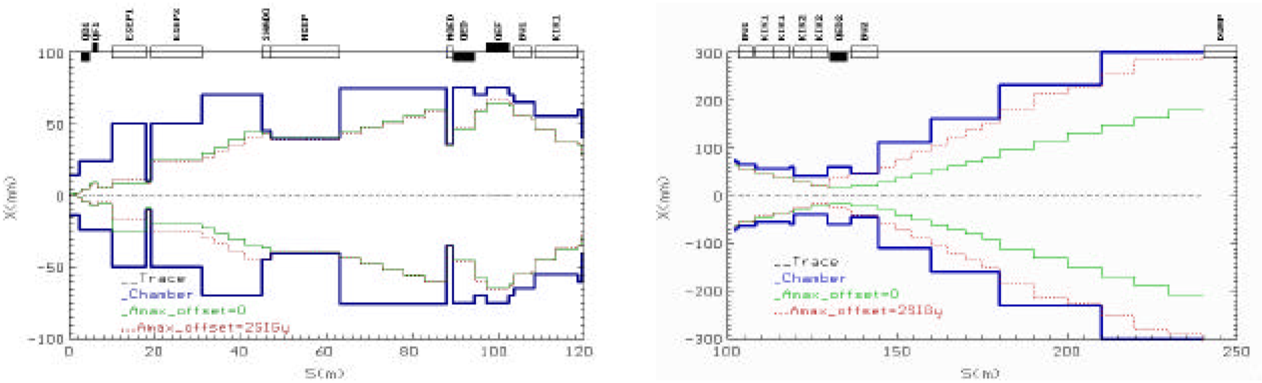

Figure 8: Horizontal beam pipe aperture of extraction beam line.

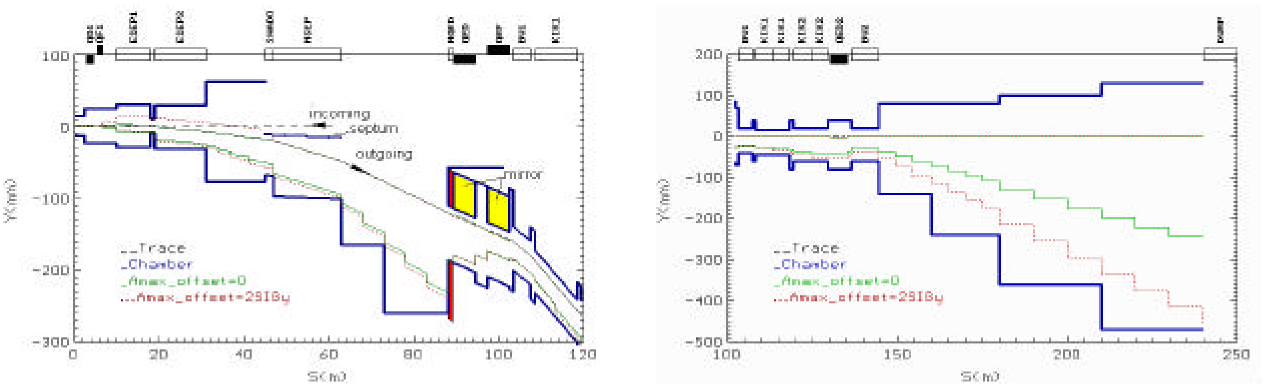

Figure 9: Vertical beam pipe aperture of extraction beam line.

Tolerating up to 0.15% beam loss leads to a solution where the collimator apertures are ±35 mm in X and [–65 mm, +10 mm] in Y. The required apertures of the magnets and of the vacuum chamber along the beam line are represented in Figs.8 and 9 (in the vertical plane, the apertures are plotted relative the incoming beam axis from IP to KIK1, and relative to the axis of the on-energy extracted beam from BV1 to the dump). The beam sizes (maximum displacements) for 0 and 2σ_y vertical IP offset are also plotted in these figures.

The resulting losses along the beam line are shown in Fig.10 for the beams colliding without offset. One can see that the losses are localized on the dump, on the collimator (about 0.1%), on the septum-magnet (about 0.01 %) and a very small fraction on the synchrotron radiation collimator COLL1 within the separator.

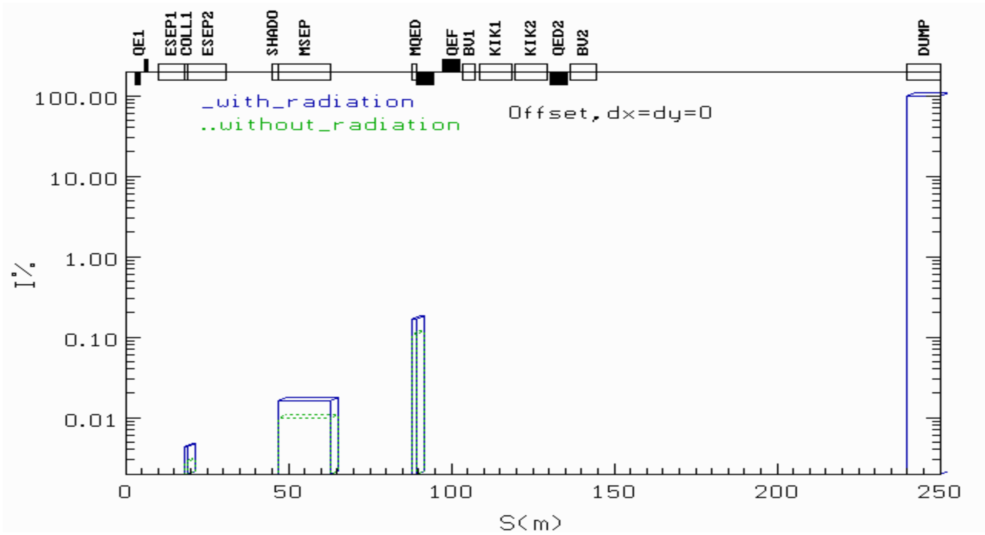

Figure 10: The histogram of the losses along the beam line.

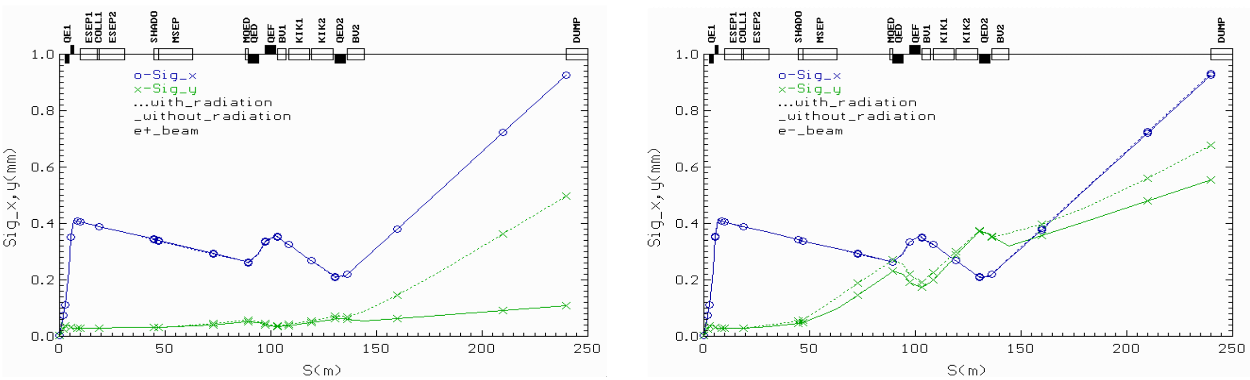

Figure 11: The e+ (left) and e- (right) RMS beam sizes with synchrotron radiation and without it.

Low emittance beam transport

During the accelerator commissioning and tuning phases it is important to ensure that no overheating of the dump water occurs due to the very small dimensions of the low emittance non-colliding beams. Fortunately some growth of the vertical beam emittance is generated by the synchrotron radiation in the bending magnets, as shown by Fig.11. Due to their different initial energy spread (see Table 1), the electron and positron beams have different vertical spot sizes along the beam line. The positron beam which has the smallest energy spread and therefore the smallest dimension nevertheless reaches about $\sigma_x \times \sigma_y = 0.92 \times 0.50\ mm^2$ RMS spot sizes at the dump which satisfies the $0.4\ mm^2$ specification. The transverse profiles of the non-colliding positron beam on the dump is shown in Fig.12, where the central value corresponds to the on-energy (zero synchrotron radiation loss) trajectory.

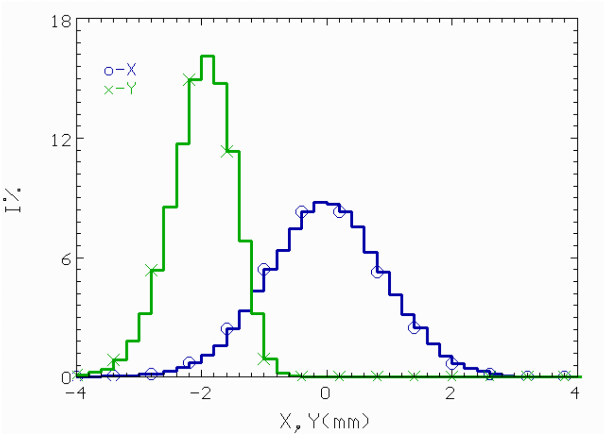

Figure 12: Low emittance e+ beam profiles on the

3 CONCLUSION

A beam extraction line has been designed for the 500 GeV TESLA linear collider in combination with a 11 MW water dump located 240 m from the IP. It achieves the two antagonistic goals of blowing up the sizes of non-colliding low emittance beams, in order not to vaporize the water, while controlling the beam-beam disrupted beam sizes to fit in the dump window. Extraction is done vertically with a net 15 mrad downward angle at the dump. This angle is generated in stages by electrostatic separators, followed by septum magnets and finally by normal dipoles. Septum quadrupoles with magnetic mirror plates are included to control the beam focussing and the large vertical dispersion. The main part of all spent beam losses are localized on the collimator and on the main dump, whereas the rest of the beam line after collimator is practically free from radiation.

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