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TESLA Parameters Update
A Progress Report on the TESLA Collider Design

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Abstract

This paper presents a concise summary of the TESLA linear collider conceptual design as it has developed to date. An overall picture of the TESLA approach is sketched, including the main linac, the final focus, and the electron and positron sources. This is a report on work–in–progress. Though a thorough consistant picture with a sense of optimization is yet to emerge, the ingredients are taking shape. Most of the discussion is devoted to TESLA 500, but preliminary parameters are given for the 1 TeV center–of–mass version.

1 Introduction – Overview and General Parameters

There is wide spread consensus among the HEP community that an e^+e^- collider with a center of mass energy of 500 GeV and luminosity of a few times 10^{33} $cm^{-2}sec^{-1}$ should be considered as the next accelerator after the LHC. Such a collider would provide for top analyses via t - $\bar{t}$ production and also have the potential for discovery such as Higgs with mass below ≈ 350 GeV.

Within the accelerator community a number of alternate linear collider design efforts are being pursued that meet the above stated energy and luminosity requirements. These designs have many features in common such as the overall linear collider/injector layout, but differ mainly in the choice of spot size, bunch charge and frequency. The differences mainly come down to trade off between the amount of beam power that is accelerated vs the spot size which has to be provided at the interaction point. The greater beam intensity can be used to balance more relaxed beam emittance and final focusing requirements. Typically, bunch intensities vary by an order of magnitude and vertical spot sizes by as much as a factor of 20. Also the different designs span a variety of RF frequencies from 1.3 to 30 GHz. The TESLA approach lies at the low frequency, high intensity end of the present parameter ranges. The use of superconducting RF cavity structures aids in achieving the higher beam intensity design. The resulting beam power could as well be applied toward higher luminosity design values if more stringent emittance and focusing were employed. However, the major appeal of the SCRF approch is that it allows

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Table 1: TESLA 500 Linac Parameters

Gradient	MV/m	25
RF Freq	GHz	1.3
Number of bunches/pulse		800
Bunch separation	μsec	1
Rep Rate	Hz	10
Number e	/bunch	5×10^{10}
RF pulse length	msec	1.3
Bunch length, σ	mm	1
Cavity aperture	mm-radius	35
Cavity cells		9
Cavity length	m	1.035
R/Q	Ω/m	973
E_{peak}/E_{acc}		2.1
B_{peak}/E_{acc}	mT/MV/m	4.2
Peak RF Power	kW/m active	206
Cryo 2K load	W/m active	2.8
HOM k_{long}	V/pC/cavity	8.5
HOM k_{trans}	V/pC/m/cavity	18

for the more relaxed tolerances and less ambitious extrapolations from the state of the art operation at SLC.

The technical advantages of the superconducting RF cavities stem from their high Q values and low wall losses. This allows for the use of large aperture structures operating at relatively low frequency, with relatively long pulse lengths and low peak RF power requirements. The large aperture of the cavities are perceived to be a major advantage as it results in substantially reduced wake effects for both longitudinal and transverse wake fields (the longitudinal wake scales with the aperture (a) as $1/a^2$ and the transverse wake as $1/a^3$). As the aperture of an L band sc cavity is $\approx$ 70 mm diameter, or about ten times larger than in some of the higher frequency designs, relaxed linac alignment and vibration tolerances should result even with the large bunch charge contemplated. With the larger emittance, more dilution can be tolerated in the linac, in the optics after the linac and the final focus. In addition the focusing strength, optical quality and alignment needed is not so stringent because of the higher beam power and larger spot. The result for the detector is more longitudinal space after the last focusing element and a long beam pulse with considerable time between bunch interactions. Just how much easier the alignment/vibration and field quality tolerances will be and how favorable the result will be for the detectors, will require a serious design study employing all the knowledge that has been learned at SLC and from other collider design efforts.

Summary parameters of TESLA 500 linac are given in Tab. 1. The Tab.in the appendix lists the main accelerator design parameters of TESLA 500 (1/2 TeV cm energy), and also lists very preliminary parameters for TESLA 1000 (1 TeV cm energy). Considerable work has been done to analyze the emittance growth control in the case of the TESLA 500, however, analysis of the TESLA 1000 parameters is only beginning. In this paper discussion will focus on the TESLA 500 design.

Table 2: TESLA 500 parameter changes to Final Focus and resulting effect

		old	new
σ_x	nm	640	1000
σ_y	nm	100	64
β_x^*	mm	10	25
β_y^*	mm	5	2
L(10×10^{33})	$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	9.4	6.1
δE_{beam}	%av	9.3	3.1
Υ	av	0.064	0.029
D_x		1.22	0.54
D_y		7.7	8.5
H_y		3.6	2.3
N_γ	/beam e	4.3	2.5
N*[a]	/crossing	41.6	14.5

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[a] N* is number of e^+ (or e^-) per crossing produced with $p_t > 20$ MeV/c and angle > 0.15 rad.

Minor changes in the Final Focus parameters have been made in the last year in order to improve the quality of the beam for the experiments. These changes are reflected in Tab. 2.

2 Parameter Changes and Optimization for Experiments

As can be seen from Tab. 2 rather minor changes to the beam aspect ratio at the IR, without changing the linac beam properties (emittance, bunch length) were necessary in order to significantly improve the beam energy spread and the background of electrons and photons. All of these are a result of strong deflection of particles in one beam by the oncoming beam and their resulting radiation and pair creation.

The luminosity equation may be written as a function of average energy degradation, δE/E, or Disruption Parameter D, or Beamstrahlung Parameter Υ depending on which resultant experimental property one considers most important[1]. For instance considering energy degradation, the luminosity (non–enhanced) can be written

$$L = f_c \frac{N_b^2}{4\pi\sigma_x\sigma_y} \tag{1}$$

or

$$L = A \frac{P_b\sqrt{\frac{\delta E}{E}}}{\gamma\sqrt{\epsilon_{n,y}}} \tag{2}$$

where

$$\frac{\delta E}{E} = \frac{0.22 r_e^3 4\gamma N_b^2}{\sigma_z \sigma_x^2} \tag{3}$$

for $\beta_y^* \approx \sigma_z$, where A=1.2 $\times 10^{36}$ $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, P_b is in [MW], $\epsilon_{n,y}$, is in [m-rad].

Such expressions show clearly the limited flexibility one has if one is interested in maintaining reasonable quality end use physics parameters.

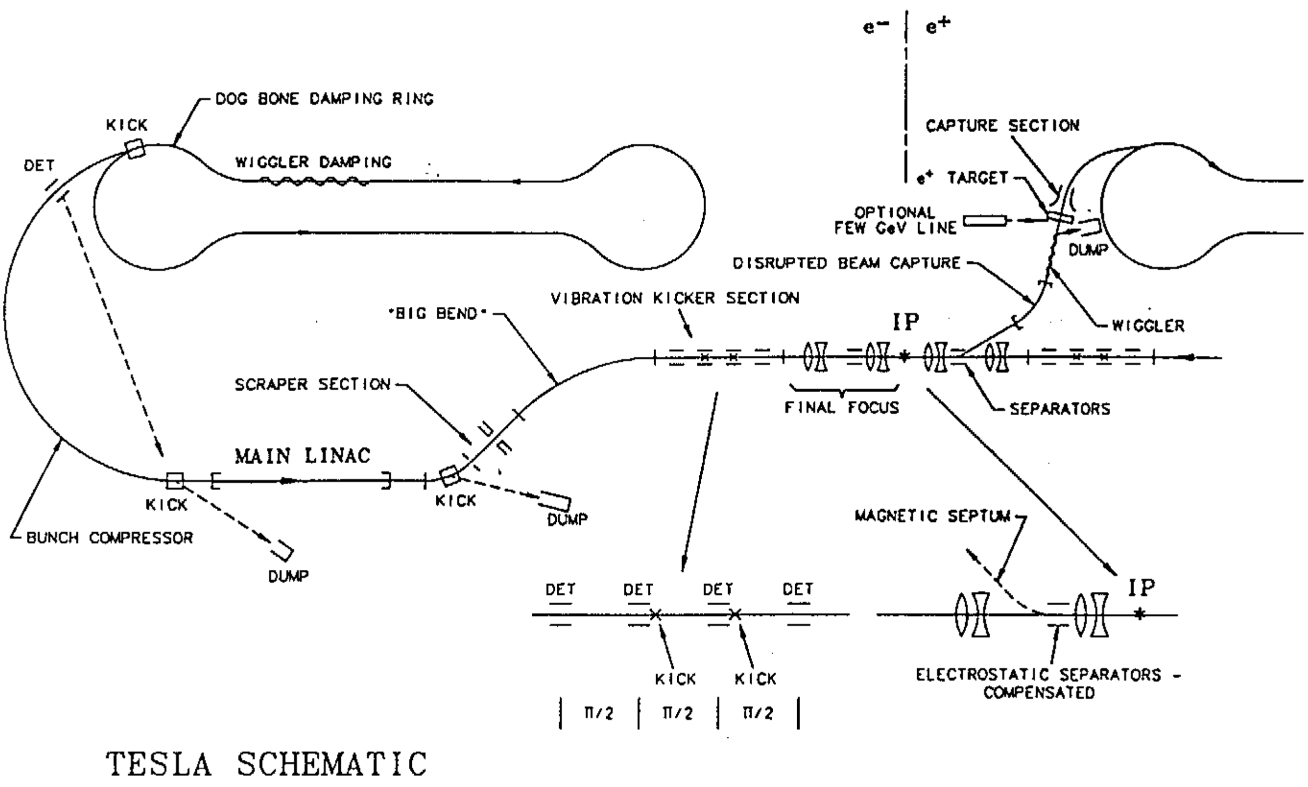

Figure 1: Prelininary layout for TESLA 500

It is further valuable to note that δE/E, D, and Υ all depend on N_b/σ_x so depending on what R = σ_x/σ_y you think is achievable throughout the linac and what single bunch luminosity experimenters can accept determines whether one chooses to have a few high charge, flat very extended bunches in x, or for the same current more lower charge bunches, of less horizontal extent.

Both of these ideas are useful in understanding the changes in choice of parameters for TESLA 1000. For the TESLA 1000 parameters it should be noted that the bunch charge, separation has been reduced about a factor of 5. The vertical emittance has been dropped considerably from 100 to 6×10^{-8} m-rad, and the horizontal by a factor of 4. β_y^* has dropped from 2 to 1 meter. These changes have been necessary in order to obtain a luminosity of 10^{34} without significant deterioration of the final experimental beam characteristics at the IR. It is interesting to note that the total power usage is only slightly increased from the TESLA 500 case. This is a result of dropping the rep rate to 5 Hz (from 10), even though the linac length has increased by a factor of two while holding the gradient at 25 MV/m. In summary then a first look at the TESLA 1000 parameters requires a substantial reduction in the vertical emittance. The emittance dilution down the linac must now be analyzed for this more demanding requirement and it is likely that more stringent quad and BPM alignment will result.

3 Layout of TESLA

Over the past year a picture has begun to emerge of a consistant overall layout for TESLA 500. This is not to say that an actual conceptual design has been worked out but rather that there are ideas and that those ideas are beginning to fit together so that we may begin to develop the individual pieces of the conceptual design.

Fig. 1 illustrates the ideas which are presently being thought about. It of course is a varient of the "standard" NLC schematic layout. In talking about the layout it is easiest to begin with the main linac which though the major part of the collider shows up as only one of many elements.

The linac is superconducting and operates at 2 K. It includes cavity structures and focusing quadrupoles and steering elements.

At its end is the high energy beam transport section leading to the final focus and Interaction Point (IP). Immediately after the linac is a kicker which can be used to send the beam to a dump if a dangerous condition is detected like improper beam energy.

Next comes a section which provides beam halo scraping and collimation. This can also sense off momentum beam and provide a trigger to the upstream kicker.

Following this is a section of transport, the "Big Bend." Its design and extent will be determined by the need to eliminate muon background.

Next is a section containing fast kicker magnets and beam position detectors arranged at $\pi/2$ intervals. These kickers will be used to correct minor variations in the bunch to bunch position of the beam that may be caused by ground vibrations, by multi–bunch cavity modes, or by beam energy variations bunch to bunch down the linac. These kickers will correct each bunch based on the position of previous bunches. They are placed as near as possible to the IP so as to compensate for as many effects and elements as possible.

Finally comes the Interaction Region with the Final Focus optics and experimental detector. For TESLA there is the possibility of head on collisions. This is a result of the large bunch spacing. Head on collisions are accomplished with the use of large aperture superconducting magnets as the final elements and with a combination of magnetic and electrostatic separation of the counter moving e^+ and e^- beams.

At the downstream (for each beam) side of the IP the outgoing beam is deflected away from the incoming beam. A proposal under serious consideration is to use the "spent" high energy e^- beam for e^+ production. Following the downstream final doublet is a section which is designed to capture the outgoing disrupted beam, with its resultant poor quality energy spread and emittance. The goal for this section is to repackage the beam so it is suitable to be sent through a wiggler which acts as the first element in the positron source.

Positron production is accomplished by using photons produced in the wiggler on a thin production target. The high energy beam after it has traversed the wiggler is then bent away from the straight ahead photon beam and dumped. The scheme of wiggler and thin target is preferred over a standard thick target source because of the severe difficulty in heating which would result from the required number of positrons each beam pulse. Polarized beams appear possible from this arrangement, as well.

The positron target is followed by a capture section and linac to accelerate to ~ 4.5 GeV before injection into the damping ring.

The damping ring needs to be of considerable circumference in order to be able to hold the 800 bunches required for a single collider beam pulse. The ring needs to hold the 800 bunches with enough space between them that a fast kicker (~ 20 nsec) could extract one bunch at a time every μsec into the linac.

Under consideration at present is a "dog bone damping ring" which would be constructed with two long straight sections in the same tunnel as the main linac and with turn around arcs at either end. Such a ring could have a circumference of 30 km if it ran adjacent to its own linac. Damping would be accomplished by a wiggler scheme in these rings.

Table 3: Sources of emittance dilution

injection error of	1/2 σ_y or 28 μm
rms alignment errors of	
quads (with respect to a long base smooth line after initial beam based alignment)	100 μm
cavities (with respect to line or quads)	500 μm
beam position monitors with respect to quads	100 μm
beam position monitor resolution	10 μm

From the damping ring beam would be transported and injected into the linac through a compressor section. This section would also provide for only injecting proper quality beam into the linac. This can be accomplished by monitoring the beam leaving the damping ring and through line of sight transit of the signal vs circular path for the beam bunch, be able to deflect any bunch into a dump before it enters the linac.

4 Main Linac and Emittance Dilution

Emittance dilution is produced from off axis trajectories in conjunction with chromatic effects from δE/E spread or variation, and from both single bunch and multi bunch wake field effects. Analysis of emittance dilution for TESLA has been performed by Mosnier[2] and by Mosnier and Napoly[3]. The assumed alignment errors are summarized in Tab. 3

Additional error sources are vibration, energy spread per bunch, and energy variation over many bunches.

The preferred lattice was found to be a constant $\langle\beta\rangle = 66$ m lattice. This corresponds to a half cell every 24 cavities or about every 33 m.

Single bunch emittance growth is summarized as follows:

- Injection offset errors of 28 μm lead to $\delta\epsilon/\epsilon = 4\%$.
- Alignment errors and a $\delta E/E = 1.5\ 10^{-3}$ at the end of the linac produce
  - $\delta\epsilon/\epsilon = 20\%$ for one to one steering correction,
  - $\delta\epsilon/\epsilon = 5 - 10\%$ for "dispersion or wake free" correction.

Multi bunch emittance growth is summarized as follows:

- HOM Q's in the 10^5 range and frequency spreads of 1 MHz are assumed.
- With $\delta E/E = 10^{-3}$ bunch to bunch, and injection offset of 28 μm $\delta\epsilon/\epsilon = 2\%$.
- Cavity alignment errors of 1 mm without energy variation also produce small $\delta\epsilon/\epsilon = 4\%$.
- However, when bunch to bunch energy variation of δE/E of 10^{-3} is introduced, emittance dilution becomes ten times greater. This dilution is not of the single bunches but rather that different bunches do not fall on top of one another.

Ground motion vibration produces similar bunch to bunch or pulse to pulse position variation of the beam. Random uncorrelated motion produces a magnification of beam motion at the end of the linac to quad motion of $y_{beam-end}/y_{quad} \approx 30$, which would yield for typical expected 0.1 μm quad motion a $\delta\epsilon/\epsilon = 6\%$.

However, the ground motion is not expected to be random, but rather coherent over some distance at least. Long distance coherence though probably not realistic would lead to resonance behavior in the constant β lattice and possible magnification factors of y_{beam}/y_{quad} of 100 to 250.

A possible advantage to TESLA is the time between bunches. We believe that it will be possible to measure individual bunch position variations and make corrections to following bunches. This would assume small motion bunch to bunch but slowly varying trends over the one msec bunch train. Analysis needs to be done to determine if it is sufficient to make this correction at the end of the linac or if it will need to be done a few times along the linac as well. The expected size of the kick needed is of order 50 μrad.

TESLA appears to have clear advantages over other linear collider designs as far as tolerances are concerned. However, it should be noted that as higher energies and smaller emittances are considered tolerances will become much more important.

5 High Energy Beam Transport and Final Focus

Optics for TESLA final focus has been described recently by O. Napoly[4]. It has a good acceptance for ± 1/2% energy spread.

The philosophy of the TESLA final focus is to use large aperture quadrupoles and only collimate the beam at as large as possible amplitudes in order to minimize backgrounds produced by upstream collimators.

The beam trajectories of importance are the ones with angle-like phase at the IP, as these are the ones most likely to hit magnets in the high β region of the final focus. It is also important to consider the cone angles of disrupted beam and photons produced in the interaction region and to try to assure that upstream collimation will effectively mask the final focus and detector region. Synchrotron radiation produced in the upstream doublet must also pass through the aperture of the downstream magnets. R. Brinkmann[5], has investigated this question and recommends collimation of 10 σ in x' and 30 σ in y' (where the angles x' and y' are referenced to the collision point).

The collimation optics scheme he suggests provides for simultaneous collimation in x' and δp/p. It would provide 2% δp/p, 30 σ_x, and 100 σ_y in addition to the above stated values for x', y'.

Optics has been worked out by Brinkmann for the case of the DESY S-Band linear collider design which requires higher β sections than for TESLA. The layout consists of a sextupole, dipole bending to produce horizontal dispersion, two high β, high dispersion regions where spoilers are located, and a downstream absorber to catch degraded off momentum particles. The sextupole provides a kick for large amplitude particles in x and y, so they will interact with the downstream spoilers. The spoilers are one half wave length apart, and $n\pi + \pi/2$ from the final focus to provide primary collimation both in angle at the collision point, and in momentum ($x' \pm\delta$p, y').

The requirements for high β are set by the possible damage the spoilers may experience if beam hits fully on the face of the spoiler (say from off momentum beam). In the case of TESLA the one μsec bunch spacing is an advantage as one can consider placing a kicker 90° upstream of the spoiler and extracting the beam to a dump if it begins to hit the spoiler face on. With a β of 1000 m, up to about 10 bunches could hit the spoiler before overheating occures. This should be more than sufficient to fire an upstream kicker. At this β the half gap of the spoilers would be about 2 and 1.3 mm for x' and y' respectively. With this size aperture wake fields should not present a problem. The overall length of the spoiler section is about 500 m (and might be shorter in the case of TESLA).

The final focus described by Napoly has two demagnifying telescopes separated by horizontal and vertical chromatic correction sections. The overall (half) distance is about 600 m. The second telescope near the IP consists of two doublets separated by about 50 m. Within this space the combination of electrostatic separators and magnet septa must be placed, to provide the bending of the outgoing beam. Strengths of 250 kV/4 cm and 200 gauss are contemplated. Detailed designs must be worked out of the actual geometry and to assure ourselves that the tripping off of one separator unit would not cause disastrous damage to the components of the interaction region or detector.

Downstream from the IP the disrupted beam is deflected by the separators into the disrupted beam capture section. This section is similar to the final focus optics but requires broad energy acceptance. Of less importance is the exact optical match to the IP β^*. Here the criteria is efficient capture of a large fraction of the beam for recirculation schemes mentioned below. Brinkmann is in the process of designing this section.

6 Source Production and Damping Rings

The proposed positron source has been described by Flöttmann et al[6]. The idea is to use the disrupted high energy beam by putting it through a wiggler of about 40 m length and 1.5 T field strength. The beam is then sent to a dump in the simplest scheme under consideration. Photons from the wiggler impinge on a 0.4 radiation length titanium target to produce e^+, e^- pairs. The target is followed by an adiabatic matching solenoid and normal conducting travelling wave cavity/solenoid section to accelerate the beam to 100 - 200 MeV, where positrons are separated from other particles before injection into the superconducting linac. The preaccelerator could be either S or L Band with gradients of about 13 MV/m and might make use of a SLED-like power source.

In addition to the source described above which makes use of the high energy beam, it would be prudent to plan for a more conventional low energy electron driver so as to allow for tuning up the positron system without the need of a fully operating electron system. A few GeV electron linac and the production target would be used for this backup source.

The possibility of providing for polarized positrons is being evaluated by considering the use of a helical undulator instead of the wiggler mentioned above. It is too early to know just how difficult this would be.

The electron source might be able to provide the required emittance directly without requiring a damping ring. One version of this source would make use of a laser driven RF gun with asymmetric geometry to supply the needed asymmetric beam emittance. This type of gun is being investigated by J. Rosenzweig and collaborators. Though it is not absolutely essential to the TESLA design it would allow for the option of needing only one damping ring of the positrons (and none for the electrons). One of the challenges of this approach is the pulse operation of the laser itself.

The "dog bone damping ring" is a proposal by Flöttmann to make use of the existing linac tunnels. The actual design of this sort of ring must be looked at carefully as it is rather different from usual designs. A major design issue is proving that sufficient momentum compaction can be obtained with this geometry. The microwave instability threshold might severely limit the minimum bunch length that would be possible, and the present estimate is about 20 mm. Damping and momentum compaction would be provided by separate wiggler systems, the second might be of a very long period. The energy of the damping ring must be balanced to optimize between damping wiggler costs and instabilities on the low energy side, and emittance and compaction limitations on the high energy side. The relative costs of wiggler damping vs damping in a circular ring must also be considered.

Bunch compression of more than a factor of ten with one compressor is unlikely. The compressor design in final form must wait for the outcome of the damping ring design. A bunch length of 1 mm is required in the linac.

In addition to the scheme outlined above using the high energy beam for positron production, and the "dog bone ring," other more complicated schemes of recycling the beam have been devised by Rossbach and Flöttmann[7] [8]. These schemes may have more application as the linac collider energy is increased and more bunches required.

7 Conclusions

A number of ideas have been produced to provide a first look at what a design of a TESLA linear collider might look like overall. It remains to continue detailed design work and evaluation of these ideas in order to proceed toward a coherent conceptual design.

Acknowledgements

To a large extent the paper represents a report on the work of Flöttmann – on the positron source and damping rings, Rossbach – on the damping rings and recirculation schemes, Mosnier – on the main linac emittance dilution effects, Brinkmann – on collimation, and final focus disrupted beam recovery, Napoly – on final focus optics and parameter selection, Schulte – on luminosity, beam interaction and background analysis, and Tigner – on overall parameters.

In addition many of the ideas follow concepts developed at SLAC.

References

[1] private communication with R. Brinkmann and J. Rossbach. Similar remarks have been made by other authors.

[2] A. Mosnier *Beam Instabilities Related to Different Focusing Schemes in TESLA* (DESY Print, TESLA 93-22, To be published in Proc. 1993 IEEE Part. Accel. Conf.)

[3] A. Mosnier, O. Napoly *Wakefield Effects in a Superconducting Linear Collider* (Proc. 15th Int. Conf. on High Energy Acc., Hamburg, World Scientific, 1992)

[4] O. Napoly *A Large Aperture Final Focus System for TESLA* (To be published in Proc. 1993 IEEE Part. Accel. Conf)

[5] R. Brinkmann, see *Proceedings LC92, ECFA Workshop on e^+e^- Linear Colliders, Garmisch Partenkirchen and LC93, Stanford*

[6] K. Flöttmann, J. Rossbach *Emittance Damping Considerations for TESLA* (To be published, forthcoming TESLA Report)

[7] J. Rossbach *Positron Recycling in High Energy Linear Colliders* (Nuclear Inst and Methods A309 (1991) 25-36 North-Holland)

[8] K. Flöttmann, N. Holtkamp, J. Rossbach *Positron Source Considerations for TESLA* (DESY Print, TESLA Report 93-21)

[9] D. Schulte *Simulation des Untergrundes durch inkohärente Paarerzeugung in Linearbeschleunigern* (DESY Print, TESLA 93-39)

A Appendix

Table 4: Parameters of TESLA 500 and TESLA 1000. Items marked with a dagger (†) are analytical results, while items marked with a double–dagger (‡) are the results of simulations carried out by Schulte[9].

Parameter	Units	Values	Values
(unchanged values from previous column not filled in)			
		TESLA 500	**TESLA 1000**
LINAC-Primary Parameters			
Energy (CM)	GeV	500	1000
Energy-Linac	GeV	250	500
N_b	10^{10}	5.14	.91
f_c	kHz	8	20.9
Rep Rate	Hz	10	5
# bunches/pulse		800	4180
bunch separation	μsec	1.0	0.2
Beam pulse	ms	0.8	0.836
$\epsilon_{n,x}$	m $\times 10^{-8}$	2000	520
$\epsilon_{n,y}$	m $\times 10^{-8}$	100	6.3
σ_z	mm	1	0.5

Parameter	**Units**	**Values**	**Values**
(unchanged values from previous column not filled in)			
		TESLA 500	**TESLA 1000**
Final Focus System			
σ_x^*	nm	1000	325
σ_y^*	nm	64	8
β_x^*	mm	24.5	20
β_y^*	mm	2	1
L_o-nominal	10^{33} cm^{-2}sec^{-1}	2.6	5.3
R		15.6	41
D_x		0.54†	0.24
D_y		8.5†	9.8
H		2.3‡	1.9‡
L with pinch	10^{33}cm^{-2}sec^{-1}	6.1	10.4
Υ		0.03‡	0.058‡
δE_{beam}	% av	3.1‡	2.7‡
Cross angle	mrad	0	
N_γ	/beam e	2.5‡	1.3‡
N*	/crossing	14.5‡	4.5†
LINAC-Secondary Parameters			
Gradient	MV/m	25	
RF freq	GHz	1.3	
2 linac RF length	km	20	40
cavity length	m	1.04	
2 linac # cavities		20224	40448
2 linac # klystrons		1264	2528
# cavities/kly		16	16
Kly peak power req	MW	3.25	2.90
Kly pulse length	μsec	1.33	1.37
a/wave length		0.15	
P_b-beam power/beam	MW	16.5	15.2
P_{ac}-2 linac AC power	MW	139	153
P_{ac}-cryo	MW	55	74
P_{ac}-RF	MW	84	78
Damping Ring Energy	GeV	4.5	