SUMMARY
TESLA PARAMETERS AND COMPARISONS WORKING GROUP (GROUPS 1 AND 2)

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I. SUMMARY

This combined working group decided to concentrate on the following subjects on the grounds that they are the most important parameter topics currently identified:

- II. The design formulary
- III. Examples of parameter lists using the design formulary
- IV. The proposed DESY test bed, including:
  - A. Suggested goals, considering selected parameter lists
  - B. Instrumentation needs for such a test bed
- V. Accelerator physics issues, including:
  - A. Q_L needed for controlling the multi-bunch instability
  - B. The energy spread needed with the selected Q_L
  - C. Final focus needs
  - D. Top factory service
- VI. Contributions to other groups, including:
  - A. Cost
  - B. RF distribution scheme
- VII. Frequency optimum
- VIII. Specific problems, including:
  - A. Radiation pressure shock excitation of mechanical vibrations
- IX. Comparison to normal conducting approaches, with emphasis on the S-band approach proposed by the DESY-TH Darmstadt Collaboration.

II. DESIGN FORMULARY

At the First International TESLA Workshop at Cornell University, held July 23 - 26, 1990, James Rosenzweig provided a spreadsheet program·(based on R. Palmer's review article) for evaluating the consequences of various parameter choices; this program was invaluable to the functioning of the Parameters Committee at that workshop. For the present workshop, Hasan Padamsee has re-written Rosenzweig's program in MATHCAD, added some

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features, and made it available for use. The additional features include cost calculations, klystron optimization, calculation of alignment and vibration tolerances, and electromagnetic backgrounds as calculated by P. Chen. He has also developed a parameter set using this program, and made it available for discussion at the workshop. A report on this program and parameter lists developed using it are attached as Appendix I.

Members of the Parameters Committee very briefly discussed the program, and it was adopted without modification. Should any users of this program detect any deficiencies, it is requested that they bring them to Hasan Padamsee's attention.

III. EXAMPLES OF PARAMETER LISTS USING THE DESIGN FORMULARY

One change which has evolved since the last workshop is emphasis on a center-of-mass energy of 0.5 TeV. This change has occurred largely to preserve direct comparability to normal conducting designs, which now emphasize 0.5 TeV as a design energy.

In the examples discussed, it was noted by Ugo Amaldi that the power per meter among the various superconducting cases was not constant, unlike the examples considered at the 1990 TESLA Workshop. The reason this is a concern is that it creates a requirement for the development of a number of different klystrons or different power distribution schemes. The reason for the change in the examples provided is that current plans (at DESY, for example) do not call for starting large scale construction until a gradient of 25 MV/m is reached, whereas previous plans had contemplated starting construction of lower energy accelerators (such as a top factory) at lower gradients. It was agreed, with the caveat that large scale construction not start until 25 MV/m is reached, that the present examples are sensible.

It was also noted that the gradients and costs used in the examples are goals, not values which have been demonstrated.

In the 1990 TESLA Workshop, the RF frequency was narrowed down to the 1.5 to 3.0 GHz range, based upon economics and beam dynamics questions. Since that time, DESY has adopted a frequency of 1.3 GHz, based upon the ready availability of power sources at that frequency. Unless someone develops a clever scheme for coupling more cells together in a single resonant structure without creating unacceptable trapped mode conditions, the cost optimum presumably lies near the bottom of the 1.5 to 3 GHz range. Accordingly, the working group accepted 1.3 GHz as a reasonable working value for the examples.

Several other working groups suggested parameter changes:

1. The cavity group suggested that the aperture be decreased from 4.6 cm to 3.3 cm. This would have the advantages of higher R/Q and lower $\varepsilon_p/\varepsilon_{acc}$, and the disadvantage of higher wakefields, both longitudinal and transverse. Unresolved questions were whether a single bunch transverse instability would occur, whether the increase in HOM power would be tolerable, whether the energy curvature due to the higher longitudinal wakefield would be acceptable, and whether the trapped mode situation is made better or worse by the change.
2. It was noted that the assumption of 50% low temperature absorption of higher-

order-mode (HOM) power is probably overly pessimistic, and that 10% is likely to be a more reasonable number (which puts a premium on having good damping of longitudinal HOM's). The relatively high dissipation is caused by the high frequency components of the beam, since $R_{BCS} \propto f^2$. It was noted that operating at a lower temperature would decrease the fraction of the HOM power dissipated in the liquid helium, and that this could be part of the temperature optimization. Aside from the thermodynamic optimization, it was pointed out that the diameter of the return transfer line increases rapidly as the temperature is reduced, which increases the cost. Since there is no experience operating a superconducting cavity with such a short and intense bunch, it would be a worthwhile measurement for the DESY test bed.

3. It was also observed that the $k_{||}$ value used in the examples may be incorrect when applied to nine cells. Because of the short bunch length, too fine a mesh would be required to calculate the value using existing codes, the fraction of the total volume occupied by the bunch and the immense number of overlapping modes involved make bead-pull measurements impractical, and analytic extensions are approximations with unknown error magnitudes. Accordingly, this would also be a desirable test bed measurement.

Since there was insufficient time to explore the ramifications of adopting any of these changes, none of them were made part of the baseline example; however, this decision was not intended to indicate that these concepts do not deserve further exploration.

IV. PROPOSED DESY TEST BED

The TESLA test bed proposed at DESY (see sketch attached as Appendix II) was recognized as a valuable tool for developing the TESLA concept further. It was noted that an essential part of the program is a substantive effort to continue improving cavity gradients, while design for cost optimization, construction of the test bed, and operation of the test bed proceed in parallel. Cost optimization and gradient improvement are both essential ingredients of the program.

A. Suggested Goals

Considerable discussion preceded the recommendation of specific goals. It was noted that generation of full-charge, 1 mm bunches is difficult but worthwhile for the test bed. In the injector, superconducting cavities have the disadvantage that they cannot be used inside solenoids, and normal conducting cavities have the disadvantage that they will not tolerate long pulses at high gradients. It was adjudged that production of more than 10^9 electrons per bunch will be difficult. Without the availability of such bunches, some of the desirable goals cannot be reached, but use of a damping ring would qualitatively increase the scope of the test bed.

For injection into a cryomodule, one needs $\sigma_z = 1$ mm, and $q = 5 \cdot 10^{10}$ e^-. The energy needs to be greater than a few MeV (the exact value needs to be calculated), and there needs to be flexibility to generate different bunch patterns, with 0.4 to 2.0 μs between bunches. It was suggested that it would be useful for the spectator bunch to be off-energy so that it could be easily separated from the primary bunch.

The specific goals recommended are:

1. Transfer full pulse power to the beam at the pulse length that would be used in the full-energy accelerator,
2. Measure ΔE/E, energy stability, and beam path stability. These need to be measured bunch-by-bunch,
3. Measure $\varepsilon(t)$, $\phi(t)$ in each cavity unit,
4. Measure Q_0 calorimetrically or with a variable coupler,
5. Measure the HOM power dissipated in the liquid helium,
6. Measure the HOM power coming out the beam pipe,
7. Measure the cavity alignment by looking for the beam position which yields a transverse mode null,
8. Measure the bunch length,
9. Measure the wakefields, both $\parallel$ and $\perp$, with a witness bunch. Compute requirements.
10. Measure the static heat leak of the cryostat,
11. Measure the temperature profile for each cell and coupler on at least one cavity,
12. Look at the X-radiation pattern and spectrum, without beam, using a radiation telescope, and
13. Measure microphonics, including radiation pressure.

B. Suggested Instrumentation

With reference to the above goals, the suggested instrumentation includes:

1. Capability to measure RF forward and reflected power for each cavity unit, with recording digital data acquisition; video apparatus for bunch by bunch energy measurement; and feedback stabilization of the RF drive power,
2. A spectrometer with a resolution of $\sim 10^{-3}$; a secondary emission readout; an injector with $\Delta E/E \leq 10^{-3}$; and an injector for a witness beam of variable energy and phase,
3. Field probes in every cavity unit,
4. A variable coupler and/or a calorimeter with resolution < 1 W,
5. Use of transition or Cerenkov radiation with a streak camera yielding resolution ≤ 1 ps,
6. HOM coupler outputs brought to room temperature for power measurements,
7. Parallel beam translation capability,
8. An X-ray telescope,
9. Thermometry for cavity walls,
10. A microwave calorimeter on the beam line (to measure power propagated down the

beam pipe),

11. Capability to record $\mathcal{E}(t)$ and $\phi(t)$ in the control system,
12. Closely spaced beam intensity and position monitors,
13. Cavity position transducers referenced to room temperature.

V. ACCELERATOR PHYSICS ISSUES

The limited length of the TESLA portion of the workshop permitted only the first of the four identified accelerator physics issues to be discussed extensively.

A. Q_L needed to control multi-bunch instability

The Accelerator Physics Working Group reported that a HOM Q_L of $\sim 10^9$ is no worse than a Q_L of $\sim 10^7$, but that a Q_L of 10^6 is significantly better than a Q_L of $\sim 10^7$. That working group was continuing to work on quantifying these results.

VI. CONTRIBUTIONS TO OTHER GROUPS

A. Cost

It was noted that reducing unit costs is just as valuable as increasing gradient. It was also noted that the Cornell group has made extensive measurements of the times required to manufacture cavities, and of the associated costs, including materials. These costs were discussed in more detail by the Structures Working Group.

B. RF Distribution Scheme

It is generally recognized that one of the most significant costs of an RF system is the extensive set of controls and interlocks associated with each cavity structure which has its phase and amplitude actively controlled. The number of cells in a cavity cannot be increased arbitrarily because certain HOM's, due to high mechanical tolerance sensitivities caused by passband "collisions," become trapped. Accordingly, it would be desirable to connect many cavity structures together with an RF manifold. In order for a manifold to cause a group of cavities to have their fundamental modes all behave as one mode, the manifold needs to have a moderate amount of stored energy in it (typically a few percent of the total stored energy). Due to the high gradients planned, this dictates that the manifold be superconducting. An alternative is to use a scheme in which each cavity has an independent mechanical tuner, and in which the vector sum of the voltages in the cavities is regulated; such a scheme requires the addition of these tuners and their controls, and requires the cavities to be mechanically more rigid, but permits the manifold to have a much smaller stored energy, and therefore to be normal conducting. These options need to be studied in much more detail to explore possible designs and to determine which of them is most cost effective.

VII. FREQUENCY OPTIMUM

As previously discussed, the optimum frequency was discussed at the 1990 TESLA Workshop, and the consensus was reached that the cost-optimum lay between 1.5 and 3 GHz. It was also agreed that 3 GHz is the beam dynamics limit for a machine that can be constructed with reasonable mechanical tolerances, and the requirements on Q_L can be relaxed somewhat by going to the 1.5 GHz end of the range. DESY has chosen, for its test bed, a frequency of 1.3 GHz because of the ready availability of RF sources and other components at that frequency. The absence of any simple concepts of how to build a manifold to tie several cavities together indicates that this is a reasonable choice, since the length of cavity with a given number of cells scales as f^{-1}. Going to an even lower frequency has the disadvantage that the stored energy per meter, which is dumped after each bunch train, scales as f^2.

VIII. SPECIFIC PROBLEMS:

A. Radiation Pressure Shock Excitation of Mechanical Vibrations

Since continuous wave (CW) operation at ≥25 MV/m would require a very high Q_o value (ca. $6 \cdot 10^{10}$) in order to keep losses due to RF dissipation in the cavity walls to a tolerable level, pulsed operation is an attractive operating mode for TESLA. Pulsed operation does not have the objectionable features of pulsed operation of a normal conducting structure, however, because the pulse length of a superconducting structure can be much longer than for a normal conducting structure at the same gradient. The long pulse avoids the problems of having to supply energy to fill the structure at a high rate, avoids difficulties in regulating the field in the structure, and avoids parasitic collisions of bunches that are closely spaced. In addition, it is easier to achieve a high ratio of Q_o(fundamental) to Q_L(HOM) in a superconducting cavity than in a normal conducting cavity.

One problem presented by pulsed operation at high gradients, however, is that the radiation pressure in a cavity is of the order of 0.012 Torr/(MV/m)^2. Since this pressure is present only when the cavity is powered, the fairly rapid appearance of this pressure can shock-excite mechanical vibrations in the cavity, which will cause the resonant frequency to "ring." Using some existing cavities to make rough estimates of the magnitude of this effect indicates that some stiffening mechanism will be required to reduce the amplitude to an acceptable level. A calculation of this effect is included as Appendix III. Bars along the sides of the cavity, either as originally used at HEPL, or detachable as presently being developed at HEPL, may be the most practical solution.

IX. COMPARISON TO NORMAL CONDUCTING APPROACHES

The comparison to high frequency normal conducting approaches (~11 GHz) has been made a number of times in the past, pointing out the severe problems that such approaches have with wakefields, alignment tolerances, and required high peak power RF sources. The choice of a high frequency has been driven by the need to minimize the amount of stored energy dumped after each pulse, where the repetition rate is very high because a very small number of bunches is being accelerated during each pulse to minimize cumulative wakefield effects.

A DESY-TH Darmstadt collaboration has recently proposed a 3 GHz normal conducting accelerator in which many bunches are accelerated in each pulse, and the cumulative wakefield effects are controlled by stagger-tuning the cavity cells for all important modes except the fundamental. Since this is a new concept, the Parameters Working Group decided to compare this approach with the superconducting approach. A summary of the parameters for the normal conducting approach is shown in Appendix IV. The results of the comparison are shown in Appendix V.

In addition to the technical comparison in this table, R. Sundelin presented a cost comparison which has been made to the cost of such an accelerator based solely on the cost of building SLAC. The working group did not have time to evaluate and comment on this presentation. The SLAC unit costs have been adjusted for inflation, but no savings for improvements in available technology have been taken into account; as a result, the calculation should be viewed only as an upper limit for the normal conducting approach. At the KEK Linear Collider Workshop, Greg Loew presented information on the magnitude of cost reductions which can be expected from intervening developments in klystron technology. In addition, no economies associated with the larger scale have been taken into account in the estimate presented here. The costs are based on the actual SLAC construction costs, with various cost components allocated as discussed in Cornell-CLNS-85/709. The way in which the coefficients derived in this report would be applied to an 0.5 TeV center-of-mass normal conducting collider is shown in Appendix VI.

The normal conducting collider has the advantage that it could be built, figuratively starting today. The upper limit for the construction cost at the planned gradient would be $12.0 \cdot 10^9$ U. S.$ (FY'91$), and at a gradient of 6.15 MV/m it would be $7.9 \cdot 10^9$ U. S.$ (FY'91$). It should be noted that the actual cost and the optimum gradient will depend on what technological improvements are incorporated.

The full superconducting linear collider has two reasons it cannot be built starting today. The first is that a gradient of 25 MV/m must be achieved on a reliable basis that is adaptable to mass production. The second is that the design must be improved to reduce costs. If both of these objectives are achieved to the level assumed in the parameters list, the cost of the superconducting linear collider would be approximately $2 \cdot 10^9$ U. S.$ (FY'91$).

In summary, the superconducting linear collider requires additional research, development and design to be viable, and the degree to which the cost goals can be achieved remains to be determined. This approach has the largest safety margin in its ability to achieve the design luminosity. The high frequency normal conducting linear collider requires additional research, development, and design to be viable, and the degree to which the cost goals can be achieved remains to be determined. The S-band normal conducting linear collider could be built now, but the degree to which its cost can be reduced below the upper limit discussed above remains to be established.

APPENDIX I

Report on Program and Parameters List Contributed by H. Padamsee

TESLA CALCULATIONS PROGRAM

H. Padamsee (for the TESLA Collaboration)

Laboratory of Nuclear Studies, Cornell University

For the 2nd TESLA Workshop, there is a need for a parameters program, as was made available by J. Rosenszweig for the 1st meeting at Cornell in July 1990[1] At this stage Rosenzweig's program is not generally available. Hence this program was written in the hope that it will be as useful to the parameters group as the orginal program was.

The program is divided into five main sections:

a) Beam Parameters
b) RF Power Calculations
c) Wall plug powr calculations
d) Wakefields, vibration and alignment tolerances
e) Capital and operating cost estimates

The approach is based on the output of the 1st TESLA Workshop[1] Beam parameter calculations come from the formulas given in Palmer's work[2] Computation of the incoherent pair production from P. Chen's work[3] was carried out with the help and advice from D. Leenen at DESY. In section (b) and (c) several improvements and additions have been made. Data on peak power vs pulse length for available Klystrons have been incorporated. HOM power has been recomputed. Addtional RF dissipation during structure filling and decay times have been included.

Sections (d) and (e) are new. Section (d) is based on D. Rubin's summary report from the accelerator physics group with further work by M. Tigner. Section (e) on costs must be taken as very prelimnary. It is hoped that better numbers for costs can be derived at the 2nd TESLA meeting and incorporated.

The program is written in MATHCAD so that formulas used are transparent. All units are MKS and $

Contents of Report

Description of the Program

Constants

The fundamental constants used throughout the program are defined below:

$ec := 1.6 \cdot 10^{-19}$	Electron Charge
$re := 2.82 \cdot 10^{-15}$	Classical electron radius
$c := 3 \cdot 10^{8}$	Velocity of light
$me := 0.511 \cdot 10^{6}$	Electron rest mass
$\epsilon := \frac{1}{137}$	Fine structure constant
$\lambda c := 3.86 \cdot 10^{-13}$	Electron Compton Wavelength/2*pi
$Z0 := 377$	Impedance of free space

(a) The input quantities for calculating the Beam Parameters are defined below:

Input Parameters - Beam

$E := 2.5 \cdot 10^{11}$	Beam Energy
$G := 2.5 \cdot 10^{7}$	Gradient
$L := \frac{E}{G}$	Linac Length
$N := 5.14 \cdot 10^{10}$	No. of Particles/bunch
$f := 8 \cdot 10^{3}$	Beam Collision Rate
$\sigma z := 2 \cdot 10^{-3}$	Bunch Length
$\epsilon x := 2.0 \cdot 10^{-5}$	Normalized hor. emittance
$\epsilon y := 1 \cdot 10^{-6}$	Normalized ver. emittance
$\beta x := 0.01$	Horizontal beta*
$\beta y := 0.005$	Vertical beta*

Beam Calculations

$$\gamma := \frac{E}{me}$$ Beam Energy

Final Spot Size

$$\sigma x := \left[\epsilon x \cdot \frac{\beta x}{\gamma}\right]^{0.5}$$ Horizontal Beam size at focus

$$\sigma y := \left[\epsilon y \cdot \frac{\beta y}{\gamma}\right]^{0.5}$$ Vertical Beam size at focus

$$R := \frac{\sigma x}{\sigma y}$$ Aspect Ratio

Disruption:

When a particle of one beam is deflected by the collective electromagnetic field of the opposite beam, the process is called disruption. The luminosity is enhanced as a result of the pinching or focussing of the particles

$$Dx := 2 \cdot re \cdot \sigma z \cdot \frac{N}{\gamma \cdot \sigma x \cdot (\sigma x + \sigma y)}$$ Horizontal Disruption Parameter

$$Dy := 2 \cdot re \cdot \sigma z \cdot \frac{N}{\gamma \cdot \sigma y \cdot (\sigma x + \sigma y)}$$ Vertical Disruption Parameter

The collision process takes place within several bunch lengths around the interaction point. The natural variation of the beam size over this distance has an impact on the disruption process due to the finite beta function. The parameter A defines the divergence of the incoming beams. Luminosity enhancement increases with Dy if the two beams are in perfect alignment. The sensitivity to offsets starts to diverge rapidly for Dy > 15. Hence Dy < 15 is recommended

$$A := \frac{\sigma z}{\beta y}$$ Divergence of incoming beam

Disruption Enhancement Round beam:

$$HDr := 1 + Dy^{0.25} \cdot \left[\frac{Dy^3}{1 + Dy^3}\right] \cdot \left[\ln\left[Dy^{0.5} + 1\right] + 2 \cdot \ln\left[\frac{0.8}{A}\right]\right]$$

$$HD := HDr^{0.333}$$ Disruption Enhancement flat beam

$$Lum := N^2 \cdot f \cdot \frac{HD}{4 \cdot \pi \cdot \sigma x \cdot \sigma y}$$ Luminosity

$$\Upsilon := 0.43 \cdot re \cdot \lambda c \cdot \gamma \cdot \frac{N}{\sigma z \cdot \sigma y'} \cdot \left[\frac{2}{1 + \frac{\sigma x'}{\sigma y'}} \right]$$ Beamstrahlung Parameter

Beamstrahlung

Beamstrahlung is the emission of acceleration radiation by individual particles as a result of bending by the e&m fields of opposing bunches. Particles with different trajectories experience different energy losses, resulting in an energy spread. This adds in quadrature to the energy spread from the linac. High energy spread means larger uncertainties in the interaction energy, which limits the performance of the machine for useful physics. Quantum effects have to be taken into account for the calculation of energy loss and energy spectrum when the beamstrahlung parameter approaches unity or exceeds it.

$$H\Upsilon := \left[\frac{1}{1 + 1.33 \cdot \Upsilon^{0.667}} \right]^2$$ Quantum correction for beamstrahlung effects, also known as the reduction factor

$$\delta cl := 0.22 \cdot re^3 \cdot \gamma \cdot \frac{N^2}{\sigma z \cdot \sigma x \cdot \sigma y} \cdot \left[4 \cdot \frac{R}{(1 + R)^2} \right]$$ Fractional Energy Loss (Classical)

$$\delta := \delta cl \cdot H\Upsilon$$ Fractional Energy loss, including quantum corrections

Enhancement factors due to Pinch Effect:

$$Hx := 1 + 1.37 \cdot \left[\frac{1}{1 + Dx^{-5.5}} \right]^{0.5}$$

$$Hy := 1 + 1.37 \cdot \left[\frac{1}{1 + Dy^{-5.5}} \right]^{0.5}$$

$$\sigma x' := \frac{\sigma x}{Hx} \qquad \sigma y' := \frac{\sigma y}{Hy}$$ Pinched spot size

Disruption Angles

The disruption process improves luminosity but increases the divergence of the beam which sets the aperture of the opposite beam focussing quads.

$$H\theta x := \frac{1}{\left[1 + (0.5 \cdot Dx)^5 \right]^{0.1667}}$$ Pinch Enhancement of the disruption angle

$$H\theta y := \frac{1}{\left[1 + (0.5 \cdot Dy)^{5}\right]^{0.1667}}$$

Pinch Enhancement of the disruption angle

$kx := 0.75 \qquad ky := 1.25$

For R>>1

$$\theta Dx := 2 \cdot N \cdot re \cdot kx \cdot \frac{H\theta x}{\gamma \cdot \sigma x}$$

Horizontal disruption angle

$$\theta Dy := 2 \cdot N \cdot re \cdot ky \cdot \frac{H\theta y}{\gamma \cdot \sigma x}$$

Vertical disruption angle

$$\theta d := \frac{\sigma x}{\sigma z}$$

Diagonal Angle

$$\theta m := \theta Dx$$

Maximum Disruption Angle

$$\theta c := (\theta m \cdot \theta d)^{0.5}$$

Beam Crossing Angle

No. of Coherent Pairs from Beamstrahlung radiation [4]

$$Npairs := 0.044 \cdot N \cdot \left[\alpha \cdot \sigma z \cdot \frac{\Upsilon}{\gamma \cdot \lambda c}\right]^{2} \cdot \exp\left[\frac{-16}{3 \cdot \Upsilon}\right]$$

Calculation of Incoherent pair production. [3]

Constants:

$\Gamma 1 := 2.6789 \qquad \Gamma 2 := 1.3541 \qquad \gamma 8 := 0.7818 \qquad \gamma 1 := 0.5772$

Detector Properties:

$pt0 := 4 \cdot 10^{-5} \qquad c0 := \cos(0.1)$

Effective Beamstrahlung parameter to agree with Chen's definition:

$$\Upsilon' := \Upsilon \cdot \frac{5}{12}$$

Breit-Wigner Cross-Section:

$$\sigma bw := \frac{9}{16 \cdot \pi} \cdot \Gamma 1^{-1} \cdot \Gamma 2^{4} \cdot \frac{re^{2}}{\gamma^{2}} \cdot \left[\alpha \cdot \frac{\sigma z}{\gamma \cdot \lambda c}\right]^{2} \cdot \left[6 \cdot \frac{\Upsilon'}{pt0}\right]^{1.33}$$

$$\sigma bw := \sigma bw \cdot \ln\left[\frac{1 + c0}{1 - c0}\right]$$

Bethe-Heitler Cross-Section:

$$\sigma bh := \frac{54}{5 \cdot \pi} \cdot \Gamma 2 \cdot \alpha \cdot \frac{re^2}{\gamma^2} \cdot \left[\alpha \cdot \frac{\sigma z}{\lambda c \cdot \gamma}\right] \cdot \left[36 \cdot \frac{\Gamma'^2}{pt0^5}\right]^{0.33}$$

$$\sigma bh := \sigma bh \cdot \left[\left[\frac{1 + c0}{1 - c0}\right]^{0.167} - \left[\frac{1 - c0}{1 + c0}\right]^{0.167}\right]$$

$$mu := \ln\left[\frac{pt0}{2} \cdot \left[\frac{1 - c0}{1 + c0}\right]^{0.5}\right] + \gamma 8 - \gamma 1$$

$$\sigma bh := \sigma bh \cdot mu \cdot -1$$

Landau-Lifshitz Cross-Section:

$$\sigma ll := \frac{8}{\pi} \cdot \alpha \cdot \frac{2\, re^2}{\gamma^2} \cdot \frac{1}{(pt0)^2} \cdot \ln\left[\frac{1 + c0}{1 - c0}\right]$$

$$qu := 3 \cdot \ln\left[\frac{pt0}{2}\right] + \frac{73}{12} - \frac{\pi^2}{6}$$

$$\sigma ll := \sigma ll \cdot \left[\ln\left[\frac{pt0}{2} \cdot \left[\frac{1 + c0}{1 - c0}\right]^{0.5}\right] \cdot \ln\left[\frac{pt0}{2} \cdot \left[\frac{1 - c0}{1 + c0}\right]^{0.5}\right] + qu\right]$$

$$Lb := \frac{Lum}{f}$$ Luminosity/bunch

$Nbw := 2 \cdot \sigma bw \cdot Lb$ $Nbh := 2 \cdot \sigma bh \cdot Lb$ $Nll := 2 \cdot \sigma ll \cdot Lb$

$Nbw = 101.0612$ $Nbh = 131.51429$ $Nll = 16.7777$

$\sigma sum := \sigma bw + \sigma bh + \sigma ll$ Total cross-section

$incprs := 2 \cdot \sigma sum \cdot Lb$ Total number of incoherent pairs

According to Chen, a few hundred incoherent pairs are acceptable. For the large bunch spacing of microseconds for TESLA, it is not necessary to multiply by the number of bunches in the train. This is probably not the case for normal conducting machines where the bunches are spaced nanoseconds apart

Input Parameters - RF Power

$nb := 800$	No.of Bunches/Pulse
$bs := 1 \cdot 10^{-6}$	Bunch separation (s)
$rf := 1.3 \cdot 10^{9}$	RF frequency
$ROQ := 960 \cdot \frac{rf}{1.5 \cdot 10^{9}}$	Cavity shunt impedance R/Q

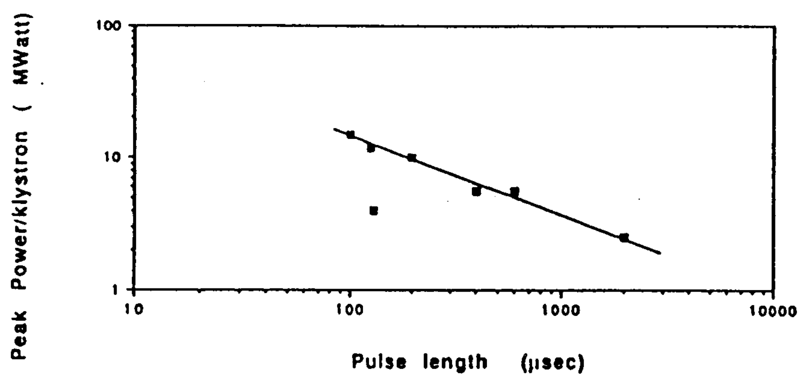
RF Power Calculations

$\lambda := \frac{c}{rf}$	RF Wavelength
$\omega := 2 \cdot \pi \cdot rf$	RF frequency angular
$tbeam := nb \cdot bs$	Beam on time
$d := f \cdot bs$	Duty Factor
$rep := \frac{f}{nb}$	RF Rep rate
$Pb := N \cdot ec \cdot f \cdot E \cdot 2$	Total Beam Power
$u := \frac{G^2}{ROQ \cdot \omega}$	Stored Energy/length
$QL := \frac{G^2}{ROQ \cdot \left[\frac{Pb}{2 \cdot L \cdot d}\right]}$	Loaded Q to match beam power
$\tau e := \frac{QL}{\omega}$	Filling time constant to equilibrium to match beam power
$\tau d := \frac{QL}{\omega}$	Power decay time
$decay := \tau d$	Area under decay
$fill := 2 \cdot \ln(2) \cdot \tau e$	To compensate for beam loading energy transient in a standing wave structure, fill time before bunch train starts should be as determined by R. Miller [5]
$trf := tbeam + fill$	Total RF on time

$Ppk := \frac{u}{\tau e}$ — Peak RF Power/meter (using matched conditions). This is also the same as the peak beam power

$RF := Ppk \cdot L \cdot 2$ — Total Peak RF Power

Peak Power of klystrons (MWatts) depends on RF pulse length as shown

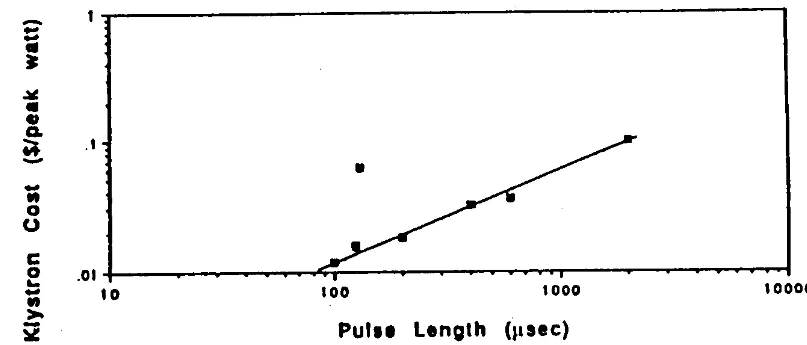


$LPkly := -0.577 \cdot \log\left[\frac{trf}{10^{-6}}\right] + 2.304$ — Log of peak power

$Pkly := 10^{LPkly} \cdot 10^{6}$ — Klystron peak power

$Nkly := \frac{RF}{Pkly}$ — No. of Klystrons

$/peak RF Watt for klystrons is determined from the following graph derived from klystron catalog information:



$LCrf := 0.708 \cdot \log\left[\frac{trf}{10^{-6}}\right] - 3.335$ — Log of cost

$Crf := 10^{LCrf}$ — Cost of Peak power ($/watt)

$BW := \frac{rf}{QL}$ — Bandwidth

$AvRF := RF \cdot rep \cdot trf$ — Total Average RF Power: Includes beam power, dumped structure stored energy and RF power for filling

Input Parameters for Wall Plug Power Calculations

$a := 4.6\cdot 10^{-2}$	RF cell aperture (radius)
$nc := 9$	No of Cells/cavity
$nk := 0.65$	Assumed klystron efficiency
$T := 2$	Cryogenic Temperature
$nr := 0.2$	Assumed refrigerator efficency
$h := 1$	Static heat leak (watts/m)
$frac := 0.5$	Fraction of HOM power at cryo. temp.
$Qr := 6\cdot 10^{9}$	Residual Cavity Qo
$Lcell := \frac{\lambda}{2}$	Cell length
$LDR := nb\cdot 7$	Length of damping ring assuming 7 meter spacing between bunches for kicker operation
$ODR := 2000$	Operating power (watts/m) for DR (U. Amaldi/TESLA workshop addendum)

Power Calculations

$Rr := \frac{290}{Qr}$	Residual surface resistance
$Rbcs := 2\cdot 10^{-4}\cdot e^{\frac{-17.67}{T}}\cdot\frac{\left[\frac{rf}{1.5\cdot 10^{9}}\right]^{2}}{T}$	BCS Surface resistance
$Qbcs := \frac{290}{Rbcs}$	Geometry factor = 290 Ohms
$Q := \frac{290}{Rbcs + Rr}$	Q value
$x := \left[\sigma z\cdot 10^{3}\right]^{-0.5}$	
$bcis := -9.2926 + 40.493\cdot x$	BCI calculations of total loss factor on single cell shape V/C/m, bcis for 3GHz and bcil for 1.5 GHz
$bcil := -5.8374 + 18.749\cdot x$	

$bcis := \frac{bcis}{1.55}$ $\quad bcil := \frac{bcil}{1.55}$ — Multicell BCI calculations at Cornel show that loss factor of multicells is 1.55 times less than N x single cell

$kfun := \omega \cdot \frac{ROQ}{4}$ — Loss factor for the fundamental mode alone

$ktot := if\left[rf > 2 \cdot 10^{9}, bcis, bcil\right]$

$kll := ktot \cdot 10^{12} - kfun$ — HOM Loss factor in V/C/meter

$Pdump := u \cdot L \cdot 2 \cdot rep$ — Total Dumped RF Power

$Pdumpac := \frac{Pdump}{nk}$ — AC power for dumped RF stored energy

$nc := \frac{T}{293 - T}$ — Carnot Efficiency

$nt := nc \cdot nr$ — Overall refrigerator efficiency

$filla := \int_0^{fill} \left[1 - e^{\frac{-t}{\tau e}}\right] dt$ — Area under fill

$d' := rep \cdot (nb \cdot bs + filla + decay)$ — Effective duty factor

$Pdiss := G^{2} \cdot L \cdot 2 \cdot \frac{d'}{ROQ \cdot Q}$ — Total Fund. Power at Cryo. Temp.

$Pdbeam := G^{2} \cdot rep \cdot \frac{tbeam}{ROQ \cdot Q}$ — Dissipated power/meter during beam on time

$Pdfill := G^{2} \cdot rep \cdot \frac{filla}{ROQ \cdot Q}$ — Dissipated power/meter during fill

$Pddecay := G^{2} \cdot rep \cdot \frac{decay}{ROQ \cdot Q}$ — Dissipated power/meter during decay

$Pstat := 2 \cdot L \cdot h$ — Total Static Heat Leak

$Phom := (kll) \cdot 2 \cdot L \cdot (N \cdot ec)^{2} \cdot f$ — HOM power

$Phomcryo := frac \cdot Phom$ — HOM Power at Cryo Temp

$Pdhom := \frac{Phomcryo}{2 \cdot L}$	Dissipated HOM power/meter
$Pcryo := Phomcryo + Pstat + Pdiss$	Total Refrigerator Load
$Pacref := \frac{Pcryo}{\eta c \cdot \eta r}$	Total Refrigerator AC Power
$Pacrf := \frac{AvRF}{\eta k}$	Wall Plug Power for RF
$PDR := CDR \cdot LDR \cdot 2$	AC Power for damping ring
$AC := Pacrf + Pacref$	Total Linac Wall Plug Power
$Eff := \frac{Pb}{AC}$	Beam/Linac Wall Plug efficiency
$Pbac := \frac{Pb}{\eta k}$	AC power for Beam Power
$Prfac := Pacrf$	AC Power for RF
$Phomac := \frac{Phom}{\eta k}$	AC Power for for HOM
$Phomcryoac := \frac{Phomcryo}{\eta t}$	AC Power for HOM Power lost in He
$Pstatac := \frac{Pstat}{\eta t}$	AC Power for static heat leak losses in He
$Pdissac := \frac{Pdiss}{\eta t}$	AC Power for RF dissipation in He
$I := N \cdot ec \cdot f$	Average Beam current
$Ipk := \frac{I}{d}$	Peak beam current

Wakefield and Alignment Tolerances for Quadrupoles

$E0 := 3\cdot 10^{9}$ Injection energy

Energy spread is important for
1) Quadrupole alignment tolerances
2) Energy bandwidth of the final focus

Variation in accelerating voltage over the length of a bunch leads to an energy spread. Change in voltage over (+- 2) x bunch length is considered:

$$\sigma Erf := 2\cdot\left[2\cdot\pi\cdot\frac{\sigma z}{\lambda}\right]^{2}$$

Energy spread from RF wavelength (Rubin-Tesla) [6]

Wake voltage induced by the head of the bunch and witnessed by the tail:

$$\sigma Ewake := 2\cdot N\cdot ec\cdot ktot\cdot\frac{10^{12}}{G}$$

Energy spreads from wake (Rubin-Tesla)

$$\sigma Ewake' := \frac{\sigma Ewake}{10}$$

The wake induced energy spread can be reduced by a factor of 10 by accelerating the bunch ahead of the peak RF voltage [6]

$$valwake := \begin{bmatrix}\sigma Ewake'\\ \sigma Erf\end{bmatrix}$$

Choose the larger of the two energy spreads

$$\sigma E := max(valwake)$$

Transverse wakes dilute the emittance of a bunch. In a 2 particle model, the tail witnesses a transverse field from the displacement of the head (x). We want to limit the displacement of the tail (dx) w.r.t the head, ie dx/x. This quantity is given in terms of the beta function, the transverse wakes and the energy along the length of the machine. (See D. Rubin's summary in TESLA proceedings.) Putting the integral of dx/x along the linac to be = 1, allows us to determine the beta function if we also take the energy scaling of the beta function, i.e. beta increases as the square root of the energy. The strength of the quads allows us to determine the number of quads. The alignment tolerance for the quads then can be determined as it depends on the size of the beam at the end of the linac, the energy spread and the the number of quads.

To calculate the transverse wake of a cavity/unit length we use the formula from Gluckstern given in the TESLA proceedings

$$crit := \frac{a^{2}}{5\cdot\sigma z\cdot Lcell}$$

Range for validity of kt formula below

$$test := \begin{bmatrix}crit\\ nc\end{bmatrix}$$

Here nc is the number of cells

$$val := min(test)$$

$$kt := Z0\cdot c\cdot\frac{\sqrt{\pi\cdot\frac{\sigma z}{Lcell\cdot val}}}{4\cdot\pi\cdot a^{3}}$$

Transverse loss factor (Rubin-Tesla) [6]

$$\gamma 0 := \frac{E0}{me}$$

Injection energy

$$\beta av := 2 \cdot \frac{G}{3 \cdot ec \cdot N \cdot kt}$$

Average beta from ∂x/x =1 (Rubin-Tigner)

$$\beta 0 := \beta av \cdot 1.5 \cdot \sqrt{\frac{E0}{E}}$$

Initial beta from energy scaling of the betal function

$$\beta f := \beta 0 \cdot \sqrt{\frac{E}{E0}}$$

Final beta from energy scaling of the beta function

$$\psi := \frac{\pi}{4}$$

Phase advance per cell

$$Nq := 4 \cdot \frac{L}{\psi \cdot \sqrt{\beta 0 \cdot \beta f}}$$

Number of quads(Palmer-87) [7]

$$\sigma fx := \sqrt{\epsilon x \cdot \frac{\beta f}{\gamma}}$$

Final horizontal beam size in linac

$$\sigma fy := \sqrt{\epsilon y \cdot \frac{\beta f}{\gamma}}$$

Final vertical beam size in linac

$$xrms := \frac{\sigma fx}{2 \cdot \sigma E} \cdot \sqrt{\frac{3}{Nq}}$$

Horizontal alignment tolerance

$$yrms := \frac{\sigma fy}{2 \cdot \sigma E} \cdot \sqrt{\frac{3}{Nq}}$$

Vertical alignment tolerance.

$$\Delta x := \sigma fx \cdot \sqrt{\frac{0.375}{Nq}}$$

Horizontal vibration tolerance (Rosenzweig-Tesla from Ruth)

$$\Delta y := \sigma fy \cdot \sqrt{\frac{0.375}{Nq}}$$

Vertical vibration tolerance

Input Parameters - Cost ($)

$Cmod := 1.35\cdot 10^{5}$ Cost of modulators & High Voltage

$CDR := 20\cdot 10^{3}$ Cost/meter damping ring

$Clin := 50\cdot 10^{3}$ Cost/Active meter -Linac

$bp := 0.394\cdot T^{5.798}$ He bath presssure vs T

$Cref := 1250 + 3\cdot 10^{4}\cdot\left[\frac{1}{bp} - \frac{1}{760}\right]$ Cost/watt in He

$Cref = 2.57905\cdot 10^{3}$

$El := 0.08$ Cost/Kwatt-hour

$Life := 4$ Integrated running time (years)

Cost Calculations

$Linac := Clin\cdot L\cdot 2$ Linac Cost

$DR := LDR\cdot CDR\cdot 2$ Damping rings cost

$Ref := Cref\cdot Pcryo$ Refrigerator Cost

$RFc := Crf\cdot RF + Nkly\cdot Cmod$ RF cost

$Cap := Linac + Ref + RFc + DR$ Total Capital Cost

$Op := \left[\frac{AC + PDR}{1000}\right]\cdot Life\cdot 365\cdot 24\cdot El$ Operating Cost including damping ring power

Baselir. ,esign Exercise (0.5 TeV CM)

(All in MKS Units)

Input Parameters - Beam

$E = 2.5\cdot10^{11}$	Beam Energy
$G = 2.5\cdot10^{7}$	Gradient
$L = 1\cdot10^{4}$	Length
$N = 5.14\cdot10^{10}$	No. of e/bunch
$f = 8\cdot10^{3}$	Beam Collision Frequency
$\sigma z = 0.002$	Bunch Length
$R = 6.32456$	Aspect Ratio
$\epsilon x = 2\cdot10^{-5}$	Normalized Horizontal Emittance
$\epsilon y = 1\cdot10^{-6}$	Normalized Vertical Emittance
$\beta x = 0.01$	Horizontal beta*
$\beta y = 0.005$	Vertical beta*
$bs = 1\cdot10^{-6}$	Bunch separation (s)

Derived Beam and Final Focus Parameters

$I = 6.5792\cdot10^{-5}$	Average Beam Current
$Ipk = 0.00822$	Peak beam current
$\sigma x = 6.39375\cdot10^{-7}$	Horizontal Beam Size
$\sigma y = 1.01094\cdot10^{-7}$	Vertical Beam Size
$Dx = 2.50317$	Horizontal Disruption Parameter
$Dy = 15.83146$	Vertical Disruption Parameter
$HD = 1.90856$	Disruption enhancement
$\theta Dx = 5.50033\cdot10^{-4}$	Maximum Horizontal Disruption angle
$\theta d = 3.19687\cdot10^{-4}$	Horizontal Diagonal Angle
$\Upsilon = 0.03761$	Beamstrahlung Parameter
$\delta = 0.01762$	Fractional Energy Loss
$Npairs = 0$	No. of Coherent Pairs
$incprs = 249.3532$	No. of incoherent pairs
$\theta c = 4.19331\cdot10^{-4}$	Beam Crossing Angle
$Lum = 4.96629\cdot10^{37}$	Luminosity MKS Units

Input Parameters -Power

$a = 0.046$	RF cell aperture (radius)
$nc = 9$	No of Cells/cavity
$nk = 0.65$	Assumed klystron efficiency
$T = 2$	Cryogenic Temperature
$nr = 0.2$	Assumed refrigerator efficency
$rf = 1.3\cdot 10^{9}$	RF frequency
$h = 1$	Static heat leak (watts/m)
$frac = 0.5$	Fraction of HOM power at cryo. temp
$Qr = 6\cdot 10^{9}$	Residual Q
$Qbcs = 2.65268\cdot 10^{10}$	BCS Q
$Q = 4.89322\cdot 10^{9}$	Cavity Qo
$RoQ = 832$	Cavity shunt impedance R/Q
$\lambda = 0.23077$	Wavelength
$Lcell = 0.11538$	Cell length
$nb = 800$	No.of Bunches/Pulse

Derived Power Parameters

$kll = 3.08822\cdot 10^{12}$	Loss Factor in V/C/meter-BCI22
$tbeam = 8\cdot 10^{-4}$	Beam on time
$trf = 0.00142$	RF Pulse Length
$rep = 10$	RF Rep rate
$d = 0.008$	Duty Factor
$d' = 0.01532$	Effective duty factor
$fill = 6.20106\cdot 10^{-4}$	fill time
$filla = 2.84622\cdot 10^{-4}$	Area under fill
$decay = 4.47312\cdot 10^{-4}$	Area under RF decay
$u = 91.96731$	Stored Energy/length
$Pb = 3.2896\cdot 10^{7}$	Total Beam Power
$Pdump = 1.83935\cdot 10^{7}$	Total Dumped RF Power
$AvRF = 5.83948\cdot 10^{7}$	Average RF power, includes beam power and dumped stored energy
$nt = 0.00137$	Overall ref. efficiency

$nc = 0.00687$	Carnot Efficiency	$Ppk = 2.056 \cdot 10^{5}$	Peak RF Power/meter
$Pdiss = 4.70362 \cdot 10^{4}$	Total Fund. Power at Cryo. Temp.	$Nkly = 1.34568 \cdot 10^{3}$	No. of Klystrons
$Pdbeam = 1.22815$	Watts/m into He during beam on	$Pkly = 3.0557 \cdot 10^{6}$	Peak power of klystron
$Pdfill = 0.43695$	Watts/m into He during fill	$RF = 4.112 \cdot 10^{9}$	Total RF Power
$Pddecay = 0.68671$	Watts/m into He during decay		
$Pdhom = 0.83548$	Watts/m HOM power into He	$AvRF = 5.83948 \cdot 10^{7}$	Average RF Power
$h = 1$	Watts/meter into He static	Breakdown of AC Power	
$Pstat = 2 \cdot 10^{4}$	Total Static Heat Leak	$Pbac = 5.06092 \cdot 10^{7}$	Ac power for beam power
$Phom = 3.3419 \cdot 10^{4}$	HOM Power	$Pdumpac = 2,82976 \cdot 10^{7}$	AC power for dumped stored energy
$Phomcryo = 1.67095 \cdot 10^{4}$	HOM Power at cryogenic temp		
$Pcryo = 8.37457 \cdot 10^{4}$	Total Refrigerator Load	$Phomac = 5.14139 \cdot 10^{4}$	AC power for HOM RF
		$Phomcryoac = 1.21562 \cdot 10^{7}$	AC Power for ref- hom
$Pacref = 6.0925 \cdot 10^{7}$	Total Refrigerator AC Power		
		$Pstatac = 1.455 \cdot 10^{7}$	AC power for ref -static heat leak-
$Pacrf = 8.98381 \cdot 10^{7}$	Total AC power for RF		
$QL = 3.65371 \cdot 10^{6}$	Loaded Q to match beam	$Pdissac = 3.42188 \cdot 10^{7}$	AC Power for ref. - rf losses in cavity
$BW = 355.80314$	Bandwidth (Hz)		
		$LDR = 5.6 \cdot 10^{3}$	Length of damping ring
$\tau e = 4.47312 \cdot 10^{-4}$	Filling time constant to equilibrium		
		$PDR = 2.24 \cdot 10^{7}$	AC Power for damping ring

$AC = 1.50763 \cdot 10^{8}$	Total Linac Wall Plug Power
$Eff = 0.2182$	Beam power /Linac Wall Plug Power

Input Parameters - Cost ($)

$Clin = 5 \cdot 10^{4}$	Cost/Active meter -Linac
$Cref = 2.57905 \cdot 10^{3}$	Cost/watt in He
$Crf = 0.07886$	Cost/watt RF
$Cmod = 1.35 \cdot 10^{5}$	Cost/modulator
$El = 0.08$	Cost/Kwatt-hour
$Life = 4$	Integrated running time (years)
$ODR = 2 \cdot 10^{3}$	Operating cost for Damping ring (watts/m)
$CDR = 2 \cdot 10^{4}$	Linear cost for damping ring ($/m)

VI. Derived Cost Parameters

$Linac = 1\cdot10^{9}$	Linac Cost
$DR = 2.24\cdot10^{8}$	Damping ring cost
$Pcryo = 8.37457\cdot10^{4}$	Total cryogenic heat load
$Ref = 2.15984\cdot10^{8}$	Refrigerator Cost
$Ppk = 2.056\cdot10^{5}$	Peak RF power/m
$RFc = 5.05929\cdot10^{8}$	RF cost
$Cap = 1.94591\cdot10^{9}$	Total Capital Cost
$Op = 4.85411\cdot10^{8}$	Operating Cost (includes damping ring AC power)
$AC = 1.50763\cdot10^{8}$	Linac AC Power
$TOTAL := Cap + Op$	
$TOTAL = 2.43132\cdot10^{9}$	Total cost

Wakefields, Alignment and Vibration Tolerances

$E0 = 3\cdot10^{9}$	Injection energy
$\beta0 = 20.89951$	Initial beta
$\beta f = 190.78559$	Final beta
$\beta av = 127.19039$	Average beta
$Nq = 806.54618$	Number of quads
$kt = 1.59335\cdot10^{13}$	Transverse wake V/C·m^2
$\sigma Erf = 0.00593$	Energy spread from RF
$\sigma Ewake = 0.00315$	Energy spread from wakes
$\sigma E = 0.00593$	
$xrms = 4.54099\cdot10^{-4}$	Horizontal alignment tolerance
$yrms = 1.0154\cdot10^{-4}$	Vertical alignment tolerance
$\Delta x = 1.90427\cdot10^{-6}$	Horizontal vibration tolerance
$\Delta y = 4.25808\cdot10^{-7}$	Vertical vibration tolerance

The end

Parameters for a 1 TeV Machine

As in the first TESLA workshop, we have allowed the final spot size to shrink to 50 nm for the 1 TeV case by using smaller final focus beta values. The source emittances are the same as in the baseline case, however. It is expected that techniques for achieving and colliding smaller beams will have advanced when the time is ripe to proceed from 0.5 to 1 TeV. A luminosity of 10^{34} is possible in this design exercise, while keeping the AC power below 200 MWatts. To permit such a high luminosity the collision energy spread has been allowed to grow to 12%, and the beamstrahlung parameter to 0.25, still near the classical regime. It was necessary to shorten the bunch length to near 1 mm to keep the vertical disruption parameter near 15. Any shorter bunch lenth will increase the number of coherent pairs very fast. Wakefields, quadrupole alignment and vibration tolerances all remain attractive as in other superconducting machines.

TeV Parameters		Units
Length	16.6 x2	km
Gradient	30	MV/m
No. of Bunches	800	
Injection Energy	3	GeV
CM Energy	1000	GeV
Luminosity	10	10^{33} cgs

Beam Parameters		
emittance x,y	2×10^{5}, 1×10^{6}	m-rad
final beta x,y	8, 2.5	mm
No. of e/bunch	5.8	10^{10}
Collsion Freq	4.1	kHz
Bunch Length	1.1	mm
Bunch Separation	1	µsec
Beam size vert	50.5	nm
Disruption Dy	16	
Beamstr. Param.	0.25	
Coll. Energy Spread	12.2	%
No.of Coherent. Pairs	40	
No. of Incoh. Pairs	235	

Beam Power	38	MWatts
Linac Efficiency	19	%

RF Parameters		
Q_0	4.9	10^{9}
RF Frequency	1.3	GHz
Aperture	4.6	cm
R/Q	832	Ohms
RF pulse length	1.46	msec
Rep rate	5.1	Hz
Eff. duty factor	0.8	%
RF Dissipation	1.78	watts/m
Total HOM power/m	2.14	watts/m
Total Cryogenic Load	129	kwatts
Loaded Q	3.9	10^{6}
Bandwidth	335	Hz
Peak RF Power/m	278	kwatt/m

Wakes, Alignment and Vibration		Tolerances
RF Ind. energy spread	0.18	%
Wake ind. en. spread	0.48	%
beta initial	29	m
beta final	369	m
beta average	246	m
No. of Quads	827	
Vert. Align. Tol	326	µm
Vert. Vibration Tol.	0.41	µm

Cost		
Capital	3.39	10^{9} $
AC Wall Plug Power	200	Mwatts

Parameter Exploration

Baseline Parameter Set

At the June Workshop on TESLA in DESY, this program was used to create parameter sets according to a strategy outlined by B. Wiik.[1] Consider a 10 km active length machine to provide the maximum possible luminosity at 0.5 TeV cm energy, with an AC power limit of 150 Mwatts. A gradient of 25 MV/m can be adopted. Further consider operating such a machine at lower gradients in Top Factory and W Factory modes. For the Top Factory an additional requirement of $\delta E/E < 0.001$ is imposed from physics. For the W factory, a Luminosity > 2×10^{33} is desirable to be an order of magnitude above LEP II. In all operating modes the source and final focus are taken with the same characteristics. This is an attractive strategy as it calls for a gradient of only 10 MV/m for the Top Factory mode and 12.5 MV/m for the W-Factory mode, both within reach with existing cavity preparation techniques. Higher Q_0's were used for the lower gradients.

Table 1 compares some of the parameters for the three operating modes. It was possible to design a Luminosity of 5×10^{33} for the 0.5 TeV mode with a collision energy spread below 2%.

Using the 0.5 TeV machine as the baseline, further exploration of the parameter space has been carried out. Of course the relative trends shown by these exercises depend on our choices of the relative cost coefficients, so that some of these conclusions may be revised after the collective judgement of the second workshop is incorporated.

Fixed Parameters for All Three Modes of Operation :

Length	10	km
emittance x,y	2×10^{-5}, 1×10^{-6}	m·rad
final beta x,y	10, 5	mm
No. of Bunches	800	
Injection Energy	3	GeV
RF Frequency	1.3	GHz
Aperture	4.6	cm
R/Q	832	Ohms
AC Wall Plug Power	150	Mwatts

Beam Parameters

	W-Factory	Top-Factory	1/2 TESLA	Units
CM Energy	200	250	500	GeV
No. of e/bunch	3	2	5.14	10^{10}
Collision Freq	45	40	8	kHz
Bunch Length	2	1	2	mm
Bunch Separation	0.8	0.4	1	μsec
Beam size vert	0.16	0.14	0.1	μm
Disruption Dy	9.2	3	16	
Beamstr. Param.	0.0054	0.0056	0.038	
Coll. Energy Spread	0.12	0.16	1.8	%
No. of Coh. Pairs	0	0	0	
No. of Incoh. Pairs	125	18	249	
Beam Power	43	32	33	MWatts
Linac Efficiency	28	22	22	%
Luminosity	3.6	1.8	5	10^{33} cgs

RF Parameters

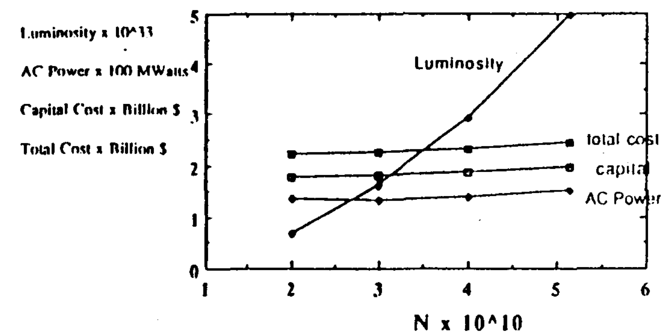
	W-Factory	Top-Factory	1/2 TESLA	Units
Gradient	10	12.5	25	MV/m
Q_0	7.3	6.1	4.9	10^9
RF pulse length	0.98	0.64	1.42	msec
Rep rate	56	50	10	Hz
Eff. duty factor	5.8	3.5	1.5	%
RF Dissipation	0.97	1.06	2.35	watts/m
Total HOM power/m	3.2	2.8	1.7	watts/m
Total Cryogenic Load	71	68	84	kwatts
Loaded Q	2	1.9	3.7	10^6
Bandwidth	649	692	355	Hz
Peak RF Power/m	60	100	200	kwatt/m

Wakes, Tolerances and beta function

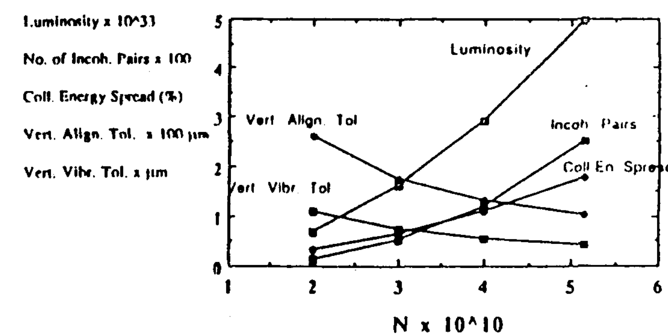
	W-Factory	Top-Factory	1/2 TESLA	Units
RF induced energy spread	0.59	0.15	0.59	%
Wake ind. en. spread	0.46	0.43	0.31	
beta initial	22.6	75.9	20.9	m
beta final	131	490	191	m
beta average	87	327	127	m
No of Quads	936	264	807	
Vert Align. Tol	0.12	1.6	0.1	mm
Vert. Vibration Tol.	0.52	1.7	0.42	μm

Variation of Input Parameters

In the first study, we vary the number of particles per bunch down from the baseline value of 5×10^{10} to 2×10^{10}.



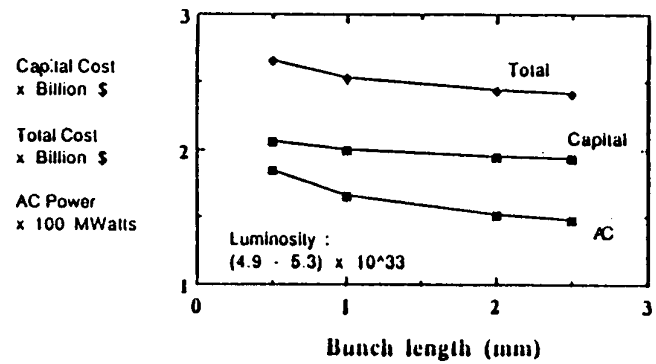
Not much impact is seen on the capital and operating cost, but there is a substantial loss of luminosity shown in Figure above. The companion figure below shows the down side of a high bunch charge.



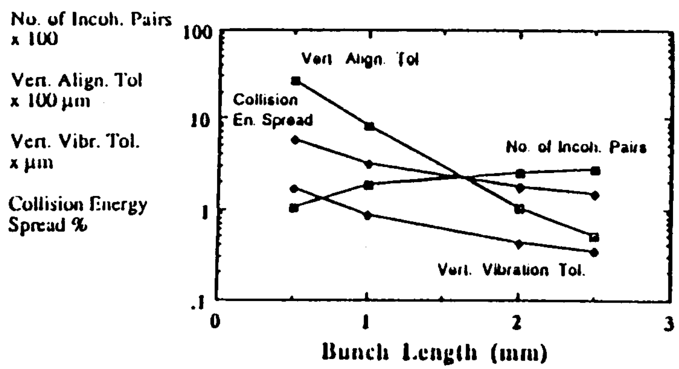
Vertical quadrupole alignment and vibration tolerances get more stringent, but still far relaxed (> 100 μm) over normal conducting versions (< 30 μm). The collision energy spread and the number of incoherent pairs likewise increase significantly with bunch charge but still superior to normal conducting colliders. Of course the multi-bunch effects (not covered by the program) also get worse.

but existing simulations reported in the 1st TESLA proceedings suggest that the baseline values are acceptable if Qext of the HOM's can be kept below 10^6 .

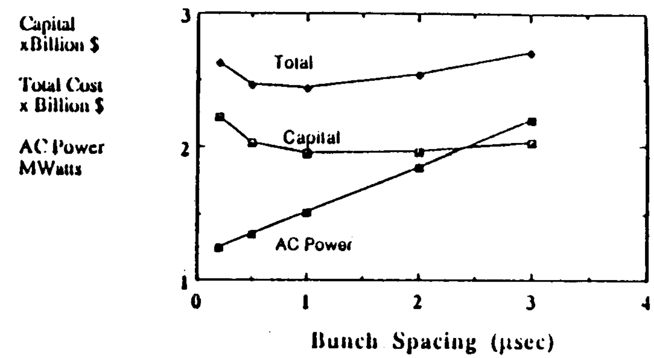
Longer bunch lengths are preferred from the standpoint of AC power, and collision energy spread, but do not have a strong impact on the capital or total cost.



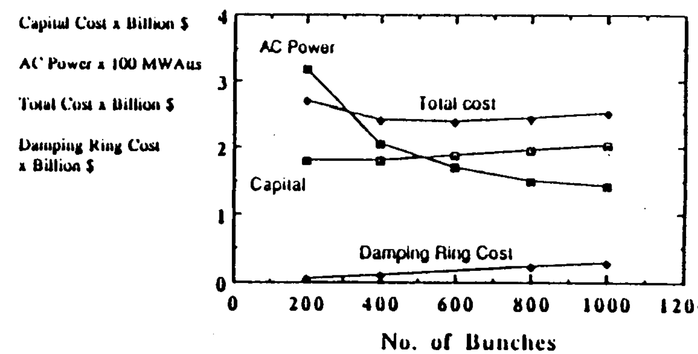
On the other hand short bunch lengths are strongly preferred for relaxed alignment and vibration tolerance as well as for limiting the number of incoherent pairs generated. A bunch length between 1 - 2 mm appears to be good compromise.



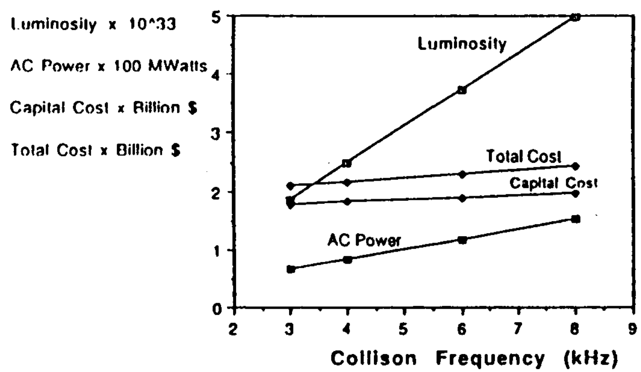
Next we explore the effect of varying the bunch spacing from the baseline value of 1 µsec. The AC wall plug power increases nearly proportional to bunch spacing, whereas the capital cost has an optimum near the baseline value of 1 µsec. Again, multibunch effects prefer long bunch spacing.



Reducing the number of bunches below the baseline 800 increases the AC power but lowers the capital cost, so that a broad optimum number is 600 - 800 bunches.



Finally, the choice of collision frequency is dictated essentially by the desired luminosity and the allowable AC power. Attractiveness for physics would suggest shooting for the highest possible collision frequency.



<u>ON THE CHOICE OF THE RF FREQUENCY FOR TESLA</u>

To make progress on TESLA, it will be important to narrow down the RF frequency as early as possible, so that machine parameters can be optimized, and prototypical hardware made at the appropriate size. At the1st TESLA worskhop, there appeared to be no overwhelming criteria in favor of 1.5 or 3 GHz. We present arguments here to show that 1.3 -1.5 GHz is definitely preferred.

As pointed out at the TESLA workshop and in other references, the advantages of the lower frequency are:

a) The BCS losses in the walls of the cavity decrease as f^2. Losses can be lowered for the higher frequency by choosing a lower operating temperature, but this would drive up the capital cost of the refrigerator, as well as the operating cost for removing heat from other sources such as static heat leak and higher mode losses.

b) The number of RF input feeds and cryostat penetrations per unit length decreases with f, reducing the capital cost. The same is true for HOM couplers.

c) The longitudinal wakefields decrease as f^2, and the transverse wakefields decrease as f^3. Wakefield induced energy spread is less, and alignment and vibration tolerances are relaxed. The advantages offered by the lower wakefields can be alternately realized by reducing the bunch spacing, which lowers the RF pulse length and consequently the RF dissipation for establishing the gradient. Alternatively, the lower wakefields permit use of higher bunch charge for gains in luminosity. These advantages can be used to optimize the parameters in design exercises.

d) The higher mode loss factor decreases with frequency, so the higher mode power deposited at liquid helium temperature is less.

e) In principle, with longer wavelengths, longer bunch lengths (σ_z) are permissible for the same RF curvature related energy spread, which opens up a favorable parameter for adjusting other performance aspects. For example, HOM losses decrease with increased bunch length. For the same collision spot size (σx, σy) the beamstrahlung induced energy spread decreases with σz and so does the beamstrahlung parameter. This reduces the number of coherent pairs. On the other hand, the number of incoherent pairs and the disruption parameters increase with σ_z, so longer bunch lengths must be used judiciously.

The advantages of the higher frequency are:

a) The shunt impedance/unit length is proportional to f, therefore the RF power dissipated in the cells is lower for the same Q_0. This lowers both the capital and operating cost, depending on the scenario for Q_0.

b) The dumped power when the RF is turned off decreases as (f^{-2}).

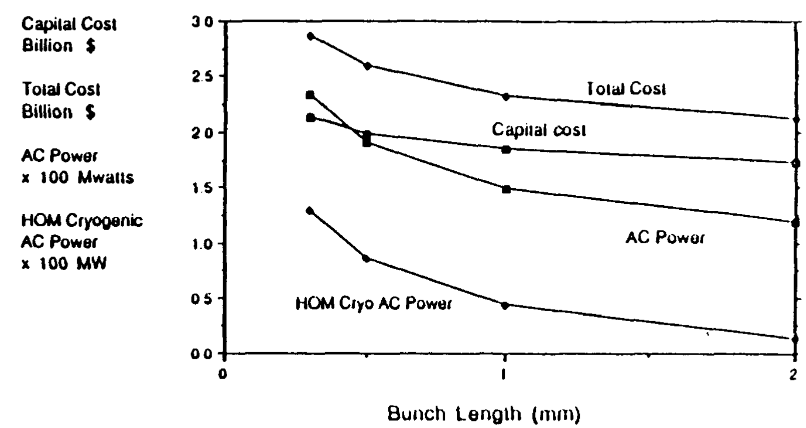
c) The RF fill time and decay time decrease as f^{-2}, reducing RF losses.

All arguments in favor of the higher frequency translate to the possibility for savings in operating cost.

Here we show that at the lower frequency, two of the above discussed factors more than offset the savings in operating power at the higher frequency. At the higher frequency, a shorter bunch length is demanded by the need to keep down the wakefield induced energy spread, and to keep the alignment and vibration tolerances from becoming too severe. Also a larger bunch spacing is demanded by multibunch stability considerations. At the shorter bunch length, the increased HOM power at 3 GHz offsets the savings in dumped RF power, and the larger bunch spacing offsets the reduced RF dissipation.

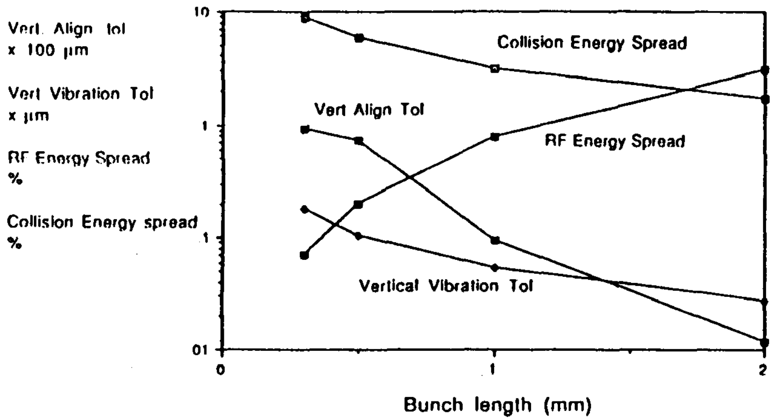
Using the parameters program and the baseline parameters for the 0.5 TeV machine, we changed the RF frequency from 1.3 to 3 GHz. In anticipation of the requirements from multibunch stability, we also increased the bunch spacing from 1 µsec to 2 µsec. Only more detailed simulations can show if this increase is enough.

The figure below then shows how the AC power, capital and total costs change as the bunch length is reduced from 2 mm



Note that at 2 mm bunch length, the 3 GHz case appears to have significant advantages over the baseline : lower capital cost (1.74 vs. 1.95 B$) , lower AC power (110 vs. 151 Mwatts)

However as shown in the next figure below, there are some very serious problems arising from the choice of 2 mm bunch length.

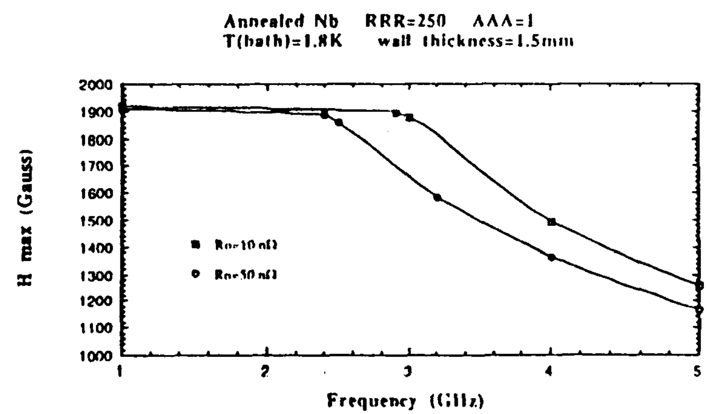


The RF induced energy spread is 3.1 % vs. 0.6%. which leads to severe alignment tolerances (1.2 µm vs. 102 µm) and vibration tolerances (27 nm vs. 426 nm). These numbers are poorer than for normal conducting colliders sacrificing key attractive features of superconducting colliders. As the bunch length is reduced to correct these serious difficulties, the advantages of capital and operating cost at 3 GHz evaporate. A bunch length of less than 0.5 mm is needed to come close to the tolerances of the baseline case. In this case the costs and AC power exceed the baseline. Most of the increased cost and AC power arise from the increased HOM losses with shorter bunch length. Of course the problem can be attacked by trying to remove larger fractions of the HOM power than the 0.5 assumed. (Recall that in all cases we have taken 0.5 of the HOM power to be deposited in liquid helium) But the same technique can then be applied to the 1.3 GHz case.

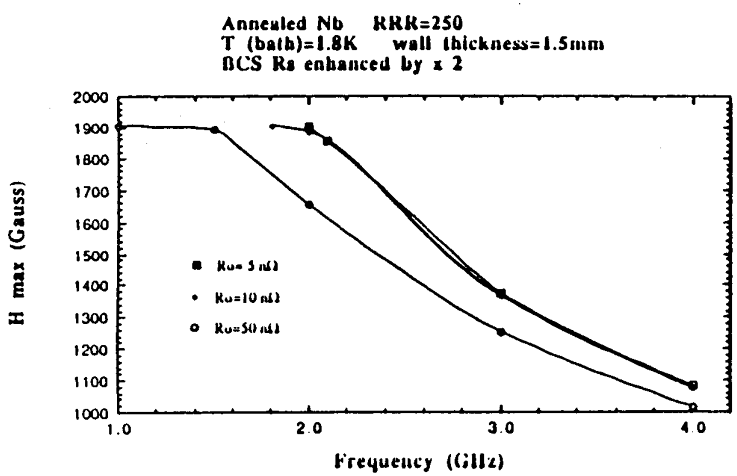
One idea that may be proposed for 3 GHz is to lower the operating temperature so that the Q_0 is higher. Note that by going to the low temperature, the gains in RF dissipation are lost by the impact of the decreased refrigerator efficiency on the static heat leak and higher mode loss.

In totally separate arguments, we show that for the higher frequency case, the ultimate magnetic field limit is lower than at 1.3 or 1.5 GHz. This fundamental field limit arises mainly from the strong temperature dependence of the BCS surface resistance, which leads to a thermal instability in the defect free case, the best we may hope to achieve.

The Figure below shows the defect free magnetic breakdown limit calculated (from a numerical thermal model program) as a function of RF frequency for two levels of residual losses corresponding to $Q_r = 3\times10^{10}$ and $Q_r = 6\times10^{9}$. While there is no significant penalty for the lower frequency, the maximum field drops from 1920 Oe to 1650 Oe at 3 GHz. Here we have assumed a favorable case for the BCS surface resistance, corresponding to a low surface RRR. The bulk Nb RRR was taken as 250.



Under certain circumstances, the theoretically allowed accelerating field at 3 GHz can become as low as 32 MV/m, compared to 48 MV/m at 1.5 GHz. In the Figure below is considered the double jeopardy of a high surface RRR along with increased residual loss. Again the low frequency is insensitive, but at 3 GHz defect free breakdown can be encountered at 1250 Oe. For a good structure geometry, with 40 Oe/MV/m, this translates to an accelerating field limit of 31 MV/m. Recently, just this type of thermal instability was encountered in an S-band single cell cavity [9]], and clearly demonstrated by thermometry data. This type of limitation has also been suggested to explain past maximum fields reached at 3 Ghz and higher frequencies. [10]



Thus the maximum achievable field becomes significantly more sensitive to expected variations in the residual surface resistance, and to the possible rise in the BCS surface resistance through increased surface RRR.

In principle these limits would rule out a very high energy (1.5 TeV CM) TESLA machine at 3 GHz, for which a gradient of 40 MV/m was used at the 1st TESLA workshop. At present, however, with field emission as the predominant limiting mechanism, this argument by itself is not overwhelming

Given the other advantages of the low frequency, as well as the new factors pointed out here, we recommend the selection of 1.3 -1.5 GHz. Given the present availability of klystrons at 1.3 GHz makes the choice clear.

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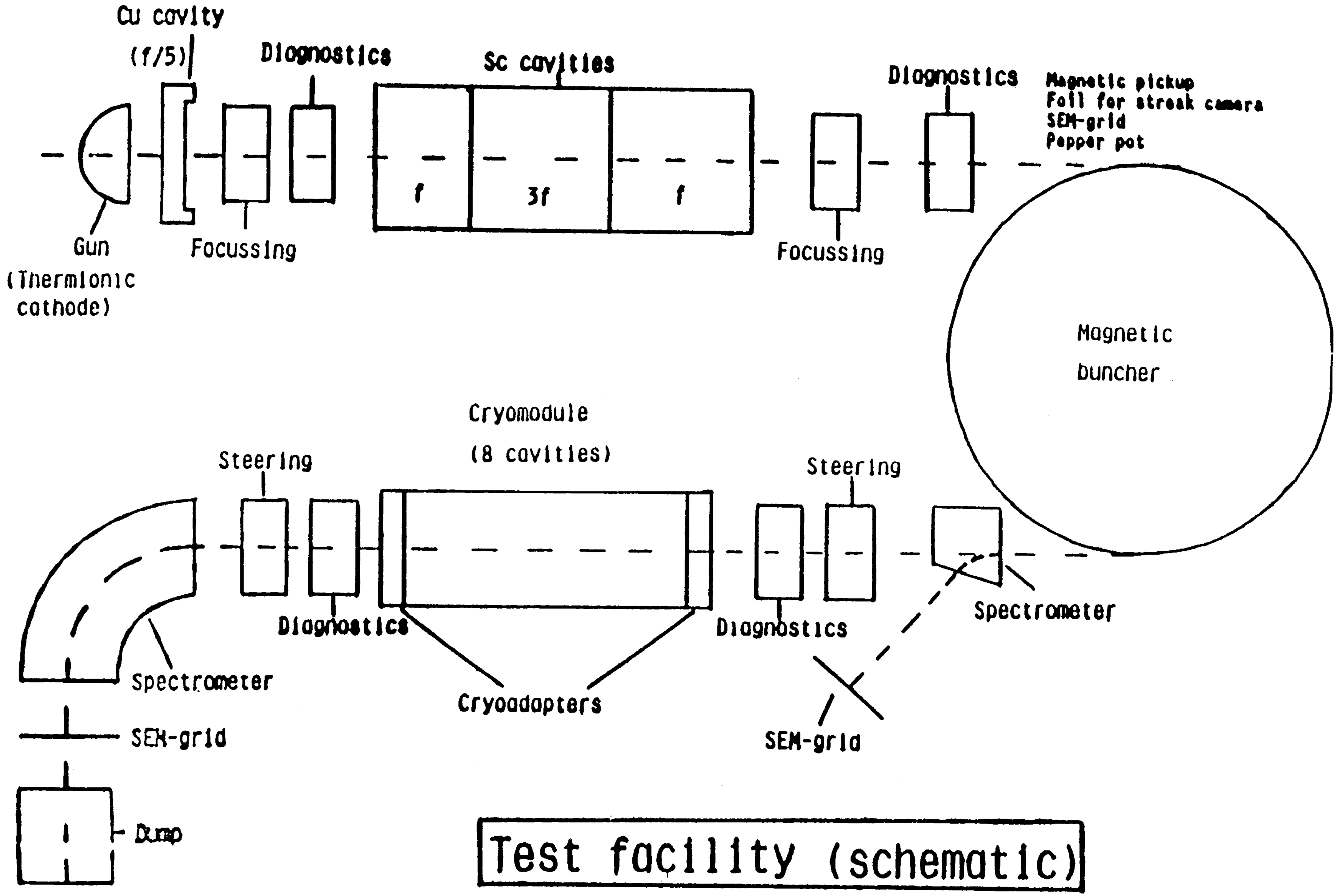
APPENDIX II

Drawing of the TESLA Test Bed Proposed at DESY



APPENDIX III

Estimate of Microphonic Shock Excitation by a Radiation Pressure Pulse

Starting with the usual equations for a harmonic oscillator, and ignoring damping, we have

(1) $F = -k\,x$,

(2) $d^2x/d\,t^2 = F/m = -k\,x/m$

(3) $d^2x/d\,t^2 = -A\,\omega^2 \cos(\omega\,t) = -\omega^2 x$, and

(4) $\omega^2 = k/m$.

For the Cornell-CEBAF cavities, which are 1.5 GHz and have 3.3 mm wall thickness, the pressure sensitivity is approximately -3 Hz/(MV/m)^2. This coefficient is larger than would be expected if the radiation pressure were uniform, which it is not. This coefficient yields a frequency shift of 1875 Hz at 25 MV/m. The most easily excited mechanical modes of the cavity have frequencies around 60 Hz. That these modes are the relevant ones for RF frequency shifts has been verified by observing ponderomotive oscillations of the cavities when the incident power at fixed RF frequency, rather than the cavity field, is regulated. Thus $f \approx 60$ Hz, and $\omega \approx 377$ Hz.

If we now define F = 1 as the value which, in equilibrium, causes a 1875 Hz RF frequency shift, and apply F = 1 as a step function, the undamped solution is

(5) $f_{RF} = f_{RF_0} - 1875\,(1 - \cos(\omega t))$.

Since the RF pulse will typically be short compared to $1/\omega$, the maximum "velocity" of the cavity walls will occur at the end of the RF pulse. Although this equation is not difficult to solve exactly, the physical process is more transparent if the following approximation is made. Using the definition of F above, and defining x in units of the frequency shift, in Hz, that it produces, yields $k = 0.000533$, and $m = k/\omega^2 = 3.752 \cdot 10^{-9}$. Assuming an RF pulse length of 0.00142 seconds, and approximating its effect as an impulse yields

(6) $v = F\,t/m \cong 0.00142/3.752 \cdot 10^{-9} = 378$ kHz/second $= A\,\omega$.

$\therefore$ $A = (A\,\omega)/\omega = 378{,}000/377 = 1004$ Hz, which is approximately half of the steady state effect. For a loaded Q of $3.9 \cdot 10^6$, the bandwidth, $f/Q_L = 1.3 \cdot 10^9/3.9 \cdot 10^6 = 333$ Hz. The amplitude, A, of the microphonic oscillation is therefore approximately 3 times the bandwidth. An acceptable maximum amplitude is approximately 0.25 of the bandwidth, so a factor of ≥12 reduction in the microphonic amplitude is needed through stiffening methods. Enough damping should be present so that resonant build-up with multiple pulses is not an additional problem.

APPENDIX IV

Parameter List for a 3 GHz, 0.5 TeV Normal Conducting Linear Collider Under Consideration at DESY

List of Parameters

General Parameters		100 mA	300 mA
energy	GeV	$250 + 250$	–
luminosity (incl. crossing angle, no enhancement from disruption)	$(\mathrm{cm}^2\,\mathrm{sec})^{-1}$	● $2.4 \cdot 10^{33}$	● $1.4 \cdot 10^{33}$
active length	m	● 29 411	–
repetition rate	Hz	● 50	–
number of particles per bunch		● $7 \cdot 10^{9}$	● $21 \cdot 10^{9}$
Particle Production and Damping Rings			
damping ring energy	GeV	3.15	–
damping time	msec	3.8	–
ring circumference	m	650	–
invariant emittance $\gamma\,\epsilon_{x,y}$	m / 10^{-8}	410/4	1000/100
energy spread	%	0.112	–
rf–voltage	MV	5.0	–
rf–frequency	MHz	469	–
bunch length σ_s	mm	3.6	–
wiggler peak field	T	2.0	–
wiggler period length	m	0.20	–
wiggler total length	m	84	–
dynamic acceptance	m	$4 \cdot 10^{-6}$	–

Main Linac		100 mA	300 mA
wave length	m	0.10	–
average shunt impedance	MΩ/m	53.6	–
attenuation	neper	0.57	–
structure length	m	• 6	–
group velocity	% of c	4.1–1.3	–
filling time	μsec	0.825	–
maximum energy width (peak)	%	± 0.6	± 1.27
klystron power	MW	• 112	• 145
number of klystrons		2451	–
structures per klystron		2	–
klystron efficiency	%	45	–
total rf–pulse length	μsec	2.8	–
zero current energy	GeV	540	613
mean power	MW	86	110
rf–peak power	MW	275 000	355 000
average pulse current	mA	100	300
current pulse length	μsec	2	–
number of bunches per pulse		172	–
bunch to bunch distance	m	3.2	–
bunch length (rms)	mm	• 0.2	• 0.5

Final Focus and Interaction		100 mA	300 mA
β–function at IP $\beta^*_{x,y}$	mm	3, 0.3	5, 0.8
beam dimension at IP $\sigma^*_{x,y}$	nm	• 169, 5.48	• 316, 40
aspect ratio		• 30.8	• 8
crossing angle	mrad	± 0.8	–
disruption parameter D_x, D_y		0.55, 16.9	1.1, 8.4
luminosity enhancement		1.7	1.6
maximum disruption angle	mrad	0.36, 0.10	0.57, 0.29
dilution parameter		0.38	3.5
critical energy of beamstrahlung	GeV	80	47
mean number of beamstrahlung photons per particle		1.6	2.3
critical radiation parameter		0.214	0.126
mean fractional energy loss		0.07	0.06
mean fract. reduct. for c.m. energy		0.03	–
momentum acceptance	%	± 1.8	–

Efficiencies		100 mA	300 mA
rf ⟶ beam	%	[redacted]	[redacted]
wall-plug ⟶ beam	%		

APPENDIX V

Comparison of Advantages and Disadvantages of a 3 GHz Normal Conducting Linear Collider and a Superconducting Linear Collider

Number	Advantage NC	Advantage SC	Characteristic
1		√	Lower transverse wake
2		√	RF sources do not push state-of-the-art
3		√	Potential for performance exceeding design specs
4		√	Higher level of interest in technology
5		√	Traveling wave structure has aperture defined by needed group velocity
6		√	Potential for reducing beam diameter further for scaling to higher energies
7		√	Luminosity is more conservative
8		√	Has the capability to have small ΔE/E
9		√	RF feedback is more applicable to longer pulses
10	√		Structures with the required properties are an existing capability

APPENDIX VI

Application of Cost Coefficients to a 3 GHz, 0.5 TeV Normal Conducting Linear Collider

This appendix contains an evaluation of the cost of a 3 GHz normal conducting linac with a center-of-mass energy of 0.5 TeV. As stated in the text, these numbers are an upper limit, based on the assumptions that there are no technological improvements since SLAC was built, and that there are no economies of scale relative to SLAC. The actual costs of building SLAC, and typical power costs for operating it continuously for ten years, have been divided into terms which have various dependencies on the gradient, the energy, and the pulse repetition frequency; these coefficients (except for $C_{5'}$, which makes the assumption that a total of two damping rings are used) are derived in Cornell-CLNS-85/709, and are in 1985 U. S. $.

The total construction plus ten year electrical power operating cost for the accelerator is given by

(1) $C = C_1\, E/\varepsilon + C_2\, E\, \varepsilon + C_3\, E\, \varepsilon\, f_P + C_4\, N\, E\, f_B + C_{5'}\,$ Circ,

where C is the cost in 1985 dollars, the C_i's are the coefficients, E is the energy of each of the two beams in eV, ε is the gradient in V/m, f_P is the RF pulse repetition frequency in Hz, f_B is the bunch repetition frequency, N is the number of particles per bunch, and Circ is the damping ring circumference in meters. The coefficients are \$70,082, $\$1.820 \cdot 10^{-9}$, $\$6.352 \cdot 10^{-13}$, $\$2.243 \cdot 10^{-18}$, and $\$3.3 \cdot 10^{5}$, respectively, with appropriate units for each.

Using the parameters for the DESY normal conducting proposal yields

(2) $C(1) = 70{,}082 \cdot 2.5 \cdot 10^{11}/1.7 \cdot 10^{7} = 1.031 \cdot 10^{9}\$$.

(3) $C(2) = 1.820 \cdot 10^{-9} \cdot 2.5 \cdot 10^{11} \cdot 1.7 \cdot 10^{7} = 7.735 \cdot 10^{9}\$$.

(4) $C(3) = 6.352 \cdot 10^{-13} \cdot 2.5 \cdot 10^{11} \cdot 1.7 \cdot 10^{7} \cdot 50 = 0.135 \cdot 10^{9}\$$.

(5) $C(4) = 2.243 \cdot 10^{-18} \cdot 7 \cdot 10^{9} \cdot 2.5 \cdot 10^{11} \cdot 8600 = 0.034 \cdot 10^{9}\$$.

(6) $C(5) = 3.3 \cdot 10^{5} \cdot 650 = 0.215 \cdot 10^{9}\$$.

The costs reflected in (2), (3), and (6) are capital costs, and those in (4) and (5) are ten year operating costs.

The construction cost for the accelerator, in 1985 U. S. \$, is thus $8.981 \cdot 10^{9}$, and the 10-year electric power cost is $\$0.169 \cdot 10^{9}$.

If one now escalates to FY'91\$ at 5%/year, the numbers become $12.035 \cdot 10^{9}$ 1991 U. S. \$ for construction, and $0.226 \cdot 10^{9}$ 1991 U. S. \$ for 10-year continuous electric power.

Instead of using the specified gradient of $1.7 \cdot 10^{7}$ V/m, one can use the cost-optimum gradient by taking the derivative of equation (1). The optimum is given by

(7) $\varepsilon = (C_1/(C_2 + C_3\, f_P))^{0.5} = (70082/(1.820 \cdot 10^{-9} + 6.352 \cdot 10^{-13} \cdot 50))^{0.5} = 6.152 \cdot 10^{6}$ V/m. Note that this is close to the gradient at which SLAC was originally built.

The values for the various cost components then become

(8) $C(1) = 70{,}082 \cdot 2.5 \cdot 10^{11}/6.152 \cdot 10^{6} = 2.848 \cdot 10^{9}\$.$

(9) $C(2) = 1.820 \cdot 10^{-9} \cdot 2.5 \cdot 10^{11} \cdot 6.152 \cdot 10^{6} = 2.799 \cdot 10^{9}\$.$

(10) $C(3) = 6.352 \cdot 10^{-13} \cdot 2.5 \cdot 10^{11} \cdot 6.152 \cdot 10^{6} \cdot 50 = 0.049 \cdot 10^{9}\$.$

(11) $C(4) = 2.243 \cdot 10^{-18} \cdot 7 \cdot 10^{9} \cdot 2.5 \cdot 10^{11} \cdot 8600 = 0.034 \cdot 10^{9}\$.$

(12) $C(5) = 3.3 \cdot 10^{5} \cdot 650 = 0.215 \cdot 10^{9}\$.$

Escalating these numbers as above yields $7.856 \cdot 10^{9}$ 1991 U. S. $ for the construction cost, and $0.111 \cdot 10^{9}$ 1991 U. S. $ for the 10-year continuous operation electric power cost. It is emphasized again that these numbers assume no savings relative to SLAC from intervening technological improvements, nor from economies of scale, and should therefore be viewed as an upper limit.