CHAPTER 9

Summary of R&D Work that Remains to Be Done for Individual Machines or Collectively for All Machines

9.0 INTRODUCTION

In this chapter, the recommended R&D items that have already been indicated in Chapter 6, Chapter 7, and Chapter 8 are collected together.

To assess more precisely the importance and urgency of the proposed R&D objectives, the Working Groups established a discrete ranking list, against which they can be evaluated. Ordered by decreasing criticality, we distinguish the following:

Ranking 1: R&D needed for feasibility demonstration of the machine

The objective of these R&D items is to show that the key machine parameters are not unrealistic. In particular, a proof of existence of the basic critical constituents of the machines should be available upon completion of the Ranking 1 R&D items.

Ranking 2: R&D needed to finalize design choices and ensure reliability of the machine

These R&D items should validate the design of the machine, in a broad sense. They address the anticipated difficulties in areas such as the architecture of the subsystems, beam physics and instabilities, and tolerances. A very important objective is also to examine the reliability and operability of the machine, given the very large number of components and their complexity.

Ranking 3: R&D needed before starting production of systems and components

These R&D items describe detailed studies needed to specify machine components before construction and to verify their adequacy with respect to beam parameters and operating procedures.

Ranking 4: R&D desirable for technical or cost optimization

> In parallel to the main stream of R&D needed to build a linear collider, there should be other studies aimed at exploring alternative solutions or improving our understanding of the problems encountered. The results of the Ranking 4 R&D items are likely to be exploited for improved technical performance, energy upgrades, or cost reduction.

These rankings were applied to both the 500 GeV c.m. projects and to the corresponding upgrades. They were meant to set a scale for the evaluation of the proposed R&D, but, strictly speaking, not for the relevant concerns. However, in many cases, there is a one-to-one correspondence between concerns expressed in Chapter 6, Chapter 7, and Chapter 8, and R&D items. In fact, these rankings themselves were often perceived by the Working Groups as applicable to allaying the associated concerns.

A discrete ranking, with its benefits in terms of simplicity and clarity, unavoidably raises the difficulty of borderline cases, which can only be mitigated by adding more detailed qualifying statements in the R&D descriptions. In the same spirit, counting the number of items in each ranking for each project would give a wrong indication of the criticality of the project. The difficulty or time scale to attain a given R&D objective were not discussed as such by the Working Groups.

Many R&D items are common to all projects; they are grouped together in the following lists. Within each category, the R&D items have been grouped into those identified by the Energy, Luminosity, and Reliability Working groups. Some items pertinent to more than one Working Group are stated only once to avoid redundancy. In the case of JLC-C, only the linac R&D issues are listed separately from the JLC-X/NLC. No luminosity items have been separately identified for JLC-C, since the designs of the damping rings and of the beam delivery system are identical to those of JLC-X, and no design was made available to the Committee for the JLC-C main linac optics. For the same reason, compatibility issues arising in the upgrade of JLC-C through the addition of an X-band extension were also not considered by the group. Also, no specific luminosity-related issues were identified for the CLIC damping ring because a full solution for the CLIC damping ring lattice was not available to the committee at the time of the report. It should be pointed out, however, that the extracted vertical emittance required for the CLIC damping ring is by far the smallest among all the projects, thereby setting the scale for the design challenge.

9.1 RANKING 1

TESLA Upgrade to 800 GeV c.m.

Energy

The Energy Working Group considers that a feasibility demonstration of the machine requires the proof of existence of the basic building blocks of the linacs. In the case of TESLA at 500 GeV, such demonstration requires in particular that s.c. cavities installed in a cryomodule be running at the design gradient of 23.8 MV/m. This has been practically demonstrated at TTF1 with cavities treated by chemical processing[1]. The other critical elements of a linac unit (multibeam klystron, modulator and power distribution) already exist.

- The feasibility demonstration of the TESLA energy upgrade to about 800 GeV requires that a cryomodule be assembled and tested at the design gradient of 35 MV/m. The test should prove that quench rates and breakdowns, including couplers, are commensurate with the operational expectations. It should also show that dark currents at the design gradient are manageable, which means that several cavities should be assembled together in the cryomodule. Tests with electropolished cavities assembled in a cryomodule are foreseen in 2003.

JLC-C

Energy

- The proposed choke-mode structures have not been tested at high power yet. High power testing of structures and pulse compressors at the design parameters are needed for JLC-C. Tests are foreseen at KEK and at the SPring-8 facility in the next years.

JLC-X/NLC

Energy

- For JLC-X/NLC, the validation of the presently achieved performance (gradient and trip rates) of low group velocity structures—but with an acceptable average iris radius, dipole mode detuning and manifolds for damping—constitutes the most critical Ranking 1 R&D issue. Tests of structures with these features are foreseen in 2003.
- The other critical element of the rf system is the dual-moded SLED-II pulse compression system. Tests of its rf power and energy handling capability at JLC-X/NLC design levels are planned in 2003. As far as the 75 MW X-band PPM klystron is concerned, the Working Group considers the JLC-X PPM-2 klystron a proof of existence (although tested only at half the repetition rate). A similar comment can be made regarding the solid-state modulator tested at SLAC.

[1]Knowing that electropolished cavities sustain significantly higher gradients than chemically polished cavities, there is little doubt that cryomodules running at about 24 MV/m can be built.

CLIC

Energy

- The presently tested CLIC structures have only been exposed to very short pulses (30 ns maximum) and were not equipped with wakefield damping. The first Ranking 1 R&D issue is to test the complete CLIC structures at the design gradient and with the design pulse length (130 ns). Tests with design pulse length and with undamped structures are foreseen when CTF3 is available (April 2004).
- The validation of the drive beam generation with a fully loaded linac is foreseen in CTF3. Beam dynamics issues and achieving the overall efficiency look challenging.

Reliability

- In the present CLIC design, an entire drive beam section must be turned off on any fault (in particular on any cavity fault). CLIC needs to develop a mechanism to turn off only a few structures in the event of a fault. At the time of writing this report, there is no specific R&D program aimed at that objective but possible schemes are being studied.

9.2 RANKING 2

TESLA

Energy

- To finalize the design choices and evaluate reliability issues it is important to fully test the basic building block of the linac. For TESLA, this means several cryomodules installed in their future machine environment, with all auxiliaries running, like pumps, controls, *etc.* The test should as much as possible simulate realistic machine operating conditions, with the proposed klystron, power distribution system and with beam. The cavities must be equipped with their final HOM couplers, and their relative alignment must be shown to be within requirements. The cryomodules must be run at or above their nominal field for long enough periods to realistically evaluate their quench and breakdown rates. This Ranking 2 R&D requirement also applies to the upgrade. Here, the objectives and time scale are obviously much more difficult.
- The development of a damping ring kicker with very fast rise and fall times is needed.

Luminosity

Damping Rings

- For the TESLA damping ring particle loss simulations, systematic and random multipole errors, and random wiggler errors must be included. Further dynamic aperture optimization of the rings is also needed.

- The energy and luminosity upgrade to 800 GeV will put tighter requirements on damping ring alignment tolerances, and on suppression of electron and ion instabilities in the rings. Further studies of these effects are required.

Machine-Detector Interface

- In the present TESLA design, the beams collide head-on in one of the IRs. The trade-offs between head-on and crossing-angle collisions must be reviewed, especially the implications of the present extraction-line design. Pending the outcome of this review, the possibility of eventually adopting a crossing-angle layout should be retained.

Reliability

- The TESLA single tunnel configuration appears to pose a significant reliability and operability risk because of the possible frequency of required linac accesses and the impact of these accesses on other systems, particularly the damping rings. TESLA needs a detailed analysis of the impact on operability resulting from a single tunnel.

JLC-C

Energy

- The klystrons and modulators should be tested successfully at the nominal 100 Hz repetition rate.
- This should lead to the full test of the linac subunit, with beam. This will include klystrons, modulator, pulse compression system, LLRF control and several structures in their future environment.

JLC-X/NLC

Energy

- There must be a full test of the JLC-X PPM klystron at the specified repetition rate of 120 or 150 Hz.
- These klystrons should be tested with the NLC modulator (at full specs and including arcing tests) and form part of a linac subunit test. The latter should also comprise the dual-moded SLED-II complete system, several damped and detuned structures, installed in the accelerator environment (with temperature control, for instance), and LLRF and controls systems. The test should be made with beam. The present plan is to perform this sort of test with a full girder of structures (some of them being detuned and damped) in 2004.

CLIC

Energy

- Present tests have demonstrated the advantages of tungsten and molybdenum irises in reaching the highest gradients in accelerator structures. These tests should be pursued, possibly also with other materials, for application to CLIC and possibly other machines.
- The very high power of the drive beam and its stability are serious concerns for CLIC. The drive beam stability should be validated, and the drive beam Machine Protection System, which is likely to be a complex system, should be designed to protect the decelerator structures.
- The test of a relevant linac subunit with beam is required. This is one of the purposes of CTF3, which should start operation in 2004.
- The validation of the proposed multibeam klystron performance is needed to finalize the design choices for the CLIC drive beam generation. This applies particularly to the 3 TeV energy upgrade (long pulse).

Luminosity

Low Emittance Transport

- Calculations of the effects of coherent synchrotron radiation on the CLIC bunch compressors must be performed.

Machine-Detector Interface

- An extraction line design for 3 TeV c.m. must be developed.

Items Common to All Machines

Luminosity

Damping Rings

- For all the damping ring designs, further simulation studies are needed to understand the magnitude of the electron cloud effects and to explore possible means of suppressing these effects. Experiments in existing rings are needed to test the electron cloud simulations. Possible cures for the electron cloud (including chamber coatings, superimposed magnetic fields, and gaps in the bunch pattern) need to be experimentally investigated.
- Further simulations of the fast ion instability are also necessary. Experiments in the ATF and other suitable rings are needed to test the predictions of these simulations.
- Damping ring extraction kicker stability, required at the level of $<10^{-3}$, is an important issue. Continued studies including experiments with the ATF double kicker system are needed.

- Finally, additional simulations of emittance correction in the damping rings are needed, including the effects listed in Section 7.2.3.2. Additional experiments in the ATF and other operating rings are needed to test the emittance correction algorithms.

Low Emittance Transport

- For all low emittance transport designs, the static tuning studies, including dynamic effects during correction, must be completed.
- The most critical beam instrumentation, including the intra-train luminosity monitor, must be developed, and an acceptable laser-wire profile monitor must be provided where needed in each design. A vigorous R&D program is mandatory for beam instrumentation in general; it would be appropriate for a collaborative effort between laboratories.
- A sufficiently detailed prototype of the main linac module (girder or cryomodule with quadrupole) must be developed to provide information about on-girder sources of vibration.

Reliability

- A detailed evaluation of critical subsystem reliability is needed to demonstrate that adequate redundancy is provided and that the assumed failure rate of individual components has been achieved.
- The performance of beam based tuning procedures to align magnets and structures must be demonstrated by complete simulations, in the presence of a wide variety of errors, both in the beam and in the components.

9.3 RANKING 3

TESLA

Energy

- Improvement of the low level rf system design is needed. This system is quite complicated and critical, with many functions (field control, feedback, piezo feedforward, interlocks, fault management) and requires very specialized expertise.
- There must be a long-term testing of rf cryomodules to precisely evaluate potential weaknesses before large scale series production begins.
- Long-term testing of the multibeam klystrons is required to quantify their life-time and MTBF.
- The dark currents at the nominal operating field should be precisely evaluated.
- For the TESLA upgrade to 800 GeV c.m., besides the obvious gradient increase to 35 MV/m (Ranking 1), the capability of rf components (circulators, phase shifters, *etc.*) to handle a higher rf power must be demonstrated.

- In addition the proposed superstructures should be tested at their nominal gradient, with final HOM dampers and with higher power rf couplers.

Luminosity

Damping Rings

- A calculation of the effect of collective instabilities on the closure of the coupling bump in the damping rings should be made to determine whether a problem exists.

Machine-Detector Interface

- If the head-on scheme is maintained, then electrostatic separator performance (gradient 50 kV/cm) and a viable extraction septum design must be demonstrated in the presence of realistic radiation/power losses at 500 GeV c.m.
- The impact of shower debris produced in the secondary-collimation system on halo-induced synchrotron-radiation backgrounds, as well as the background impact of charged secondaries produced by halo particles hitting the FD, must be studied.
- The interplay of incoming-beam SR masking versus outgoing-SR stay-clear must be studied.
- The possibility of incorporating some form of FD stabilization in the baseline design should be investigated, to anticipate unexpectedly large vibration problems.
- The predicted extraction line losses at 800 GeV c.m. must be reduced from their currently unacceptably high levels.
- A collimator and masking configuration must be designed to be compatible with tolerable muon-backgrounds and SR-backgrounds at 800 GeV c.m.
- If the head-on scheme is maintained, then electrostatic separator performance (gradient 80 kV/cm) and a viable extraction septum design must be demonstrated in the presence of realistic radiation/power losses, at 800 GeV c.m.

Reliability

- The proposed undulator-based positron source for TESLA requires an electron beam before there can be a positron beam. This affects recovery scenarios as well as commissioning. TESLA needs to evaluate the operational impact of coupled electron/positron production.
- The 2.5 km segmentation of the TESLA cryogenic system is a concern because of the time required for warm up and cool down. The vacuum system size and segmentation is also an issue. The TESLA cryogenic and vacuum systems segmentation should be re-evaluated.
- TESLA needs a detailed analysis of the operational impact of structure faults.

JLC-C

Energy

- The low level rf system of JLC-C is unique because of the amplitude modulation needed to compensate the dispersion in the pulse compressor. This system is critical, as for the other machines, and requires an improved detailed design.
- Long-term testing of klystrons and modulators is needed to evaluate the life time of these components. Long-term testing of the linac modules is also needed to diagnose possible faults, before a large scale series production can start.

JLC-X/NLC

Energy

- The Low level rf system for JLC-X/NLC needs further improvements, notably to handle recovery scenarios in case of cavity trips or rf faults. Again, this is a complex and critical system, demanding very specialized expertise.
- Long-term testing of rf modules is required, before mass production.
- The continuation of the R&D to develop the NLC PPM klystron is recommended. This is to provide a second design and very likely to improve the overall reliability of klystrons.
- The development of the JLC-X linear induction modulator should continue, again to explore slightly different technical implementations and to improve overall performance and reliability.
- The test recommended in Section 9.2 should be extended to a full test, with beam, of a complete linac unit, with 24 structures and 8 klystrons.
- The studies of the cathode charge limit, using the E158 beam at SLAC, should be continued.
- Studies of conventional positron target performance are also needed. This item and the preceding one apply as well to CLIC.

Luminosity

Damping Rings

- For the JLC-X/NLC damping rings, particle loss simulations, systematic and random multipole errors, and random wiggler errors, must be included. Further dynamic aperture optimization of the rings is also needed.
- Further experiments at the ATF and other low-emittance damping rings are necessary to determine the validity of the theoretical models of IBS.

Low Emittance Transport

- In the low emittance transport, the magnetic center stability (at the 1–10 μm level) required in the quadrupoles must be demonstrated, over the relevant time scales of minutes to days.

Machine-Detector Interface

- Stabilization of the final-quadrupole doublet must be demonstrated in an environment that adequately reproduces the system constraints of an actual detector and IR.
- The predicted extraction line losses at 1 TeV must be reduced from their currently unacceptably high levels.
- It must be demonstrated that muon and synchrotron-radiation induced backgrounds are tolerable at 1 TeV.

Reliability

- For JLC-X/NLC, there is a need to evaluate the impact on operations of the interleaved positron target system.
- For the linacs of the warm rf machines, the tuning procedures require structure alignment as well as quadrupole centering. For JLC-X/NLC, there is a need to evaluate the systems aspects of a large interrelated alignment system. This item also applies to CLIC.

CLIC

Energy

Because the CLIC project is less advanced than the others, the Ranking 3 and Ranking 4 R&D items were not really discussed in detail and the list here is not believed to be complete.

- However, the control of the accelerating field in CLIC, and the necessary Low Level rf system, are unique to this kind of machine. A detailed design of the LLRF system in CLIC is certainly needed. It must be able to correct for beam loading, to handle rf and beam faults and be intimately connected with the drive beam protection system.
- A more efficient type of modulator should be studied, especially for the upgrade to 3 TeV.

Luminosity

Machine-Detector Interface

- For the 500 GeV c.m. design, an extraction line design for the spent beam must be developed.
- Stabilization of the final-quadrupole doublet must be demonstrated in an environment that adequately reproduces the *system* constraints of an actual detector and IR. The performance specifications are about two times tighter than those of JLC-X/NLC.
- It must be demonstrated that muon- and synchrotron-radiation induced backgrounds are tolerable at 500 GeV.

- At 3 TeV c.m. energy, beam-beam backgrounds increase by large factors, including the appearance of coherently produced pairs. The interaction region and detector optimization is more difficult than for 500–1000 GeV operation, so continuation of these studies is important. Similar comments apply to the design of the collimation scheme and the minimization of synchrotron-radiation backgrounds.

Reliability

- A variety of common mode problems can arise due to the fact that faults in the CLIC drive beam complex affect the whole acceleration chain of the main linac. CLIC needs to evaluate the impact of drive beam faults on reliability, stability and operations of the linac.

Items Common to All Machines

Energy

- Improvement (for TESLA), or development (JLC-X/NLC, CLIC) of the source laser are needed, to improve its stability. This is particularly critical for the CLIC drive beam and should be addressed in the CTF3 program.
- A detailed layout up to the damping rings must be used to precisely evaluate the intensity overhead, the location of beam losses, the longitudinal emittance, and the positron beam stability.
- The demonstration of beam-based structure alignment is needed to finalize the tolerance specifications and make sure that they are matched to the system analysis and procedures.
- Tracking simulations of polarized sources should be carried out.

Luminosity

Damping Rings

- For all the damping ring designs, detailed reviews of the impedance budgets are needed.
- Development of BPMs with < 0.5–1 micron resolution and excellent stability (approximately 10 microns over 1 day) is necessary. The development of fast, high resolution beam size diagnostics for the damping rings must be continued.

Low Emittance Transport

- In the low emittance transport systems, the technical noise level present in the beamline, due to klystrons, pumps, and other sources which are necessarily close to the accelerator, must be estimated.
- Collimator wakefield measurements must be performed. In the event that the wakes turn out to be as large as presently anticipated, other solutions must be investigated for the beam halo problem, which would permit relaxation of the collimation aperture, and the experimental validation of the tail-folding scheme will be necessary.

- The BPMs required for emittance preservation in the low emittance transport, and for operation of the beam-beam collision feedback, must be developed.
- The detailed tolerances for fast vibration, magnet strength stability, rf stability, *etc.*, must be computed, and it must be verified that static tuning of the low emittance transport will converge in the presence of these dynamic errors.
- The robustness of emittance tuning algorithms in the presence of malfunctioning BPMs, correctors, and element translation stages must be estimated.
- The likely cultural noise at prospective LC sites must be characterized.
- The pre-collimation systems which are intended for use between the damping ring extraction and the low emittance transport must be designed.
- Electron and ion effects in the low emittance transport should be estimated.
- The demonstration of mechanical alignment techniques to be used in the low emittance transport prior to commissioning, which are already well advanced in some studies, must be continued.
- Calculations of the multibunch wakefield effects in the pre-linac and bunch compressor regions must be completed.

Machine-Detector Interface

- A detailed model of synchrotron radiation backgrounds (core + halo) in the interaction region (inboard of the final bends), that includes backscattering and tip scattering off masks and IR vacuum pipe surfaces, must be developed.
- For an IP with crossing angle, vigorous development of compact SC quadrupoles with adequate vibration characteristics must be pursued, the capability of IP feedback to cope with field fluctuations due to thermal effects in PM quads must be evaluated, and R&D on adjustable PM quads must be pursued.
- The mechanical stability of the solenoid coil and/or iron yoke, which is required to have vibration levels in the micron range, must be evaluated.
- Background-simulation tools for better tracking of both primary and secondary particles must be improved, and the models of the machines (including a study of "tuned" imperfect machines) and their environment (*e.g.*, tunnel layout, muon spoilers) must be refined.
- Beam polarization and energy diagnostics with sufficient precision to meet particle physics requirements must be developed.

Reliability

- A detailed Machine Protection System design that meets requirements must be developed, including a careful study of failure modes.
- A comprehensive assessment of the MTBF and MTBO for rf components is required, and an adequate fraction of hot spares must be included in the final design.
- A comprehensive reevaluation of design parameter overheads throughout the complex is required.

- A comprehensive evaluation of the frequency and impact of tunnel access is needed.
- A model for communications and controls with adequate reliability must be developed.

9.4 RANKING 4

TESLA

Energy

- The understanding of the gradient limits with electropolished cavities is of great importance for TESLA, especially for the 800 GeV upgrade. Studies must continue in this direction, in a collaborative effort with other institutions and universities.
- Several alternative and/or complementary solutions are proposed for the TESLA rf distribution system. They should be tested and evaluated in the long term.

Luminosity

Damping Rings

- A correction algorithm for the TESLA damping rings, including both vertical and horizontal planes, is needed.

Low Emittance Transport

- The implications of reducing the value of D_y for TESLA should be studied, in the event that such a reduction is desired in order to ease the tolerances on the "banana" instability.

Machine-Detector Interface

- If placing beam polarization and energy diagnostics in the spent-beam extraction line eventually proves necessary, then the radiation levels in the present extraction line must be reduced by at least an order of magnitude.

JLC-C

Energy

- The proposed C-band klystrons are solenoid-focused. The development of a C-band PPM klystron and the development of a new modulator are recommended.

JLC-X/NLC

Energy

- Physics studies dedicated to the fundamental understanding of high gradient limits in accelerator structures are highly recommended. This obviously represents a joint effort between laboratories. The various experimental results already obtained under different conditions must be expanded and confronted with the simulations or theoretical expectations, to the extent that they exist.
- Further studies of standing-wave structures are recommended.
- For the energy upgrade, the studies of higher gradient structures could be particularly beneficial. These studies would benefit from a better understanding of the fundamental mechanisms of rf breakdown recommended above for all room-temperature structures.
- The initially proposed DLDS systems are to be reconsidered for the energy upgrade, as they offer a higher efficiency. Further studies on DLDS systems are recommended.

Luminosity

Low Emittance Transport

- The feasibility of an intra-train feedback which operates within the short time required should be demonstrated.(This also applies to CLIC).

CLIC

There are no Ranking 4 items for CLIC.

Items Common to All Machines

Energy

- All designs would benefit from a better understanding of the undulator-based positron production scheme. The SLAC study of an undulator-based polarized positron source should be carried out, possibly in collaboration with other laboratories.
- The studies of polarized rf photocathode guns should be encouraged.
- The ATF study of a Compton-based polarized positron source should be supported.

Luminosity

Damping Rings

- Additional experiments in the ATF and other operating rings are needed to verify that beam-based alignment can be used to align BPMs with respect to their associated quadrupole and sextupole magnets within a few microns, and to study drifts and systematic errors in the BPMs.

Low Emittance Transport

- Further simulations and studies of the formation of beam halo, and the impact of dark current, in the low emittance transport should be performed.

Machine-Detector Interface

- The detector implications of the proposed final doublet support and stabilization schemes should be investigated.
- The impact of dynamic errors on beam-beam backgrounds should be studied.