SLAC–PUB–7768
March 1998

e^-e^- Collisions in a TeV Collider Built for e^+e^- Operation[*]

R. Erickson

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

Abstract

In this paper, we discuss practical issues that must be addressed to reconfigure an e^+e^- linear collider for e^-e^- operation and argue that modest steps should be taken during the design stage to preserve this option.

Invited talk presented at
2nd International Workshop on Electron-Electron Interactions at TeV Energies (e^-e^-97)
Santa Cruz, CA
22-24 September 1997

---

[*] Work supported by Department of Energy contract DE–AC03–76SF00515.

e^-e^- COLLISIONS IN A TeV LINEAR COLLIDER BUILT FOR e^+e^- OPERATION

R. ERICKSON*
Stanford Linear Accelerator Center
Stanford, CA 94309, USA

In this paper, we discuss practical issues that must be addressed to reconfigure an e^+e^- linear collider for e^-e^- operation and argue that modest steps should be taken during the design stage to preserve this option.

1. Optimism for e^-e^- Collisions in a Linear Collider

Design studies for a TeV-scale linear collider are progressing at several laboratories around the world. While most of the effort has been directed toward positron-electron collisions, the option of colliding electrons with electrons has attracted the interest of a small but enthusiastic segment of the high energy physics community.[1] The likelihood of realizing this possibility will be much improved if a few practical issues are addressed during the design of the collider.

The Interlaboratory Collaboration for R&D Towards TeV-scale Electron-Positron Linear Colliders, a group representing most of the major laboratories involved in linear collider development, included an enticing observation in its 1995 report:[2]

> *Since the e^-e^- collider requires only minor changes to the hardware of the e^+e^- machine and detector, its programme could be pursued during the first phase of the facility...*

Implicit in this statement is the assumption that a second electron beam can be accelerated and steered to the interaction point using the linac and associated beam delivery system designed for the positron beam. Producing a high energy electron beam with the positron linac should, in principle, require little more than retracting or bypassing the positron production target, reversing the polarities of some critical bending and focusing magnets, and shifting the RF phase by 180 degrees. Similar statements had encouraged proponents of e^-e^- physics in the early 1980's when plans for the SLAC Linear Collider were forming.

2. The e^-e^- Option at the SLAC Linear Collider

The possibility of operating the SLAC Linear Collider in an e^-e^- mode was seen as interesting and relatively straightforward from the earliest days of the conceptual

---

*This work was supported by U.S. Department of Energy contract DE-AC03-76SF00515.

design. In 1982, a year before the start of construction, a workshop[3] on experimental use of the SLC included a study of e^-e^- physics prospects. The e^-e^- mode was anticipated to be a minor perturbation to the cost and operation of the SLC:

> *It is estimated that this [e^-e^-] option will cost $600,000. Additionally, time is not necessarily taken from the e^+e^- program. Time slots for e^-e^- will occur during periods of e^+ down time.*

The idea was that the SLC linac could accelerate two bunches of electrons, rather than one each of electrons and positrons, without any major changes to the hardware. The polarities of the magnets in the south arc and south final focus systems could be reversed to transport electrons to the interaction point. The only significant hardware changes would be the addition of some new devices in the Beam Switchyard to separate same-sign electron bunches from the linac into the two arcs, and some changes to the dump lines for the spent beams.

Despite this early optimism, e^-e^- collisions have never been attempted at the SLC, even though it has been in operation for about ten years. The most obvious explanation is that the physics community has been more interested in running in the e^+e^- mode to study the production and decay of Z^0 particles. The cross section for Z^0 production in e^+e^- annihilation is much larger than the cross sections expected for the processes accessible through e^-e^- collisions. The arguments for dedicating machine time to e^-e^- collisions have not been sufficiently compelling to warrant an interruption to the Z^0 program.

This argument by itself, however, is not completely convincing. If operation in the e^-e^- mode were as easy as the quotations above imply, time surely would have been found to exercise this mode, at least long enough to understand the accelerator implications and perhaps to carry out a minimal survey of the physics.

The first technical challenge in modifying the SLC to collide particles of the same charge would be to develop a method for separating the two bunches at the entrances to the arcs. A large dc magnet that symmetrically deflects the electrons and positrons apart in normal SLC operation would have to be replaced with a more sophisticated system, consisting perhaps of a fast bipolar kicker magnet or an RF separator, followed by a current-sheet septum magnet. This would have required a substantial development effort. Fortunately, this is not an issue for a TeV linear collider with two independent linacs.

The other technical challenge would arise in the final focus area. The SLC final focus system has an “S-bend” geometry, meaning that both the incoming electron beam and the incoming positron beam bend to the right as they approach the interaction point. After passing through the interaction point, the outgoing beams follow the same trajectories through which the opposing beams approached. Kicker magnets located some 350 feet from the interaction point on each side kick the outgoing beams off this path and into an array of septum magnets which further deflect the outgoing beams down special dump lines (equipped with spectrometer magnets and associated detector apparatus) and into massive, water-cooled aluminum dumps in heavily shielded alcoves.

Reversing the polarities of all the magnets in the south final focus system to transport an incoming electron beam would fundamentally change the way the outgoing beams are handled. Specifically, the outgoing electron beam from the north, upon reaching the first bend magnet in the south tunnel would be deflected to the west, away from the trajectory of the incoming beam, and into the aisle, rather than to the east along the incoming beam path. Similarly, the outgoing beam from the south, upon reaching the first bend magnet in the north tunnel, would be deflected to the east, toward the wall. With the existing hardware in place, the outgoing beam on each side would collide with the coils of a quadrupole magnet several inches off center. To provide a clear path for the outgoing beams, several magnets would have to be replaced with special designs that provided a passage for a new off-axis dump-line vacuum chamber on each side of the interaction region.

The next challenge would be to transport the beams to safe, well-shielded dumps. Two possible approaches were considered. New dumps could have been constructed on the new outgoing beam trajectories. This would have required excavations of new alcoves and construction of new concrete walls, as well as the fabrication and installation of the dumps themselves and their associated cooling systems and diagnostic equipment. Another possibility would have been to build transport lines that would snake through the tunnels near the incoming beam lines to carry the outgoing beams to the existing dumps. This option would also require excavation work in the north tunnel to make room for the new transport line.

The possibility of modifying the SLC for e^-e^- collisions was reexamined in 1995. Only a cursory study was done,[4] and no detailed engineering estimates were made; however, it was evident that the cost would be upwards of 10 million dollars, and the downtime necessary to make the modifications would be more than six months.

The hardware requirements were not the only obstacles to an e^-e^- program at the SLC. The suggestion that the e^-e^- mode could be exercised during periods of e^+ down time was, in retrospect, also unrealistic. During the years of SLC operation, there have been many times when positrons were unavailable, either because of malfunctions in the positron production system or other associated equipment. When these malfunctions have occurred, the laboratory response has invariably been to mobilize the resources needed to restore the system to operation as quickly as possible. The time needed to repair a positron-related problem can be anywhere between a few minutes and a few hours, but is almost always much less than the time that would likely be needed to tune up the machine for an unusual mode of operation. Breakdowns in the positron system that have required more than a day to repair have occurred only a few times in ten years. A viable e^-e^- program could not be planned around such infrequent events.

In summary, the SLC has never been operated in the e^-e^- mode, because the hardware was not designed to easily accommodate a conversion to this mode, and the physics motivations have not been convincing enough to justify a long-term dedicated program.

3. Modifying a TeV-scale Collider for e^-e^- Collisions

The technical details involved in switching a TeV-scale e^+e^- collider to an e^-e^- mode may be somewhat different from those of the SLC, but the real obstacles to doing this could turn out to be the same. Specifically, an e^-e^- upgrade project might never get started if the modifications require a lengthy downtime or substantial cost after the e^+e^- program is underway. These issues do not arise from fundamental limitations, but rather from practical difficulties for which technical solutions can be found. Careful attention to these details during the design stage will greatly simply the conversion to the e^-e^- mode at a later time. Some of these details are listed below, grouped according to the stage at which they should be considered.

3.1. *Planning for e^-e^- in the Conceptual Design Stage*

Any final focus design is likely to include quadrupole magnets, and possibly dipoles or other magnetic elements, close to the interaction point. These are needed to focus and steer the incoming beams into collision. Depending on the crossing angle and other design details, the outgoing beams may pass through some of these elements as they are transported out of the interaction region to the beam dumps. If the final focus system is designed with a crossing angle large enough that the outgoing beams never pass through a dipole field seen by an incoming beam, then the same dump line geometry can be used for beams of either polarity. On the other hand, if the final focus system uses any magnets that bend both the incoming and outgoing beams, the outgoing electron beam will not follow the same trajectory as the incoming electron beam, but will be deflected away from it. To ensure that this does not create an unnecessary obstacle to a later e^-e^- upgrade, the layout of the accelerator housing and utilities should reserve space for new or modified dump lines. Similarly, the dump lines on both sides of the interaction point should be designed with enough space to accommodate Compton polarimeters or other polarization-measuring apparatus, even though a polarized positron beam may not be envisioned.

If the crossing angle is small enough that the incoming and outgoing beams pass through the same focusing elements, then the envelopes of the outgoing electron beams will be different from those of the e^+e^- arrangement. This comes about because the magnet polarities will have been reversed on one side of the interaction point, while the charge of the outgoing beam will have been switched on the other side. This could have implications for the choice of beamline apertures and the design of diagnostic instrumentation.

3.2. *Optical Design Considerations to Minimize the Impact of a Polarity Reversal*

If the polarities of all the magnets in the positron linac and beam delivery system are reversed, electrons will be transported with the same trajectories and optical properties as intended for the positron design. Reversing all the polarities would entail cabling changes for hundreds, or perhaps thousands, of magnet circuits, but an easier method involving far fewer magnet reversals could almost certainly be found. The quadrupole lattice running the length of the positron linac will work as well for electrons as for positrons, but with the vertical and horizontal beam profiles interchanged. Matching this lattice into the next section of the beam delivery system may be a matter of changing a few quadrupole strengths appropriately, or of adding one or more quadrupoles. Before the final e^+e^- optical design is chosen, the implications for e^-e^- operation should be considered, with the goal of minimizing the number of magnets that must be reversed.

In a few special cases, reversing the polarity of a magnet might introduce unusual complications. For example, a magnet with two apertures might be used near the interaction point where the incoming and outgoing beam trajectories are too close together for separate side-by-side magnets. Such a magnet might have separate apertures for the incoming and outgoing beams, but be powered with a single electrical circuit in such a way that the polarity of one section can not be changed without changing the other. With this constraint, it may be difficult to find satisfactory optical configurations for both the incoming and outgoing beams when the charge of one beam is reversed. Attention to this and other optical configuration issues during the design stage could prevent the introduction of features that needlessly preclude a later e^-e^- option.

3.3. *Engineering Design to Simplify the Switch to e^-e^-*

Remotely controllable polarity-reversing switches for a large number of magnet power supply systems would entail costs and complexity that are difficult to justify unless frequent switching between the two operating modes were envisioned, a possibility that seems highly unlikely. The polarity reversal is likely to require changing DC cable connections for upwards of a hundred circuits, even with an optical system optimized to simplify this procedure. In a well-constructed accelerator installation, the cables, which may be heavy and relatively inflexible, are routed neatly and directly to their termination points. If such cables are installed without regard for a possible polarity reversal, then implementing the changes later may be tedious and difficult. Some cables may require extensions to reach the opposite-polarity power supply or magnet terminal. While this issue may be inconsequential for a small accelerator facility, the time needed to make the switch might be measured in weeks for a linear collider facility. Some minimal consideration for this issue when planning power supply locations, cable routing arrangements, and cable termination details could greatly simplify later polarity reversals.

A TeV-scale linear collider might use permanent magnets in a few critical locations. Permanent magnets are compact, dissipate no power, and have been used successfully to facilitate beam focusing close to the interaction point inside large detectors at several high energy accelerator facilities. The polarities of permanent magnet assemblies can be reversed by rolling them around the beam axis by an appropriate angle: 180 degrees for dipoles, 90 degrees for quadrupoles, or 60 degrees for sextupoles. Reorienting a permanent magnet assembly deep inside a large detector could require dismantling and reassembling major elements of the detector. With a suitably designed mounting fixture, however, a magnet of this kind can be rolled and realigned with minimal effort, even if it is inaccessible to hands-on adjustments.

A TeV collider is likely to employ a variety of other special magnetic elements, including kicker magnets and magnets that must operate within the fields of other magnets. While it may be impractical to design every special device for dual polarity operation, some consideration of these issues during the design stage will reduce the effort needed later to handle an opposite polarity beam.

3.4. *Magnetic Measurements for Both Polarities*

Proper operation of all the magnets in a linear collider must be verified before they are installed, and in many cases, the magnetic field strengths must be calibrated to an accuracy on the order of 10^{-4}. Achieving this level of accuracy typically requires a series of careful field measurements and a well-defined operating procedure. Most of the DC magnets will undergo a characterization process in which they are individually set up, tested, and measured. Through this process, a standardization cycle and set of calibration constants will be established for each one. This process would normally be done only for the polarity in which the magnet is expected to be operated, but will involve moving the magnet several times, perhaps from a fabrication facility to a test stand, from there to a magnetic measurement shop, and finally to the accelerator housing, possibly with intermediate stops at staging areas. When a magnet arrives in the measurement shop, electrical cables and cooling water hoses must be connected and magnetic measurement apparatus must be set up. When the hardware is in place and the power supply is turned on, a standardization cycle must be established and the final magnetic measurement data collected. The additional effort required to characterize the opposite polarity of a magnet at this point is relatively small. Establishing a standardization cycle and set of calibration constants for both polarities of critical magnets from the outset will make it unnecessary to disturb them later when the e^-e^- option is implemented.

4. Conclusion

In this paper, we have discussed some of the issues that must be considered in order to provide a capability for electron-electron collisions in a linear collider built primarily for e^+e^- physics. Among these are issues that should be considered in the conceptual design, engineering, and construction stages, even if all the hardware requirements for the e^-e^- mode are not included in the initial construction project. Many arbitrary design choices must be made in building a TeV linear collider, and some of these could introduce needless complications for a subsequent upgrade to add an e^-e^- mode. If some minimal effort is invested in addressing these issues from the beginning of the project, then upgrading the collider for e^-e^- collisions at a later time will be greatly simplified.

Acknowledgments

I would like to acknowledge C. Heusch for encouraging me to write up this talk and for his tenacity in promoting the e^-e^- concept.

References

1. See, for example, the various contributions to these proceedings.
2. *International Linear Collider Technical Review Committee Report*, G. Loew, editor, SLAC-R-95-471 (1995).
3. *Proceedings of the SLC Workshop on Experimental Use of the SLAC Linear Collider*, SLAC-247, March 1982.
4. R. Erickson, *Int. J. Mod. Phys.* **A11**, 1693-1697 (1996).