Required Construction for E163

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> **EPAC Comment #5: "Developing the rf gun and delivering the high-quality beam will take an extensive R&D effort. The proposal does not indicate how this will be achieved."**

Response:

The photoinjector proposed for use in this experiment is essentially identical to several operating S-band photoinjectors. Importantly, the required beam performance is *significantly less* than that proposed for more demanding projects like the Linac Coherent Light Source at SLAC where nano-Coulomb bunches of 1 mm-mrad emittance are needed. E163 only requires a 50 pC bunch with an emittance of about 2 by 9 mm-mrad from the photoinjector, while the once-per-week NLC cavity phase-shift tests require a roughly 1 nC bunch but with an emittance in the 10 to 100 mm-mrad range. These values are readily achievable by present photoinjectors. With the well-established design, no R&D is anticipated. There is substantial technical experience within the collaboration and at SLAC for delivering high quality electron beams. Two E163 collaborators (E.R. Colby, D.T. Palmer (SLAC)), along with J. Rosenzweig (UCLA), who is fabricating the rf gun, have designed, fabricated and commissioned five similar photoinjectors. E163 members regularly consult with colleagues at SLAC on problems of common interest such as low phase-noise master oscillators, electron beam and laser diagnostics, and reducing amplitude and timing jitter in lasers.

The E163 photoinjector design is basically the same as in the proposed ORION Facility for Advanced Accelerator Research at NLCTA. This design was based on the S-band Next Generation Photoinjector (NGP)[1] and is employed at the majority of photoinjector labs now in existence, including the BNL Accelerator Test Facility (ATF), Neptune at UCLA, the Argonne APS-LEUTL, the DUV-FEL at BNL, the Gun Test Facility at SSRL/SLAC, and several labs in Japan. Several years of operational experience now exist with this device. The NGP, which was developed originally as an ultra-low emittance injector for advanced light sources and advanced accelerator research, is comprised of a 1.6 cell S-band (2.856 GHz), π-mode standing-wave gun along with a single emittance-compensation solenoid magnet (Figure 1). The E163 photoinjector, its UV drive laser, and the S-band rf system are specified for a 10 Hz repetition rate and a three microsecond rf pulse length.

Several variations of this photoinjector at S-band have been built which yield a bunch population and emittance similar to those required for NLC cavity tests, as well as the much-relaxed bunch charge for E163. Recently small energy spreads of about 10^{-4}, as needed for E163, have been demonstrated at the DUV-FEL photoinjector.[2] Based on performance history, an S-band photoinjector design, optimized for minimum emittance at a bunch charge of 0.25 nC (1.6×10^{9} electrons), and adjustable up to a nominal maximum of 1 nC, was chosen as the baseline for the proposed ORION photoinjector. J. Rosenzweig and D.T. Palmer jointly performed the beam physics design for the ORION gun. The only modification for E163 relative to the ORION design has been the adoption of a magnesium cathode (versus copper), which has been demonstrated in successful operation at the BNL-ATF and Argonne APS-LEUTL for four years. The quantum efficiency of magnesium (5×10^{-4} or better) will produce bunch charges of 1 nC with only about 10 micro-Joule of UV laser light. This will meet the NLCTA bunch charge requirement, while at the same time allowing a cost savings through the purchase of a lower energy laser amplifier.

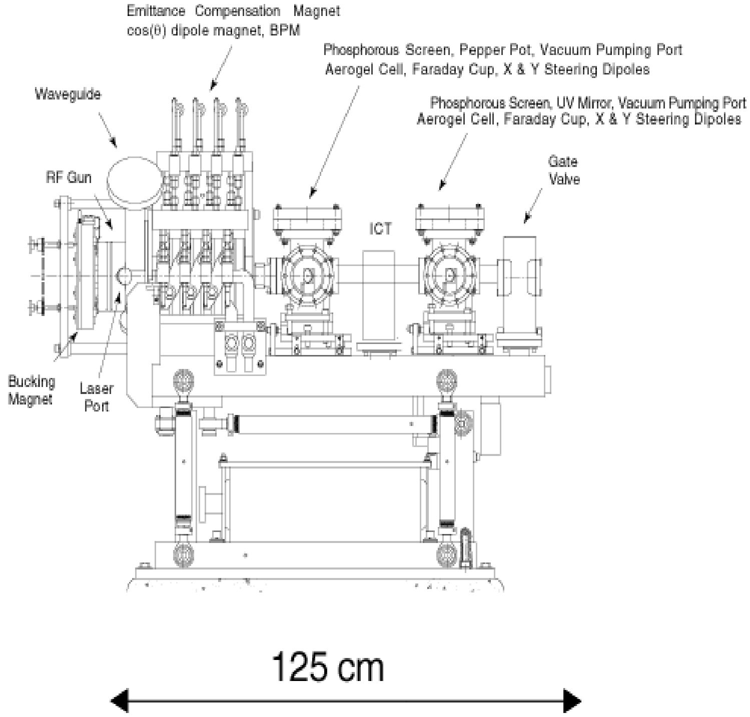

FIGURE 1. Schematic diagram of the E163 S-band, 1.6 cell photoinjector with emittance-compensation solenoid and diagnostics section.

The electrical and mechanical fabrication techniques for the S-band rf photoinjector are well understood. The vacuum properties of this photoinjector type have operationally been very good with demonstrated pressures of 1×10^{-9} torr under rf power. The S-band photoinjector operates in the $TM_{010,\pi}$ -mode and is tuned to be resonant with the 2.856 GHz rf system. The rf gun for E163 is electrically the same as the 1.6 cell photoinjector that is presently operating at the BNL Accelerator Test Facility, although it differs in a few mechanical details. The cathode/half cell vacuum joint is a 6 inch OD, rotatable stainless steel conflat knife-edge flange. Continuity of the rf current paths is satisfied using press fit point-to-point contact between the half cell OD surface and the cathode plate edge. The edge of the cathode plate is Ti:N coated to facilitate cathode plate removal after high-temperature bake-out. This arrangement allows for cathode inserts made of different materials to be retrofitted to the plate. The laser pulse for photoemission may be introduced either through a port at 72 ^{o} or using a nearly normal incidence mirror in the first cross downstream of the gun, and will illuminate the magnesium cathode. The first cross, and the cross that follow it, are equipped with diagnostics for electron beam charge, position, transverse and longitudinal profile, and emittance (via pepper pot), permitting setup and diagnosis of the gun. Beam position and bunch charge are measured with non-intercepting diagnostics and will be available at all times.

Delivering the high quality beams needed for the experiment will require instrumentation specific to the task, and a period of learning how to tune the machine correctly. The small energy spread ($5x10^{-4}$) and short bunches (0.9 ps FWHM) will require high resolution spectrometry and bunch length measurement capability to ensure that the gun and linac phases are set correctly, and that the chicane and extraction dogleg dispersions (temporal and spatial) have been cancelled. Streak camera measurements of beam-induced Cerenkov radiation in an aerojel radiator will be used to determine pulse lengths after the extraction dogleg to ensure the chicane and dogleg have been tuned isochronously. Initial tuning of the E163 beamline will take place at higher charge (~1 nC) for ease of diagnosis, and to establish magnet settings for the NLCTA RF testing program. Once this operating point is established, charge and pulse length will be reduced gradually and the beamline tuned until the E163 requirements are approached, and will conclude with the setting of the energy collimator. Finally, the E163 experimental beamline will use the very high-resolution spectrometer ($dE/E \sim 10^{-5}$) presently in use for the LEAP experiment for conducting the experimental measurements.

EPAC Comment #7: “The modifications to the NLC Test Accelerator are extensive. It would seem appropriate to detail these changes in much greater detail.”

Response:

A number of changes and additions are necessary at NLCTA to carry out the E163 laser acceleration experiment. Most of these changes are similar to those previously studied in significant detail for the proposed ORION Facility for Advanced Accelerator Research. The NLCTA changes for ORION were described in the draft ORION Technical Design Study of 2 February 2001, a copy of which is attached. That document was a snap shot of work in progress for the 2001 NSF “Physics Frontiers Center” funding request. Naturally, our approach to NLCTA modifications needed for E163 has evolved from the early ORION study. *The scope of NLCTA changes has been reduced to only those necessary to enable the E163 laser acceleration and the nominally once-per-week delivery of 1 nC single bunches for NLC cavity tests.* A natural outcome of E163 will be that most of the technical investment at NLCTA will be applicable to a future ORION facility. Figure 1 illustrates the proposed layout of E163 at End Station B. The essential NLCTA modifications for E163 and how they differ from ORION are:

- Installation of an rf photoinjector to replace the existing thermionic source. The thermionic source and its mounting will be disassembled as a unit, and stored under high vacuum for potential future use.
- Installation of an S-band rf system and UV laser for photoinjector operation.
- Construction of a 600 square-foot shielded experimental enclosure and a 500 square-foot laser room to house the drive laser. This civil construction is greatly reduced from ORION in which two experimental halls and two laser rooms are planned.
- A control system for the photoinjector, laser, and rf system to be integrated into the NLCTA EPICS control system. To reduce costs, controls for E163 apparatus not in the NLCTA beamline proper will not be integrated but only connected to the data-acquisition trailer.
- A utility upgrade at ESB for an added 66 kW of electrical power and 130 GPM of cooling water. This is about one-third less than a complete ORION facility since most utilities are used by the photoinjector, laser and rf systems.

Civil modifications of the NLCTA enclosure are modest. Two 6-inch diameter holes will be bored straight through the north wall at about ceiling height to transport the UV laser light to the photoinjector and to return the Cerenkov diagnostic light. Standard penetrations for the S-band waveguide and signal cables to the photoinjector will be bored at the west end of the NLCTA enclosure. A roughly 6-inch diameter hole will be bored on the north wall of NLCTA to permit the 25-degree angle extraction of the 60 MeV beam for the experiment. A few cables and LCW pipes will have to replumbed on the inner NLCTA wall to allow drilling and passage of this beam hole.

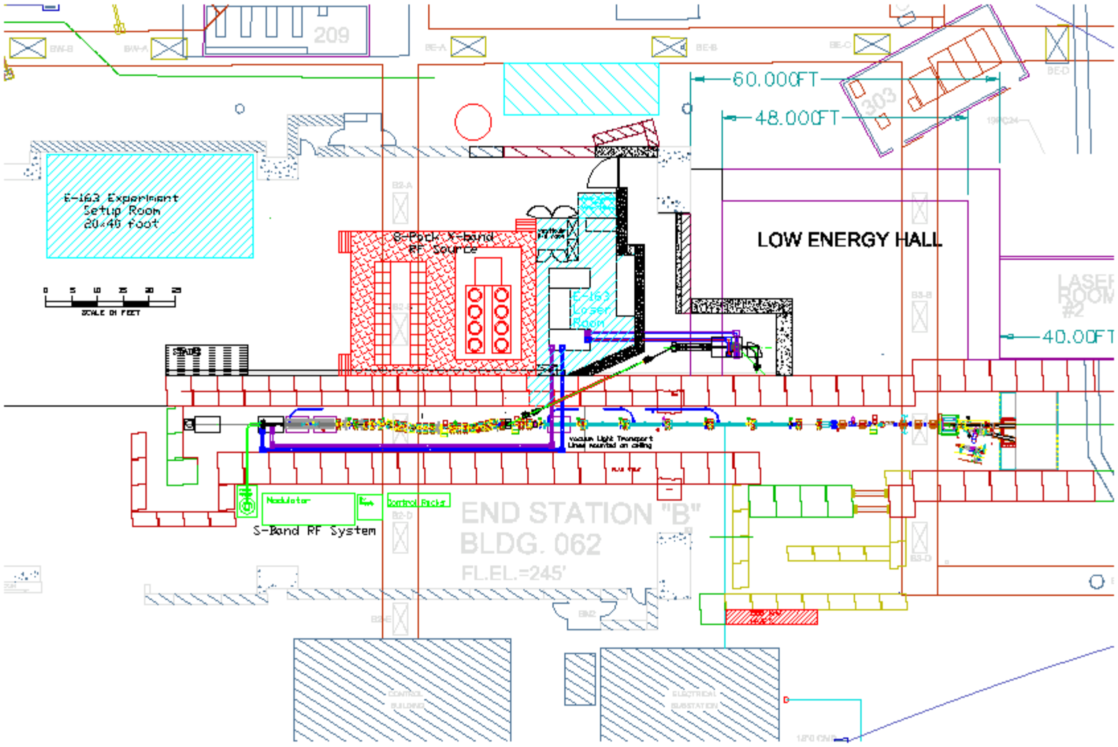

FIGURE 1: Layout of E163 at the NLCTA in End Station B. The E163 laser room and shielding enclosure are on the eastern floor area of ESB. The laser room is flanked on the west by the NLC 8-Pack RF Station (red). The S-band rf system (green) sits along the southern wall of the NLCTA enclosure. Evacuated light pipes run from the laser room to the photoinjector and to the experiment. The data-acquisition trailer will sit outside ESB along the north wall.

The NLCTA injector, with the introduction of a new S-band photoinjector, will be used to provide high quality electron beams for the E163 experiments. The rf gun was described in the Response to Comment #5 earlier and will replace the present thermionic gun. This replacement is shown schematically in Figure 2.[3] In this configuration, the rf gun was optimized for ORION for producing 0.25 nC pulses with good transverse emittances[4]. As demonstrated in the Response to Comment #6, this same configuration can be used both to generate very low energy spread, low charge bunches, and reasonable quality high charge bunches, with the only modifications required being changes in the laser pulse parameters (intensity, diameter, pulse length), the solenoid field strength, and the chicane quadrupole settings. With a peak electric field on the cathode of 120 MV/m, electron bunches of roughly 5 MeV are produced, and will be injected into the two 0.9 meter, X-band accelerating sections. These sections will be run conservatively at 30 MV/m average gradient giving a final beam energy of approximately 60 MeV. This beam will be matched into the NLCTA chicane (set to be isochronous), then extracted by a dipole into a separate beamline leading to the E163 shielding enclosure.

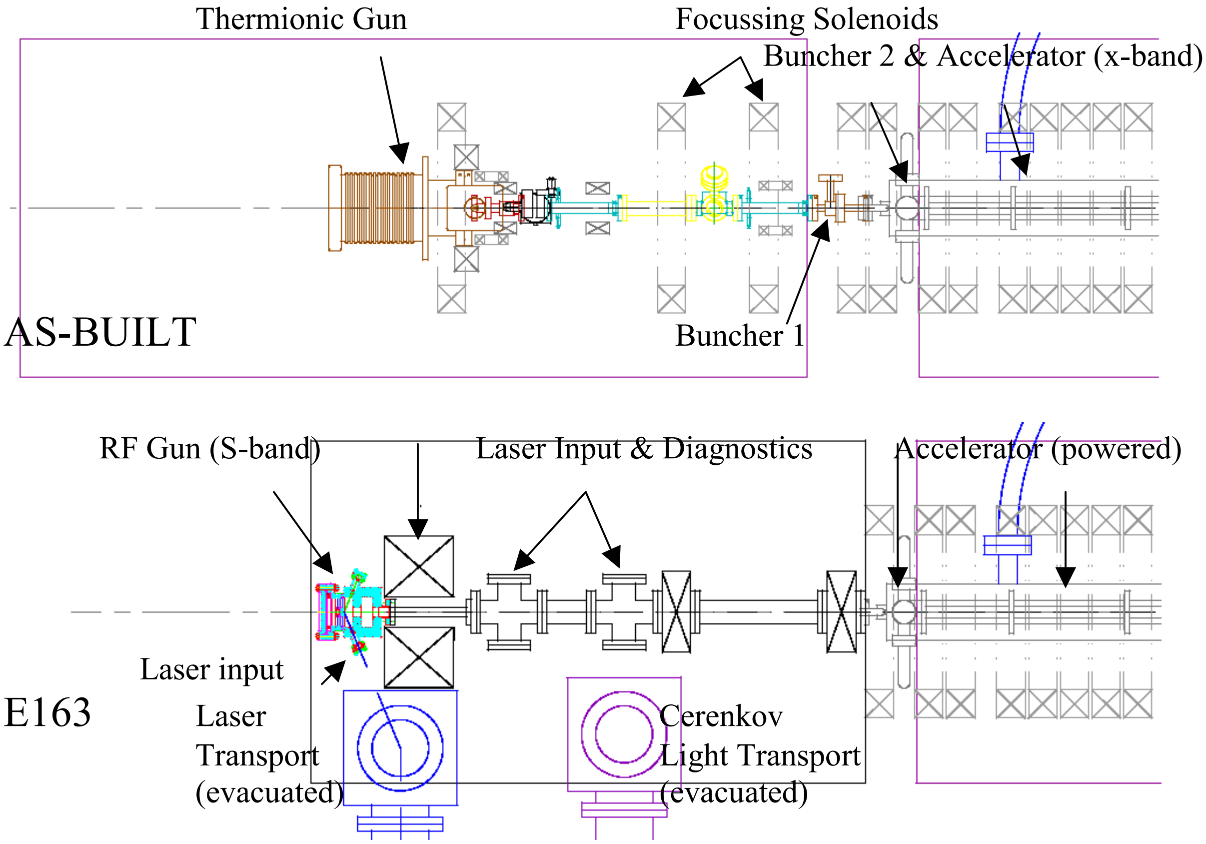

FIGURE 2: NLCTA Injector components as-built (top), and as proposed for E163 (bottom), showing the replacement of the thermionic injector and initial 1.5 meters of beamline with an rf gun and its associated beam diagnostics. Evacuated light transport lines are mounted to the NLCTA enclosure ceiling, with drops placed over the gun support girder.

This extraction dipole will be installed downstream of quad QUAD1030 in the NLCTA beamline, with space for the dipole coming from the removal of QUAD1070, and the substitution of shorter bellows than those currently installed. In addition, the beam phase monitor BPHM1050 can be moved downstream of the extraction dipole, as needed to make clearance space between the dipole and the wire scanner WIRE1090. The chosen extraction angle of 25 degrees is a compromise between floor-space constraints and beam dispersion problems, and will require a bend field of ~3 kG. Close placement of a quadrupole triplet is required to control dispersion, shown in Figure 3. Temporal dispersion must also be controlled, requiring a symmetrically placed quadrupole triplet and bend to complete the dogleg. The large dispersion (70 cm) and adjustable horizontal beta function present in the extraction arm makes this line usable as a high resolution spectrometer, and the profile screen installed just before the quad triplet is intended for this purpose.

Redundant beam stops and a lockout on the extraction dipole power supply form the three engineering controls in the beam containment system required to make the E163 enclosure safe for experimenter access while the NLCTA is running. A fast-closing gate valve (VAT 75 series) will be installed in the extraction line to provide some protection of the NLCTA against vacuum failures in the E163 area.

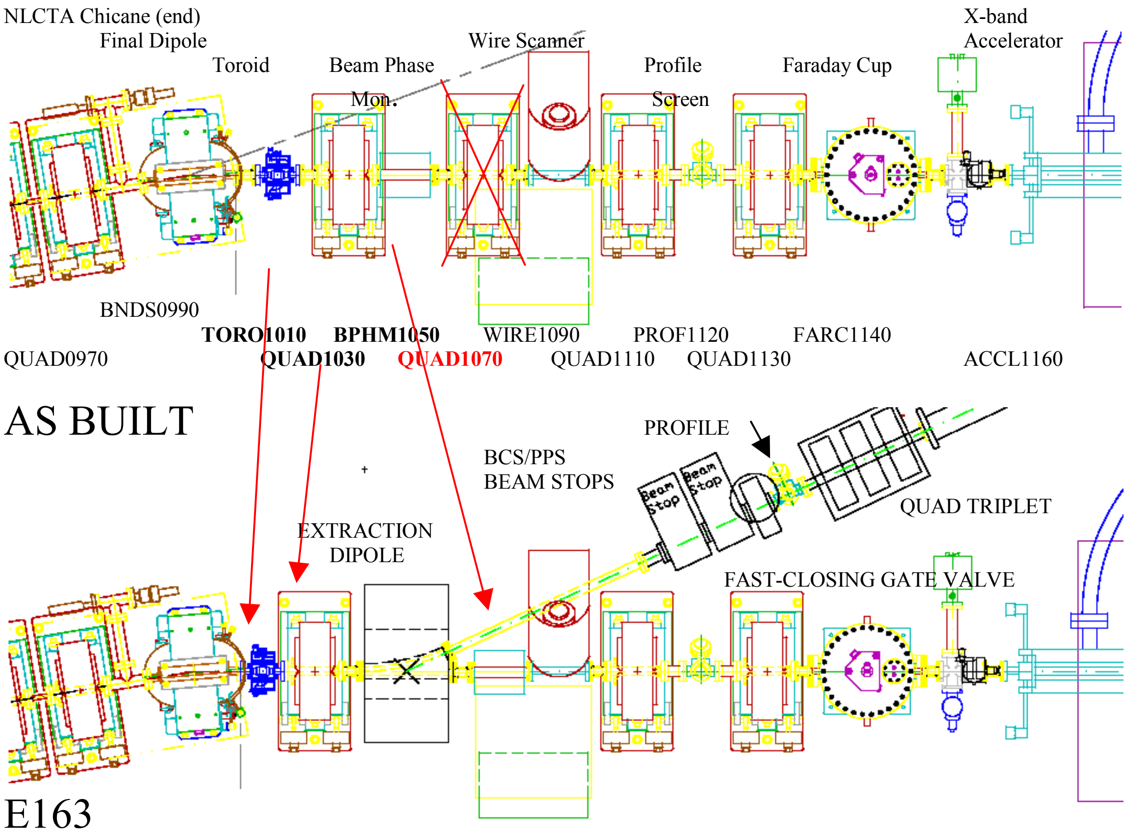

FIGURE 3. NLCTA beamline components between the chicane and main accelerator sections, as-built (top), and as proposed for E163, including the E163 extraction line.

The beamline within the E163 enclosure, shown in Figure 4, begins with the last third of the extraction dogleg. A quadrupole doublet immediately follows the final dipole of the dogleg to permit generation of large beta functions at the final triplet. A current toroid is installed after the dogleg to measure the transmitted bunch charge, permitting "vetoing" of bunches with insufficient charge—a key feature that will be used to perform both energy and time collimation—and the monitoring of actual probe bunch charge. A profile screen ahead of the final focus triplet permits beam centering and setting the appropriate beta functions at this point. The beam is focused by the triplet and drifts 1.5 meters to a focal waist at the location of the laser acceleration cell. For E163 Phase I (Laser Acceleration), no additional optics are present between the final focus triplet and the laser cell. For Phases II and III (Prebunch and Accelerate), a short undulator and a weak dipole chicane are included and require slight correction of the final focus triplet strength to achieve best focus and bunching. The undulator and chicane are very compact, spanning 20 cm from undulator entrance to laser interaction cell, and will be enclosed within the interaction region vacuum chamber itself.

Downstream of the interaction chamber is the main analyzing spectrometer, a short drift, and a YAG profile screen placed at the horizontal focus of the spectrometer. The existing straight-through port on the spectrometer vacuum chamber and a similar straight-through port included in the chamber of the final dogleg dipole will allow precise alignment of the laser and electron beam trajectories by optical alignment of the key components. Correction dipoles (not shown in Figures 1, 2, or 3) and BPMs will be included at strategic locations to permit electron beam centering.

The interaction chamber houses the laser interaction cell and a range of beam diagnostics. In addition, in Phases II and III, it also houses the undulator and chicane that form the IFEL prebuncher. Within this chamber two YAG screen beam profile monitors, and a Cerenkov cell are positioned to permit precise focusing and alignment of the electron beam onto the entrance slit of the laser interaction cell. The Cerenkov radiator is located on a movable actuator downstream of the interaction cell and is transparent, permitting both Cerenkov photons and leakage-field laser photons to pass through. Light from this diagnostic is directed into an evacuated transport line leading to a streak camera in the E163 laser room and is used to determine the absolute timing difference between the electron and laser pulses to within 20 psec.

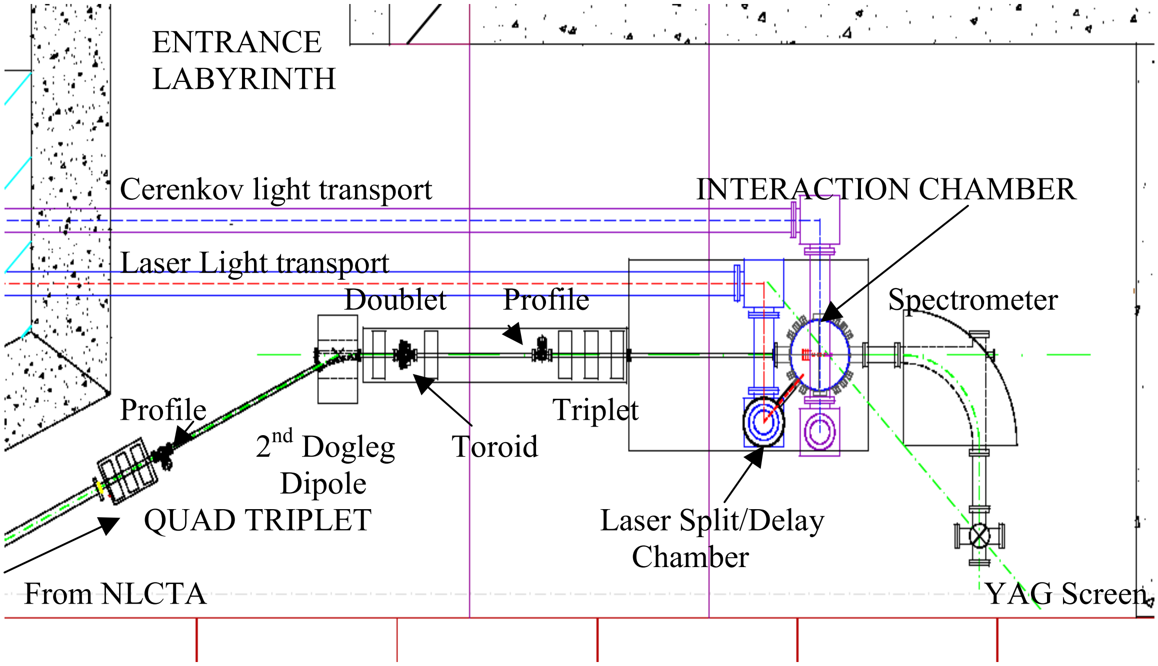

FIGURE 4. Beamline components within the E163 shielding enclosure.

A commercial Titanium-Sapphire (Ti:Sapphire) drive laser system adequate to produce bunch charges up to 1 nC in the rf gun has been specified, and a previously purchased oscillator already exists at SLAC. A diode-pumped, green laser pumps a Ti:Sapphire oscillator delivering 50 fsec pulses at 79 1/3 MHz with a wavelength selectable from 720 to 850 nm (IR). An Nd:YAG pumped Ti:Sapphire regenerative amplifier, to be purchased for this experiment, will operate at 10 Hz over a wavelength range of 750 to 840 nm and up to a pulse energy of 1 mJ. After any spatial and Fourier masking for pulse shaping, a pulse is frequency-tripled in a series of nonlinear crystals to a nominal wavelength of 266 nm (UV). About 10 per cent of the IR light is converted to

UV. The unconverted light is in fact used for the E163 experiment, providing a significant economy with *dual usage of one laser*. Taking into account the various mirror, grating, and transport losses, the UV energy per pulse arriving at the magnesium photocathode is expected to be 0.01 mJ, which is adequate for 1 nC. The system is designed to allow a straightforward upgrade in the IR energy if necessary. Bunch charge stability of 5%, rms, is desirable for consistent diagnostic readings during beamline tune-up. This has allowed reduced laser-amplitude stability compared to the more stringent ORION experimental needs with a cost savings through the use of flashlamp-pumping over more expensive diode-pumping in the regenerative amplifier.

Timing jitter and bunch energy spread are critical to E163. A laser pulse stretcher/compressor consisting of a pair of matched optical gratings allows for control of the nominal 0.8 psec pulse length (FWHM) for optimization of the E163 electron bunch characteristics. Laser pulse length will be adjustable over a range of 150 fsec to 6 psec to provide for a range of E163 and NLCTA running conditions. The laser system will be mode-locked to the 36th harmonic (79 1/3 MHz) of the photoinjector rf system (2865 MHz) and stabilized to deliver the laser pulse to within 1 psec, rms, or four degrees of rf phase at 11.4 GHz, for consistent bunch arrival timing.

The 2.856 GHz, photoinjector requires a single, high-power S-band klystron and modulator system to power its accelerator cells. The photoinjector requires about 15 MW of peak rf power. The standard and proven SLAC 5045 klystron is immediately available on site and was the baseline choice for ORION and is now the choice for E163. Its 65 MW output capability is more than adequate, and reliable operation is expected. The modulator choice is equally straightforward. A new solid-state modulator, consisting of up to twenty insulated-gate bipolar transistor (IGBT) drivers arranged in a pulse-forming network, has been designed at SLAC for the Next Linear Collider project. An NLC prototype has been successfully tested at full power with a SLAC 5045 klystron. At the nominal 10 Hz repetition rate, the HVPS is very modest and operates at only about 5 kW average power. The input drive signal to the klystron will be supplied by a new S-band TWT (traveling-wave tube) being manufactured under an SBIR for delivery to the SLAC Klystron Department in mid-2002 (R. Phillips and S. Gold, SLAC, private communication). The LLRF system will be patterned after existing S-band components as much as possible but consistent with the requirement of a maximum 0.5 psec rms timing jitter.

Civil construction and utilities installation at ESB for supporting E163 have been estimated, and no unusual requirements have been identified. The 500 square-foot laser room will be a commercial unit with HEPA filtering for class 10K, have an entry vestibule for clean suiting and PPS entry, and have standard EMI shielding. The E163 enclosure and roof will be made of pre-cast concrete slabs from a contractor (about 60 cubic yards), although some on-site shielding blocks may find use as well. Initial estimates indicate that two-foot thick shield blocks with four inches of lead are sufficient to keep external radiation levels below 1 mrem/hour for 1nC, 60 MeV beam loss at 10 Hz (D. Walz private communication with S. Rokni and W.R. Nelson, SLAC). The beam dump following the 90-degree spectrometer bend in the E163 enclosure will be a iron core surrounded by concrete, and the beam dump line will point south toward the NLCTA enclosure to minimize external radiation. This is the normal arrangement for beam-on operations. A similar straight-ahead beam dump will be placed downstream of the spectrometer in the event that this magnet loses power with beam present. Once experimental approval is received, a full civil design with earthquake-proofing will be done for the E163 enclosure. An electrical power and water-cooling estimate (attached as “Utility Needs for E163”) has been made for the E163 needs at End Station B showing that 66 kW of power and 133 GPM of LCW water are needed.

References

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[1] D.T. Palmer, “The Next Generation Photoinjector”, Ph.D. Thesis, Stanford Univ., June 1998.

[2] W. Graves, BNL, “Sub-picosecond measurements of photoinjector electron beam properties”, talk presented at the LCLS TAC meeting, December 2001.

[3] Sketches shown in Figures 2, 3, and 4 are based on the original drawing “Layout, End Station B”, Ron Rogers, SLAC drawing dated 9/29/1999.

[4] R. Siemann and R. Noble, editors, “ORION Technical Design Study”, dated February 2, 2001, https://www-project.slac.stanford.edu/orion/facilities/TDS.pdf .