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RADIATION PROTECTION IN THE NLC TEST ACCELERATOR AT SLAC*

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Abstract
This report describes the ionizing radiation protection and safety issues in the design of the Next Linear Collider Test Accelerator (NLCTA), a high-gradient, 1-GeV, X-band linac at SLAC.

INTRODUCTION

The Next Linear Collider Test Accelerator (NLCTA) is a high-gradient, X-band linac at SLAC designed to validate 2.6-cm microwave linear accelerator technology for a future high-energy linear collider (the Next Linear Collider).[1] This report describes the ionizing radiation protection and safety issues in the design of the NLCTA, including power limits, shielding, and safety systems.[2]

The NLCTA beam line (Fig. 1) consists of an injector, chicane, linac, and spectrometer. The injector contains a 3-A, 150-kV, pulsed thermionic-cathode gun and two 0.9-m-long X-band accelerator sections.[3] The sections are energized by a single 50-MW klystron, and boost the beam energy by up to 90 MeV (50 MV/m). The gun pulse has 0.125-μs duration. The repetition rate is variable up to 10 Hz. The net current loss in the injector is approximately 30%.

Downstream from the injector is a magnetic chicane containing an adjustable collimator. The dominant sources of radiation in the chicane are beam losses in the bends and collimator, for which 30% is assumed.

Downstream from the chicane is an insertable, re-entrant tungsten Faraday cup followed by an X-band linac.

The linac is designed to contain up to three pairs of 1.8-m-long X-band accelerator sections. (At present, two pairs are installed.) Each pair is powered by a single 50-MW klystron, and boosts the beam energy by up to 180 MeV (50 MV/m). The dominant source of radiation in the linac is expected to be small, distributed beam losses. The net loss is expected to be much less than 0.5%, consistent with experience in the SLAC linac and Final Focus Test Beam. However, for the purpose of estimating the radiation doses, a point loss of 0.5% in the linac is assumed.

A future upgrade of the rf system is planned in which the rf power will be tripled by replacing each 50-MW klystron with a pair of 75-MW klystrons, which will increase the gradient in the injector and linac by $\sqrt{3}$. A future upgrade of the injector is also planned which would double the peak current and change the micropulse structure for NLC accelerator-development studies. Because of the upgrade plans, the beam dump and shielding were designed for the future, upgraded beam power, with losses as described above.

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ALLOWED BEAM POWER

Allowed Beam Power (ABP) is limited by an electronic limit on the gun rep rate, and physical limits on the duration of the high-power rf pulses and the accelerating gradient.

The maximum gun rep rate is limited to 10 Hz by three re-triggerable, monostable multivibrator circuits which limit the rep rate by virtue of their finite re-charging times. The three devices have independent

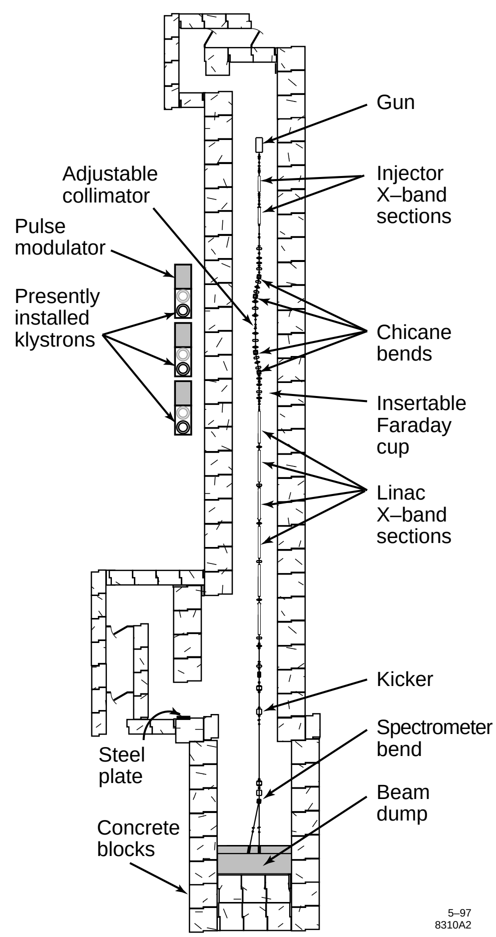

Figure 1. Plan view of the NLC Test Accelerator. The length of the beam line from gun to dump is 43 m.

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power systems and are not subject to common-mode failure.

The duration of the accelerated beam pulse (nominally 0.125 μs) is limited to 0.2 μs by the duration of the high-power rf pulses (which is determined by the physical length of the SLED-II delay-line waveguides[4]) and by the filling time of the X-band accelerator structure.

The accelerating gradient is limited by the available microwave power. If the pulse current exceeds its nominal value, the beam power is further limited by current-dependent loading of the X-band gradient. The steady-state current-loaded gradient (V) in a section of the X-band structure is

$$V \approx V_0\{1-0.25[I/(0.74\mathrm{A})][(50\mathrm{MV/m})/V_0][L/(1.8\mathrm{m})]\}, \quad (1)$$

where I is the average pulse current, V_0 is the unloaded accelerating gradient, and L is the length of the section. V_0 is 50 MV/m before upgrade, and 87 MV/m after upgrade. L is 0.9 m for the two sections in the injector, and 1.8 m for the six sections in the linac. Consequently, the pulse power (IV) is maximized for the finite pulse current,

$$I^* = 2\ (0.74\ \mathrm{A})\ [V_0/(50\ \mathrm{MV/m})]\ [(1.8\ \mathrm{m})/L].$$

Since the ABP is obtained when the current is twice nominal and the loaded gradient is two-thirds nominal, the ABP is only one-third greater than the nominal beam pulse power, for equal pulse durations. If the pulse current of the gun increases to twice the nominal value, the beam loading doubles, and the beam energy drops to 2/3 nominal.

The net effect of the increased pulse duration (×0.2 μs/(0.125 μs)), increased pulse current (×2), and decreased beam energy (×2/3) due to increased loading is that the ABP exceeds the nominal beam power by a factor of 2.1. ABP after upgrades is 3.1 kW.

MAXIMUM CREDIBLE BEAM POWER

The maximum credible beam power (MCBP) is obtained if the electronic rate-limiting devices that limit ABP fail in such a way that the beam rate increases to 180 Hz. For rates from 10 Hz up to 180 Hz, the MCBP is limited by a fail-safe electronic circuit that limits the average current to less than 11 μA. [5]

Beam loading does not significantly limit MCBP. The MCBP is attained at nearly the highest possible energy since the average current limit applies to the product of pulse rate, pulse duration, and peak current. At the maximum possible pulse rate (180 Hz) and pulse duration (0.2 μs), the 11-μA average gun current limit corresponds to a peak pulse current of only 0.3 A, which loads the gradient by only a few per cent (eq. 1).

MCBP after upgrades, calculated assuming nominal current losses, is 5.7 kW at 1070 MeV. The "safety envelope" corresponds to 100% loss of the MCBP either in the chicane, the insertable Faraday cup, the spectrometer, or the beam dump.

SHIELDING

The shielding was designed to limit the continuous dose rate at the surface of the shield in occupied areas to 2 mrem/h, assuming the ABP after upgrade, nominal beam-loss fractions, operation for 1000 h per year, and an occupancy factor of 50%. Since the ABP exceeds the nominal beam power by a factor of approximately two, operation at the nominal upgraded beam power is compatible with 100% occupancy.

The shielding-design calculations indicate the potential for some unoccupied areas, such as the roof of the enclosure and beam dump, to experience doses greater than 5 mrem/h. This is because the concrete roof is thinner than the walls, and because of vertical penetrations, offset from the beam axis, for waveguides and cables. Additionally, there are unoccupied utility tunnels, below the chicane and spectrometer areas, where continuous dose rates may approach 5–15 mrem/h. Areas receiving dose rates above 5 mrem/h are designated as "radiation areas," and are identified by appropriate signs and barriers. No areas outside the shielding are expected to be "high-radiation areas," where continuous doses exceed 100 mrem/h.

Considering the magnitude of expected losses, it is practical to divide the beam line into two regions: (1) the injector, chicane, and insertable Faraday cup, where a large fraction of the beam may be lost; and (2) the linac and spectrometer, where losses will be less than 0.5%. The thickness of the lateral concrete shielding is the same in all regions: 6-ft walls, and a 4-ft roof. The walls and roof are constructed from blocks that interlock in order to prevent direct streaming of radiation.

After the planned upgrades, the dose rate outside the walls is estimated to be 0.5 mrem/h near the chicane and Faraday cup. The dose rate on the roof, away from any penetration, is estimated to be 10–15 mrem/h above the chicane and Faraday cup. The dose rate at the nearby roof penetration will be less than 100 mrem/h.

The highest dose rates under normal conditions are expected at the end of the linac. The continuous dose rate after upgrades is estimated to be 0.9 mrem/h outside the walls, and 3 mrem/h on the roof.

BEAM DUMP

The beam dump is a stack of horizontal iron slabs. The beam impinges on only one slab (which will become activated). The power-handling capability of the dump, cooled only by natural convection and thermal radiation, is adequate for the MCBP.[6] The dump is surrounded by 6–12 ft of concrete laterally, on top, and forward.

The nuclides of greatest concern in the activated dump are ^{46}Sc, ^{48}V, ^{51}Cr, and ^{54}Mn, which have half-lives of 16–303 days, and gamma-ray energies of 0.8–1.3 MeV. The saturation dose rate will be approximately 2 rad-

m^2/kWh. Assuming nominal beam power of 1.5 kW after upgrade, the estimated dose rate inside the housing, 50 cm from the point of impact, will be 1 rad/h. In order to permit access to the housing near the dump, the middle slab of iron contains a 70-cm deep, re-entrant recess for a (radially) 20-cm thick Pb collar surrounding the beam pipe. This collar reduces the gamma dose rate below 1 mrem/h outside the beam pipe.

AIR ACTIVATION AND OZONE PRODUCTION

Beam loss may result in activation of air and ozone production in the housing if some of the energy deposited by the beam leaks out into the air as ionizing radiation. The saturation level of the build-up of activation products and ozone in the housing was estimated from the ratios of the production and decay rates. Our estimates of these effects are conservative in that they assume minimal attenuation of the ionizing radiation in the "target" (which may be quite thick), no ventillation, and whole-body exposure. Beam losses assumed for estimating these effects were 230 W at 125 MeV in the Faraday cup, and 7.5 W at 800 MeV.

The most significant nuclides for air activation are ^{13}N ($T_{1/2}$ = 10 min) and ^{15}O ($T_{1/2}$ = 2 min). The saturated concentrations are in the range of 10–20% of the limits allowed by DOE ("Radiation Protection for Occupational Workers," DOE Order 5480.11, 1988) for these species, 5% of the limit for ^{41}A ($T_{1/2}$ = 110 min) produced from ^{40}A by thermal neutrons from the Faraday cup, and less than 1% of the limits for other nuclides including ^{3}H and ^{7}Be.

The dose at the site boundary due to airborne transmission of air-activation products was estimated[7] for compliance with the Environmental Protection Agency's National Emissions Standards for Hazardous Air Pollutants (40CFR61, H). The effective dose equivalent to the maximally exposed individual of the general public was found to be 1.5×10^{-4} mrem/y, well below the 10-mrem/y limit.

To estimate the production rate for ozone ($T_{1/2}$ = 50 min) at the end of the linac, it was conservatively assumed that 0.4 W escapes into the air in the form of 10-MeV electrons. The estimated production rate of 4×10^7 molecules cm^{-3} s^{-1}, results in a saturated concentration of 10^{11} molecules cm^{-3}, which is 5% of the threshold limit for ozone. Ozone production at the Faraday cup is about 50 times less because of greater self-attenuation and the lower energy.

SITE BOUNDARY DOSE

The SLAC site boundary, 400 m away from the NLCTA, is continuously monitored by active and passive detectors which are sensitive to neutrons and gamma rays. The predominant source of boundary dose from NLCTA is secondary radiation from the primary beam, in the form of neutrons that leak through the 4-ft-thick concrete roof and scatter in air. This source is estimated to result in an annual boundary dose of less than 0.04 mrem.

The klystrons used to generate the microwave power for the accelerator can be sources of 400-keV X rays. The klystron dose rates are 0–25 mrem/h at 30 cm. The klystron dose at the site boundary is negligible.

PROTECTION SYSTEMS

A Beam Containment System (BCS), is designed to limit the beam losses to the 0.5% level. The BCS utilizes eight Protection Ionization Chambers (PICs) deployed inside the housing along the beam line between the chicane and the beam dump. The individual PICs act redundantly in that radiation from a point loss is detected by more than one PIC. PIC readings that correspond to a 1-mrem/h dose outside the shielding cause a 10-fold reduction in the gun trigger rate to allow for operator intervention. PIC readings that correspond to a 2-mrem/h dose outside the shielding cause the BCS to inhibit triggers to both the gun and the klystron pulse modulators.

The Personnel Protection System (PPS) is designed to detect radiation doses outside the shielded housing, and to control access to the housing. The PPS utilizes 10 Beam-shut-off Ionization Chambers (BSOICs) deployed outside the shielding. The trip levels of the BSOICs at ground level are set at 10 mrem/h. Three of the BSOICs are positioned in potential radiation areas on the roof and in a utility tunnel, and are set to trip at 100 mrem/h. BSOIC trips or access violations cause the PPS to turn off the high voltage for both the gun and the modulators, and inhibit the modulator triggers.

The BCS also includes physical devices designed to contain the beam at the chicane and spectrometer bends, where an unanticipated drop in energy (due to klystron failure) could cause the beam to over-bend, escape the vacuum chamber, and hit the concrete shield, which cannot absorb the maximum power. The BCS devices designed to prevent this mishap are protection collimators capable of absorbing the MCBP.

The vertical kicker has the potential to steer the beam into a pole of a spectrometer matching quad, which may result in excessive dose rates in an underlying utility tunnel (3–10 rem/h for 1.5–5.7 kW). To limit the duration of such rates, a BSOIC with a 100-mrem/h trip threshold is located in the tunnel. This BSOIC will shut off the beam if losses exceed 50 W. Since simultaneous dose rates of 0.6 rem/h outside the walls and 2.5 rem/h on the roof are anticipated, the scenario is mitigated also by three other BSOICs and two PICs, which will shut off the beam at 25-W loss.

Full functionality of the BCS and PPS interlocks and devices, and other radiation safety items, is maintained by routine testing, inspection, and configuration controls.

REFERENCES

[1] See Ronald D. Ruth *et al*., "Results from the SLAC NLC Test Accelerator, " in these proceedings.

[2] More details are available in Vaclav Vylet and Theodore Lavine, "Radiation Protection in the NLCTA," NLCTA-Note #46.2, revised 12/5/95.

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