NGLS LINAC DESIGN*

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Abstract

The Next Generation Light Source (NGLS) is a design concept for a multi-beamline soft X-ray FEL array powered by a superconducting linear accelerator, operating in CW mode with evenly spaced bunches at approximately a 1 MHz repetition rate. Electron bunches from the linac are distributed by RF deflecting cavities to an array of independently configurable FEL beamlines. This paper describes the concepts under development for a linac based on minimal modifications to the design and technology of the International Linear Collider technology in order to leverage the ILC community's extensive investment in R&D and infrastructure development. Particular emphasis is given here to high loaded-Q operation and microphonics control, as well as high reliability and operational up time.

NGLS OVERVIEW

The NGLS uses a single-pass, continuous-wave (CW), superconducting, high-brightness electron linac to provide high-repetition-rate beam to multiple FELs. The NGLS main parameters and a more complete description of this project have been presented in the Proceedings of FEL2013 [1,2].

The linac has four sections of accelerating cryomodules, separated by other elements: a laser heater, a 3rd harmonic linearizer system (a cryomodule operating at a higher harmonic frequency) and two bunch compressors as shown in Fig. 1.

LINAC DESIGN

Linac Configuration

The 2.4 GeV NGLS linac is composed of 24 cryomodules containing 8 cavities each, operating at 1.3 GHz and producing accelerating gradients from 13 to 16 MV/m. To establish a reasonable level of design conservatism, of the total of the 192 installed cavities only 94% (180 cavities) were assumed to be active. In practice all functional cavities will be active and operating at a slightly reduced average gradient.

Unlike the proposed ILC that utilizes a long string of cryomodules within a single cold envelope, the NGLS linac is comprised of fully segmented cryomodules with beam diagnostics, magnets and high frequency HOM dampers external to the cryostat. This fully segmented layout offers the many advantages as enumerated below.

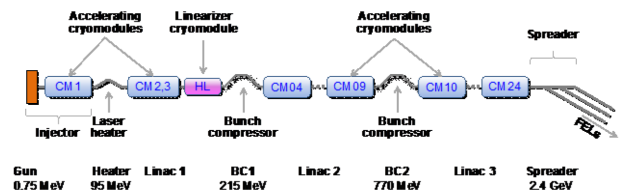

Figure 1: NGLS linac schematic layout.

1. Separated liquid management. High heat loads inherent in CW cryomodules imply high 2 Kelvin boil off rates. Managing the liquid level in the helium vessels and flow through the JT valve and 2-phase pipe or a series of helium vessels is more tractable with a short length of liquid baths.
2. Small heat exchangers combined with JT valves, distributed with the cryomodules generate the final stage of temperature reduction thus allowing flexible, discrete liquid level control in a package size that fits in the longitudinal space required by associated "warm" beamline components. Heat exchangers of this scale were utilized effectively for SNS and the general valve can layout has been used effectively in CEBAF at JLab. The effect is to place the heat loads in the large transfer line at the 4.5 K level rather than at 1.8 K.
3. Warm magnets and instrumentation between cryomodules. Separate cryomodules allow warm beam line components between cryomodules, especially useful for easier alignment of magnets, BPM's, and instrumentation, and also for absorbing the higher frequency HOM power that is produced by the relatively short beam pulses inherent in the NGLS design.
4. Active pumping between cryomodules. If needed, the insulating vacuum of a single cryomodule may be pumped, and the beam vacuum is accessible for pumping.
5. Loss of insulating vacuum to air is limited to one cryomodule (assuming vacuum isolation from the transfer line). The sudden rush of air into insulating vacuum and resulting heat fluxes with air condensation can deposit up to several Watts per square cm on liquid helium-temperature vessels and piping, depending on insulation. For a string of cryomodules, this can result in huge flow rates with requirements for extremely large vent lines and venting devices. The separate cryomodule vacuums limit this disaster to one cryomodule for the insulating vacuum loss.

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6. Replacement for maintenance. Separate cryomodules allow replacement of individual cryomodules without warming the entire string.
7. Testing and commissioning. Separate cryomodules allow installation and cryogenic operation of individual cryomodules or parts of the linac during installation and commissioning.

The other layout option is to build the linac from a string of cryomodules with welded bellows connections and single warm to cold transitions at end of the string. There are three main advantages of the string layout.

1. No external transfer line. A large transfer line with vacuum-jacketed 4K pumping line may be $5000 to $10,000 per meter including all the connections to the cryomodules. So for a 10 meter long cryomodule, it may add the equivalent of another $50K to $100K per cryomodule to the linac cost, as well as occupy tunnel space.
2. Fewer cryogenic valves. By placing the helium vessels and other piping of multiple cryomodules in series, one valve at a feed or turnaround box controls the flow through many cryomodules. This may provide significant cost and, if control of long liquid volumes is not a problem, also simplify operations by reducing the number of control valves.
3. No warm-cold transitions at the ends. Especially for systems with relatively low dynamic heat loads where static heat load is more significant, eliminating the warm-cold transitions at each end helps reduce heat load.

For a long pulsed linac with relatively low dynamic vs. static heat load long cryomodule strings make sense economically and operationally. But for linacs the size of CEBAF, SNS, Project X, NGLS, etc. (tens of cavities, as opposed to thousands), the separated cryomodule scheme with external transfer line was judged to be preferable.

RF Parameters

Table 1: Main RF Parameters

RF frequency	1300	MHz
Operating temperature	1.8	K
Average operating grad.	12-20	MV/m
Average Q_0 per CM	2×10^{10}	
Cavity length	1.038	M
R/Q	1036	Ohm
Coarse tuner range	600	kHz
Fine tuner range	2	kHz
Lorentz detuning	1.5	$Hz/(MV/m)^2$
Number of cav. per CM	8	
Peak detune allowance	15	Hz
Qext	3.2×107	
Min. RF power per cavity	5.4	kW

The choice of SCRF cavity frequency for NGLS is ultimately driven by the need to minimize development cost by utilizing existing proven technology. Specifically the NGLS plan is to takes advantage of the extensive worldwide investments in TESLA/ILC/XFEL technology extended to run at a high loaded Q to minimize RF source costs. Table 1 summarizes the main RF parameters.

CAVITY AND CRYOMODULE DESIGN

Cavity Considerations

The differences in operating ILC-like cavities in CW mode go beyond the need for increased heat rejection. The emphasis on resonance control moves from coping with the hammer-like effect of pulsed Lorentz forces, to minimizing the impact of microphonics-induced frequency shifts due to mechanical vibrations. For the NGLS cavities the most important factor is to operate at a high loaded Q, which results in reduced power consumption. This goal is realized by successful control of microphonics. We have chosen to allow for a 15 Hz peak detuning from microphonic effects without having to de-rate the cavity field due to limited RF source power. This choice corresponds to a loaded Q of ~3.2×10^7 and has a direct impact on the requirements for the RF plant. A smaller allowance for microphonics would result in significant cost savings but could compromise reliability. We are therefore monitoring progress in the community to identify the most reasonable compromise.

Recent advances in cavity processing suggest that Q_0 of greater than 2×10^{10} may be readily achievable [3]. In addition cryomodule thermal cycling up to 10 K seems to indicate that Q_0 degradation in a fully assembled cryomodule is reversible *in-situ* [4,5]. These results point to higher Q_0 than presently assumed for NGLS and therefore lower cryogenic loads.

Tuners, Couplers and HOM Dampers

Resonance control is particularly important because we want to operate at high loaded Q and therefore we need tuners able to quickly compensate for microphonics effects. One of the existing ILC tuners, composed of a fast/fine piezo coupled with a slow/coarse motor drive, is likely to suit the needs of NGLS.

There are several existing power coupler designs that could be adopted to operate in the envisioned CW power range. A very promising design, given our goal of obtaining maximum benefit from the ILC cryomodule design, is to use the coaxial input RF power coupler developed by Cornell and built by CPI for the proposed Cornell ERL. This unit, derived from the TESLA TTF-III design, has been tested in CW conditions up to 5kW [6].

HOMs are well characterized for the TESLA-type cavities, although NGLS bunches excite a very broad spectrum of modes extending into the THz range. For modes propagating outside the cavities, beam-pipe HOM absorbers at room temperature are used to avoid coupling between cryomodules, and to reduce the heat load on the cryosystem.

Cryomodule

For the reasons stated above, we will use discrete cryomodules, allowing for ease of removal and replacement, as well as accommodating equipment such as lattice magnets, diagnostics, and travelling-wave absorbers in warm sections between cryomodules. Refer to the cryomodule layout in Fig. 2. The modifications to ILC cryomodules involve a larger 2-phase pipe and nozzle from the helium vessel and a liquid control valve and heat exchanger in “end cans” of each module, shown schematically in Fig. 3 [7]. Short warm-to-cold transitions, as well as U-tube cryogenic connections to the distribution piping are required at each cryomodule end.

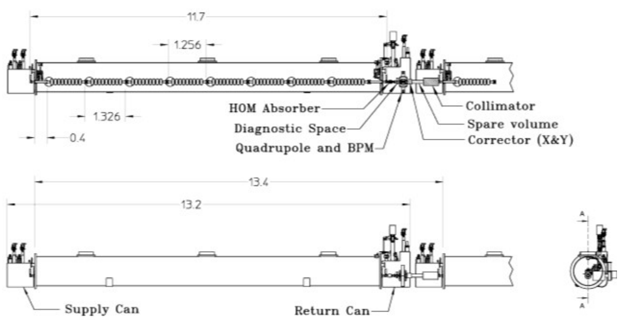

Figure 2: Cryomodule layout (dimensions in meters).

In addition to magnetic shields that keep the field around the cavities below tens of milligauss, a single thermal shield operating over the 40 K to 50 K will be used to limit radiation heat loading on the ~1.8 K structure, along with careful selection of flow direction and routing of the cold gas circuit. The expected intrinsic Q_0 of the cavities (important for reasons mentioned earlier) is significantly higher at 1.8-1.9 K than at the ILC design temperature of 2.0 K. The lower temperature, while reducing the net heat load to the cryosystem, results in a higher volumetric flow rate per watt of heat absorbed.

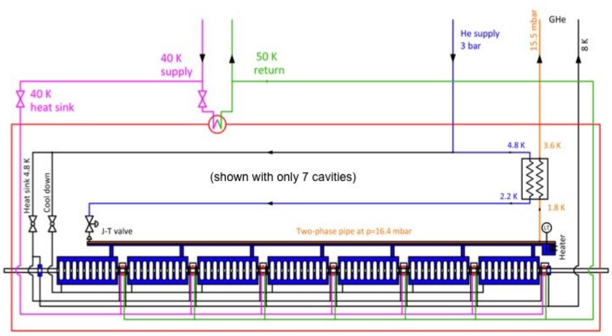

Figure 3: Helium distribution within a cryomodule.

RF SYSTEM AND DISTRIBUTION

RF Technology Options

There are two basic technologies capable of delivering the high power RF needed to energize the cavities in the NGLS linac: 1) vacuum tubes, specifically inductive output tubes and klystrons; and 2) solid state power amplifiers, in which the outputs of a number of low power (few hundred watts) transistors are summed. Klystrons have been the traditional power source for particle accelerators in these frequencies because they produce high power RF and offer high gain (~50 dB) with efficiencies around 50%. The recently completed 12 GeV upgrade of CEBAF adopted klystrons as the source of RF power [8].

Recent improvements in transistor technology have led to an increased power capability of solid state power amplifiers (SSPAs). Individual transistors can reach power levels on the order of a couple of hundreds of watts, and by combining many in a single power source, several to tens of kilowatts can be achieved with tolerable efficiency degradation. Several facilities are adopting this technology for its modularity, ease of maintenance and potential for incremental upgrades. The system operating efficiency for such L-band SSPAs does not much exceed 40%.

The solid state technology is still emerging, and further advances, including better efficiency, can be expected. However, for the same reason—the lack of maturity—the reliability of these systems at present is less well established. We plan to keep monitoring progress in this technology and defer a decision on a baseline design.

RF System Topology

Providing an individual RF power source for each cavity offers many advantages. In particular, it allows the beam energy gain in each cavity to be precisely regulated, independently of the other cavities to better optimize the operating gradients to the most reliable performance of each cavity. It also simplifies the high-power RF distribution system and minimizes the effect of source failures. Of the 192 linac cavities, only a small fraction would need be held in reserve to compensate for such failed units, likely with only a brief (or no) interruption of beam operation.

We have therefore chosen to power each cavity with an independent power source. This configuration is likely to result in the highest possible beam availability and machine reliability. The planned waveguide distribution system is shown in Fig. 4 and has been used to calculate waveguide losses and heat dissipation to the tunnel. Each cavity is fed from a dedicated power supply housed in a separate tunnel, located to the right in this diagram.

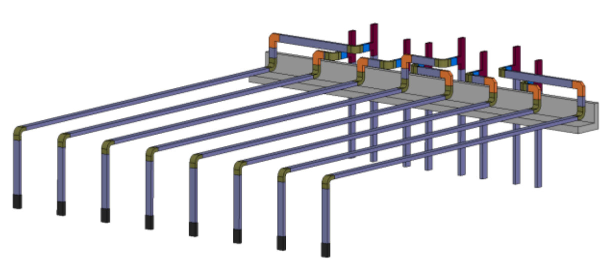

Figure 4: Waveguide distribution system, with isolators, for one cryomodule.

CRYOGENIC SYSTEM CONSIDERATIONS

Dynamic heat loads dominate the NGLS requirements due to the CW operating conditions. Heat loads were estimated from a combination of known cavity parameters, extrapolations from the ILC RDR values and measurements made on ILC type cryomodules and couplers. The selection of accelerating gradients, and therefore the number of RF cavities required to achieve the 2.4 GeV beam energy, is consistent with the use of a single large cryoplant with one 1.8K cold box. The size of the cryoplant is equivalent to the JLab upgrade and the LHC cryosystems. The estimated load on the NGLS cryoplant was estimated at 17.8 kW (4.5 K equivalent) with a commensurate utility power requirement of 3.9 MW. This value includes a 10% margin for load uncertainty multiplied by a 30% overcapacity margin to allow for off-optimal operation and system control.

Dynamic heat loads account for 85% of the cryogenic load, and these loads scale as the square of the cavity gradient. Therefore, for CW operation, a lower cryogenic system heat load can be achieved by increasing the number of active cavities for a given final beam energy, thus operating cavities at a lower average gradient and requiring a longer linac. In addition, the capacity of the latest generation of superfluid helium cryoplants is limited by the capacity of the low temperature cold box, or more specifically the volumetric flow rate limit of the cold compressors within this cold box. The heat load limitation imposed by volumetric flow limits of a single 1.8K cold box can be relaxed by allowing a somewhat higher (~1.9K) operating temperature for a higher saturated vapor density.

CAVITY PRODUCTION RUN ASSUMPTIONS

Most of the RF parameters, including the requirements on the RF power system and the expected dynamic load on the cryogenic system, depend upon the assumed performance of the RF cavities.

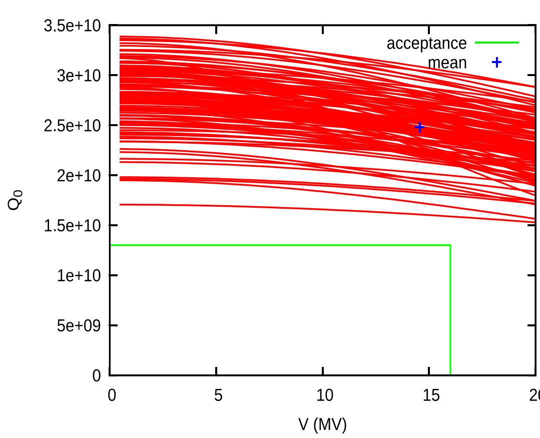

Figure 5: A simulated production run of 112 cavities.

To validate our assumptions, we have analyzed recent test results from cavity production of 17 ILC/XFEL cavities from DESY. The observed parameters have been used as the basis for a Monte Carlo simulation of a potential NGLS production run and the chosen parameter space is well within the limits of today's technology. Fig. 5 shows a simulation based on a possible cavity production run using measured cavity parameters; the green line indicates the acceptance criteria set by the NGLS requirements and shows that no cavity in this run would be rejected.

The model also helps calculating the statistics of a practical RF amplifier system and dynamic load to the cryogenic system. As shown in Figure 6, each trace represents the behavior of a randomly generated linac, with statistical performance based on actual production data, when each cavity is designed for a nominal Q_L of 3.2×10^7. This shows how a power of 5.8 kW at the cavity flange would be sufficient to operate all cavities at the stated Q_L and the corresponding cryogenic heat load would be less than 950 W. This result is one component of a larger optimization including scaling to the whole linac and adding other dynamic and static loads.

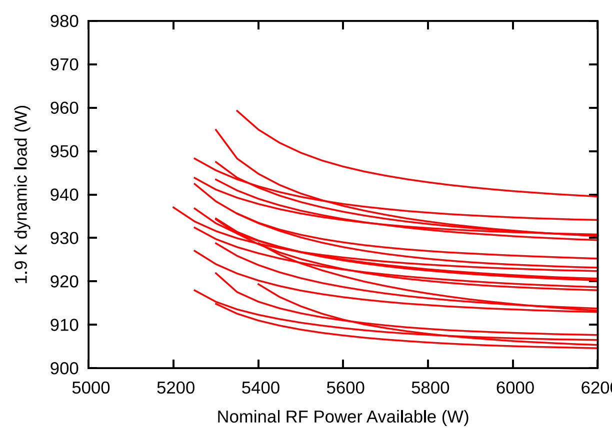

Figure 6: Modeled performance with simulated random production run of 112 cavities.

COST CONSIDERATIONS

Since the superconducting linac is one of the largest expenses in the construction of the facility, we have developed a parametric cost model that allows us to seek cost optimization. The model includes the cost of the cryogenic system, tunnel construction, cryomodules and RF power amplifiers and distribution. As expected, the cost of the RF amplifier system is relatively independent of the operating gradient because it is mostly driven by the total power delivered to the beam. On the other hand, higher gradients result in reduced cryomodule and tunnel capital expenses, but some of these savings are offset by increased costs of the cryogenic system due to the increased heat load at higher gradients. Note that curves for operating at 1.8 and 1.9K are shown up to the limit of a single cold box.

The higher electrical operating costs further offset the savings of construction of a machine running at a higher

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gradient. However, when capital cost is the main parameter, construction cost is minimized at the highest gradient, thus a choice is then determined by the desired operating reliability. Fig. 7 shows the relative cost scaling with cavity gradient.

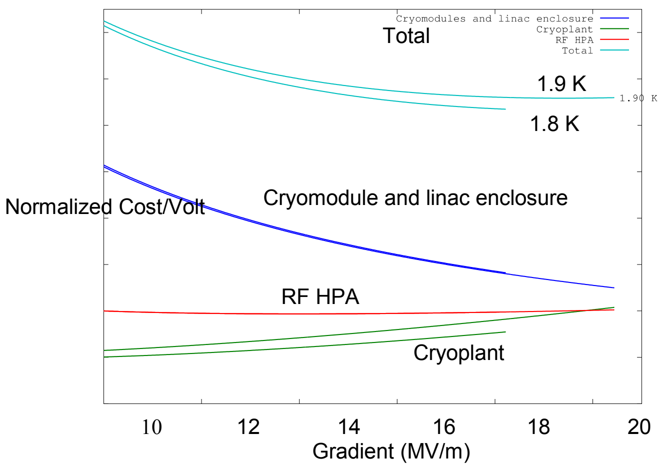

Figure 7: Relative cost of construction plus 15 years operation, as a function of cavity gradient. Operating cost assumes 8,000 hours per year and $0.12 per kW-hr.

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