SUPERCONDUCTING LINAC DESIGN CONCEPTS FOR A NEXT GENERATION LIGHT SOURCE AT LBNL*

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Abstract

The NGLS collaboration is developing design concepts for a multi-beamline soft X-ray FEL array powered by a superconducting linear accelerator, operating in CW mode, with a high bunch repetition rate of approximately 1 MHz [1]. The superconducting linear accelerator design concept is based on existing TESLA and ILC technology, to be developed for this CW application in a light source. We outline design options and preferred approaches to the linac.

NGLS OVERVIEW

Recent advances in X-ray FELs are extending the reach of photon science, and concurrently superconducting RF technologies have developed the ability to deliver high average power electron beams. There is now significant interest in increasing the average power of X-ray lasers, and in response to this need the NGLS (Next Generation Light Source) concept has been developed for an X-ray free-electron laser array powered by a superconducting accelerator capable of delivering electron bunches to a suite of independently configured FEL beamlines [1]. Each beamline, operating simultaneously at a nominal initial repetition rate of 100 kHz, and with potential for MHz operation in some beamlines, will be optimized for specific science needs.

Most notable among the design features are a high-repetition-rate (MHz), high-brightness electron source, and a superconducting radio-frequency (SCRF) electron linac operating in CW mode that will provide bunches at high rate, high average beam power, and with uniform bunch spacing. Choices for beam energy and pulse repetition rates are motivated by the science needs for soft X-ray laser pulses, and FEL technology, and necessitate the adoption of CW SCRF technology for the linac.

The linac will accept electron bunches from the injector, providing acceleration and bunch compression, before directing the beam to the spreader for distribution into the separate FEL undulator lines. Bunches from the linac will be distributed via a spreader system to an array of FELs, and each FEL may provide average brightness five or more orders of magnitude higher than existing light sources, and two or more orders of magnitude higher than other planned and under construction light sources. The high average electron beam power allows the capability of up to ~100 W of average X-ray power per beamline.

NGLS LINAC APPROACH

The CW SCRF linac will provide a “backbone” for delivering high-brightness and high-repetition-rate electron beams to an array of independent FELs. The machine design concept (see Figure 1) is for a maximum bunch charge of 300 pC and nominal 1 MHz repetition rate (i.e., an average current of 300 μA), and with upgrade paths consistent with a range of lower bunch charge at increased rate while maintaining average current. A variety of bunch time structures may be accommodated by the injector and linac, and our conceptual design allows flexibility to accommodate the desired science scope. The nominal electron beam energy of 2.4 GeV has been chosen so as to be able to produce tunable FELs which together cover an operating range from 100 eV and up to 1.2 keV photon energy in the fundamental, and 6 keV and beyond in harmonics. Table 1 shows linac and cryosystems parameters for this configuration. An alternate, low cost configuration with a 1.2 GeV linac has also been studied, which could produce a photon energy range of 50 – 720 eV in the fundamental – still accessing the K- and L-edges of the most abundant elements. Upgrade options include adding cryomodules to the main linac to increase beam energy, and a 3.5 GeV linac could extend the X-ray reach to 5 keV in the fundamental (with limited tuning range), and higher electron beam energies providing harder X-rays (5 GeV reaches the 10 keV range). For the highest energies additional cryomodules may be placed in a spreader arm dedicated to the hardest X-ray FELs, with soft X-ray capabilities provided by the better-matched lower energy beam.

The NGLS linac design is currently based on the use of TESLA-type cavities, and ILC cryomodule design developed for CW operation, including use of discrete cryomodules with warm/cold transitions at each end. The NGLS approach to the CW superconducting linac will be to maximize use of existing expertise, designs, infrastructure, and industrialization. Engineering optimizations of existing components and systems can enhance performance and reliability over today’s designs, and will be needed to meet NGLS requirements, reduce costs, and deliver a reliable and cost-effective CW SCRF electron linac.

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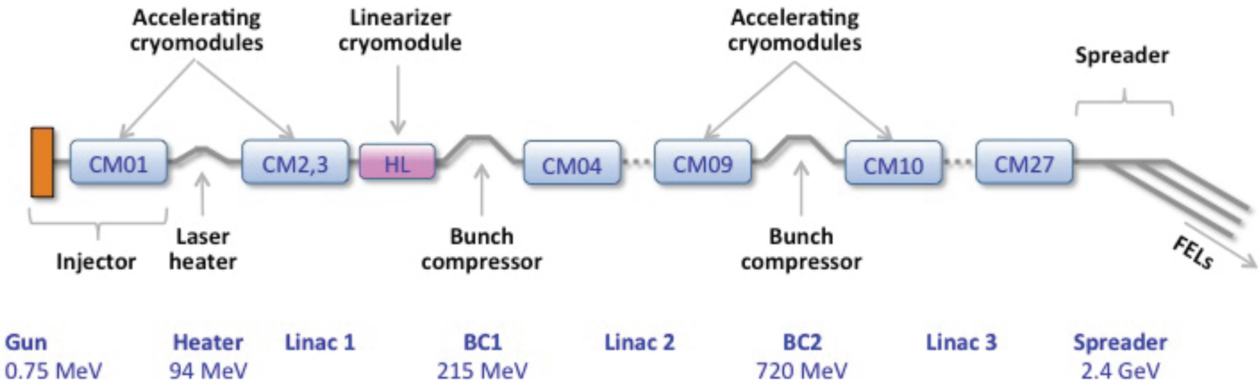

Figure 1: Schematic of the major accelerator components, for the baseline 2.4 GeV configuration.

Table 1: Linac and Cryosystems Baseline Parameters

Parameter	Value
Beam current (mA)	0.3
Bunch rate (MHz)	1
Cavity RF frequency (MHz)	1300
Operating temperature (K)	1.8
Average operating gradient (MV/m)	14
Average Q_0 per CM	2×10^{10}
Coarse tuner range (kHz)	600
Fine tuner range (kHz)	2
Lorentz detuning $(\mathrm{Hz}/(\mathrm{MV/m})^2)$	1.5
Cavity alignment requirement (mm) (RMS)	0.5
Peak detune allowance (Hz)	15
Amplitude stability per cavity (%)	0.01
Required phase stability per cavity (°)	0.01
Q_{ext}	3.1×10^7
RF beam power per cavity (kW)	4.4
RF power available per cavity (kW)	6
Dynamic load per cavity (W)	~10
Cryomodule 1.8 K dynamic load (W)	~100
RF AC power (MW)	2.6
Cryoplant AC power (MW)	3.9

CAVITIES AND PERIPHERALS

The NGLS linac is based on the TESLA 9-cell fine-grain niobium cavity design [2], which has been successfully used at the FLASH FEL facility [3], will be used at the EuXFEL facility now under construction [4], and is planned to be used in the International Linear Collider [5]. An operating temperature of 1.8 K is chosen to maximize efficiency with reasonable cryoplant requirements. Here we discuss potential modifications to the cavity peripherals and cavity surface processing for CW operation in NGLS. The cavity design will remain unchanged as much as possible.

Q_0 Optimization

NGLS design studies assume an average Q_o of 2×10^{10}. High Q_0 is a significant advantage for CW operation and can have a big impact on both cryogenic system capital costs and operational costs. Furthermore, high Q_0 which is relatively insensitive to gradient may allow for operation at higher gradient, implying a shorter linac with correspondingly reduced construction costs.

We have considered a number of R&D paths for high Q_0 in the context of NGLS, including modifications to cavity design, material, and surface processing. Since BCS resistance scales with RF frequency squared, and studies show a frequency dependence of residual resistance as well, a lower frequency cavity may be considered in the context of overall cost. A moderate gain in Q_0 could also be achieved by optimizing the cavity RF design to reduce H_{peak}/E_{acc}. Thin films of niobium sputtered on copper have extremely low surface resistance, and reach moderate gradients; however, they show a strong medium field Q-slope. The potential benefit of large-grain material is a topic of great research interest; eleven electropolished large-grain TESLA cavities had somewhat higher Q_0 than comparable fine-grain cavities at NGLS gradients in vertical test at DESY [6]. Materials such as NbN, Nb_3Sn, and NbTiN have higher critical temperature and could reduce surface resistance substantially, although development time is likely rather long. Overall, given the NGLS construction schedule goals, the potential benefit of a new cavity design or material is outweighed by the substantial benefit of using existing infrastructure and experience with TESLA cavities. Typical Q_0 of TESLA/ILC cavities (scaled from 2 K to 1.8 K) in vertical test at Fermilab, using the standard ILC electropolishing surface processing recipe, is already at the NGLS target value. Recent success in raising Q_0 in single-cell TESLA-shape cavities has been seen with simple techniques such as improving the standard high temperature heat treatments

[7,8] and incorporating a final hydrofluoric acid rinse into standard process cycles [9]. Other ongoing surface processing R&D being considered for NGLS includes tumbling (centrifugal barrel polishing), which may allow for the reduction or potentially even elimination of chemical processing which may reduce cost. Standard electropolishing or buffered chemical polishing are almost good enough for NGLS, but limited and targeted surface processing R&D to increase Q_0 may have substantial impact on costs.

At the very high Q_0 desired for NGLS, avoiding trapped flux becomes critical, and magnetic shielding and thermal cycling have to be considered carefully, i.e., high Q_0 in vertical test has to be maintained through to cryomodule operation.

Power Couplers

The NGLS baseline design assumes a fixed coupler, which provides a cost-effective approach for the parameter range of the machine. Incident power is <10 kW at the nominal beam current of 0.3 mA, and variable coupling provides only marginal power reductions even over large ranges in beam current. We consider the coupler cost not a primary choice criterion, but rather the coupler *reliability* needs to be optimized for NGLS. A fixed coupler with an external coupling matcher may be the most cost effective solution.

Several designed and tested couplers exist with parameters close to NGLS requirements, and could be used with some modifications: TTF-III [10], HZB modified TTF-III [11], Cornell ERL-main linac [12], Cornell ERL-injector [13], KEK ERL-main linac [14], KEK ERL-injector [15]. An issue with current designs is copper plating which has been known to dislocate from the surface and produce particulates that contaminate the cavity. It may be possible to design an inexpensive and reliable fixed coupler with simple geometry, without copper-coated bellows, or even without copper coating at all.

If articulating input couplers are an option, one can gain stiffness and precision in the cavity support structure (relative both to the JLab space-frame structure and to the TESLA invar rod and roller scheme) by mounting cavities directly to the helium vapor return pipe. A titanium pipe, as proposed for the Cornell ERL [16], reduces thermal contraction motion and reduces the number of titanium to stainless joints.

Waveguide couplers are a possible option; however this would require a more significant redesign of the ILC cryomodule and cavity end-group design modifications. Elimination of dipole kicks from the coupler is important for beam quality, especially at low energy in the NGLS injector cryomodule, and as a result end-group modifications will likely be required for at least some of the cavities.

Cavity Tuners

Active and passive frequency compensation is needed for CW cavity operation. For pulsed operation, Lorentz force detuning (LFD) dominates, and fast pulse-to-pulse compensation is needed, typically within a small range. For CW operation, tuning requirements are dominated by fluctuations in helium bath pressure, requiring slow compensation, however LFD remains important even in CW systems for RF turn-on, and trips cause on/off cycles. Tuning requirements for high Q_0 and small bandwidth imply the need for fine resolution which can be difficult with typical motors and mechanical systems; also strong hysteresis must be avoided, and self-generated vibrations must be avoided. The frequency sensitivity to pressure variations, df/dP, can be made close to zero if bellows stiffness is controlled with tuner stiffness. Cavity stiffness is also a variable that may have a fairly wide range and may be dependent on processing procedures. Some preliminary design estimations show a reasonable passive tuning design solution for NGLS may be achieved; reduction in mechanical vibration modes in the cavity is also important.

HOM Couplers

HOM's can limit the performance of an accelerator. Different higher-order-mode (HOM) damping schemes have been developed and successfully deployed for various accelerators: antenna/loop HOM couplers, waveguide HOM dampers, RF absorbing materials, and beamline HOM loads. The optimal design has to meet the specific machine requirements and beam parameters. CW operation with high average beam current produces HOM power in the cavities. Gate valves, bellows and flanges also add to the total HOM power. NGLS requirements are close to those of EuXFEL, but with higher CW current, and the initial design assumes a HOM damping scheme similar to EuXFEL with annular distributions of lossy materials inserted in warm sections between cryomodules. At 0.3 mA this scheme appears to be appropriate, and studies of HOM effects show only small amounts of power dissipated in cavities from resonant HOM's or from modes above cut-off, and no significant impact on beam dynamics. HOM damping is difficult and expensive to upgrade, and final design choices should include consideration of potential future beam current and time structure changes.

Production Cavity Processing

Production cavity processing models for large SRF projects - EuXFEL, CEBAF-12 GeV upgrade, and ILC R&D – have been analyzed in the context of NGLS cost optimization. For EuXFEL, with a large production volume, industry dominates processing; for >250 cavities/year this model works well. Sufficient fabrication, process and test capability is available within the US to supply cavities for NGLS, considering FNAL/ANL, JLab TEDF, and industrial partners. Assembly automation for reproducibility may be desirable, but for relatively small production runs of 200 cavities or so, may be cost prohibitive. Labor will likely remain a large component of the cost of a small (~30 cryomodule) linac. Significant improvements to

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processing costs stem from optimizing labor between and within Labs and industry, e.g., removing processing steps as described above.

An analysis of cavity fabrication and production costs indicates that R&D to achieve high Q_0 has the largest impact to cost; however, significant changes to processing recipes have to be tested with sufficient statistics through the entire sequence to cryomodule assembly.

LINEARIZER CRYOMODULE

Fermilab has built a four cavity, 3.9 GHz, linearizer cryomodule for DESY/FLASH, including cavity design and fabrication, vertical and horizontal test qualification, cryomodule assembly and delivery [17]. All cavities exceeded the 18.9 to 19.7 MV/m requirement for FLASH gradient, and the cavities are capable of being operated at 22 MV/m, with the limitation set by thermal interlocks on HOM's [18]. NGLS requires ~12–14 MV/m and 7 cavities. To support CW operation for NGLS, such a cryomodule would require study of the heat loads and cryogenic distribution particularly for the end-groups, input coupler power capability and cooling, HOM coupler and feedthrough capability, and an analysis of microphonics and fast tuning.

RF POWER SYSTEMS

Three potential technologies are currently available for RF power sources for a CW linac; klystrons, inductive output tubes (IOTs), and solid-state. Klystrons are widely used, for example at JLab including for their current 12 GeV upgrade project. IOTs have lower gain than klystrons and there is less experience and information on reliability and operational stability than with klystrons, in particular above the UHF TV frequencies and in L-band. Solid-state technology has shown great advances in recent years, and implementations in accelerators are starting to be seen. For CW application, vacuum tubes don't have the typical advantage of the ability to deliver much higher peak powers while keeping within their average power rating; thus solid state amplifiers are intrinsically a good match for CW systems. Further details of the design for NGLS RF systems can be found in [19].

Configuration Options for RF Power Sources and Distribution

The NGLS baseline design assumes a single RF power source for each cavity. Such a configuration is appealing in its simplicity and potential stability in operations, although more expensive than using a large amplifier feeding several cavities. Several advantages can be identified for this individually powered cavity configuration:

- Control of the individual cavity fields is more exact and relatively simple to achieve
- Statistical fluctuations between systems are more likely to average out
- Improved machine availability through "soft" failure of transistors (gradually losing output power)
- Ease of replacement of failing units during scheduled maintenance
- Simpler beam containment and machine protection systems to accommodate "soft" failure modes
- Short transmission line between power amplifier and cavity (less heat dissipated, higher bandwidth control)

A single large amplifier driving multiple cavities requires a large structure for RF power distribution, potentially high-power vector modulators to control phase and amplitude of each cavity, and greater impact of system failures on operational uptime.

The adoption of solid-state technology for the power amplifiers could add the potential benefit of making a future RF power upgrade more simply achieved by adding rack-mounted units. However at present this option is more expensive than the klystron based alternative.

Reliability, and Operating Modes

Institutions operating CW SCRF linacs experience multiple daily nuisance trips that would impact uptime – each cavity trip requires the beam to be shut off while a tripped cavity is slowly (over seconds) brought back into control (and other cavities may also be driven out of control when an individual cavity experiences a trip). Statistics and understanding of the causes of such trips need to be accumulated. While it is well known that lower gradient helps reduce the number of trips, most trips come from the RF power and distribution system (including RF windows) and not from the RF cavities.

JLab experience is that it is impractical to operate all cavities at the same gradient, because each cavity has different Q_0 and maximum operating gradient due to limitations such as available RF power, dark current, and field emission. A solution with each cavity powered by a single amplifier would ease this problem, since it provides the most flexibility in coping with these effects.

LLRF, CONTROLS & DYNAMICS

The state of RF control for SCRF linacs has developed to the point that the stringent specifications of a future light source based on this technology are well within reach. A single source driving a single cavity is preferred because of the advantages is overall control, flexibility, and reliability.

The combination of RF and beam-based feedback has already demonstrated sub-20 fsec jitter at FLASH. One area of improvement that has not yet been exploited is reduction of the jitter of the injected beam by direct feedback on the injector systems. Further study of the weighting of RF and beam-based feedbacks for a CW SCRF machine is needed, in particular analysis of the resolution of the diagnostics in reduction of the beam jitter.

The ultimate energy, timing, and peak current stability of the linac is driven by two factors: jitter of the beam parameters from the injector and additional jitter added to the beam from the RF system. Further details of the

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design for NGLS LLRF and feedback systems can be found in [20].

LLRF Cavity Control

The goals for NGLS RF amplitude and phase stability of 0.01% and 0.01°, have been demonstrated in several operating systems. This capability is approaching the fundamental noise limit of the RF receivers, so significant improvement beyond this level is not expected. The tremendous processing power of FPGA-based modern digital controllers can provide a number of other features including state recording for fault diagnosis, online diagnostics, learning feedforward and feedback capabilities, self calibration, self-excited loop for initial cavity powering, and microphonics control. Each controller has a strong link the accelerator control network to allow for feedback over the entire accelerator complex.

Beam-based Feedback

The use of beam-based feedback (BBF) requires measurements of the beam energy and bunch length response to amplitude and phase variations of the RF fields. The inverse of this response matrix is used to convert energy and bunch length variations to changes in amplitude and phase set points. At FLASH, the BBF is operated at the bandwidth of the bunch repetition rate of 3 MHz with delays of 2 microsec. The net result is that FLASH can reduce the arrival time jitter after the bunch compressor from 75 to 25 fsec. Other studies at FLASH have seen jitter below 20 fsec, corresponding to an amplitude stability of $3x10^{-5}$. Because of the pulsed RF and beam, there is an additional level of sophistication to the FLASH approach compared with a CW RF and beam. Feedback and stability expectations for NGLS are reported in [20].

CRYOMODULES

The NGLS linac design features discrete cryomodules each with cold/warm transitions, 8 RF cavities per cryomodule, and with magnets, diagnostics and HOM absorbers located in warm beampipe sections between cryomodules. The cryomodule concept, outlined in Fig. 2, is based on the ILC design modified for individual cryomodule implementation, and embraces JLab and SNS experience that suggests that individual cryomodule segmentation has advantages for operational and maintenance flexibility. However, Cornell and HZB have devised a TESLA-like scheme of longer cryomodule strings for CW SCRF applications. The length of a single cryomodule is limited by the ability to transport a unit.

With segmentation at the individual cryomodule level, code approval of the vacuum vessel as the containment vessel is possible and may have some advantages over code approval of individual helium vessels. Testing in a different horizontal test cryostat, however, might still force approval of individual dressed cavities, especially testing at other laboratory facilities. Proving containment by the vacuum vessel for any internal event may not be simple. Fermilab has developed a scheme for pressure vessel compliance of niobium cavities in titanium helium vessels [21].

1.8 K heat transport of approximately 10 W per cavity through saturated liquid helium to the evaporative surface via a “chimney” pipe places new requirements on pipe size for heat transport. Attention must also be given to heat transport within the cavity helium tank and at cavity end groups. Tests have verified the theoretical limits and ability to transfer heat from CW SRF cavities via helium II heat transport [22]. Electric heat at the 1.8 K portion of the cryomodules for compensating RF dynamic load and for control is standard and appears necessary.

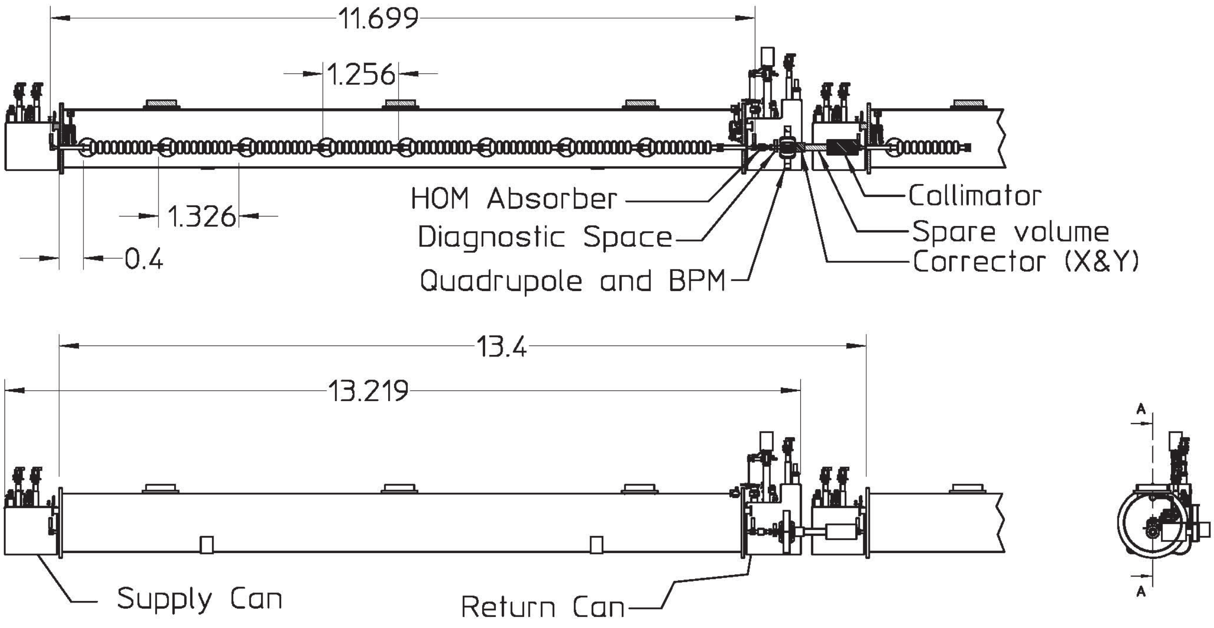

Figure 2: Engineering layout of the NGLS cryomodule concept, dimensions in m.

The NGLS heatload is 90–130 W per cryomodule at 1.8 K, dependent on which part of the linac the cyomodule is located and what beam energy the systems are optimized for, and is dominated by dynamic losses.

CRYOSYSTEMS

The NGLS cryogenics systems are designed for a total heatload of 3.8 kW at 1.8 K, including efficiency factors and uncertainties in heat loads. The systems will distribute 5 K liquid, cooled to 1.8 K by expansion at each cryomodule. The cryoplant will be designed for He mass flow similar to an existing LHC cryoplant also operating at 1.8 K. Figure 3 shows a schematic of the cryogenics distribution circuits.

Cryosystems technology for SCRF accelerators is becoming mature, and adaptations to CW operation seem straightforward and reasonably well understood. Examples of large-scale cryosystems of similar size to those needed for NGLS exist at JLab and at CERN, and there is similar relevant experience for high power pulsed systems (SNS) and smaller scale tests such as those at Cornell, HZB in Berlin, and at DESY in Hamburg. SNS experience of using failure modes and effects analysis has achieved reliability of >99.6%. [23].

Determination of the NGLS cryogenic plant installed capacity relative to load has two facets:

(a) The very large dynamic 1.8 K heat load relative to static (as much as a factor of 10 or more), which varies with RF and beam conditions. Heaters in the cryomodule two-phase system will be required to compensate these loads prior to turn-on or after turn-off of RF and beam. These heaters are also beneficial for steady-state operational control including with full RF power.

(b) Matching the plant capacity to the actual operational load. The cryogenic plant must be specified and procured before system heat loads are fully known, so plant capacity estimates include a margin for uncertainty. The nominal operating power of the cryogenic plant may end up different from its design optimum, which may result in inefficient operation and higher than optimal operating costs. Efficient plant "turn-down" can help alleviate this problem. LHC experience is for a factor 3 in turn-down capacity; a factor 10 is predicted to be feasible for their cryosystem by adjusting cold compressor discharge pressure (which equals room temperature pump inlet pressure in the CERN hybrid system) [24].

LHC experience favors a system for 1.8 K with three cold compressors in series (as opposed to four cold compressors) followed by room temperature pumping for ease of control and operational flexibility. The LHC systems differ from the JLab and SNS systems, which consist entirely of trains of cold compressors without room temperature pumping. LHC has incorporated valves and a mixing chamber in the 1.8 K portion of their cryogenic plant for restart of cold compressors with the system cold and at subatmospheric pressure [24, 25].

Instrumentation in the return vapor transfer line from each cryomodule to measure cryomodule flow rate (hence heat load) is a potentially useful improvement over existing systems. The problem of measuring flow rates in very low pressure, low temperature helium vapor could be studied in an R&D project. Flow measurement methods such as orifice plates or venturis would generally not work well due to the very low absolute pressure and requirement of low pressure drop, but other methods could be investigated.

Development of appropriately scaled systems operating below 1.8 K would likely cost more than potential savings from such a system. A new, lower stage of cold compressor would be required, operating at lower helium densities than up to now. It appears that the best choices for NGLS are limited by cold compressor technology to 1.8–2.0 K.

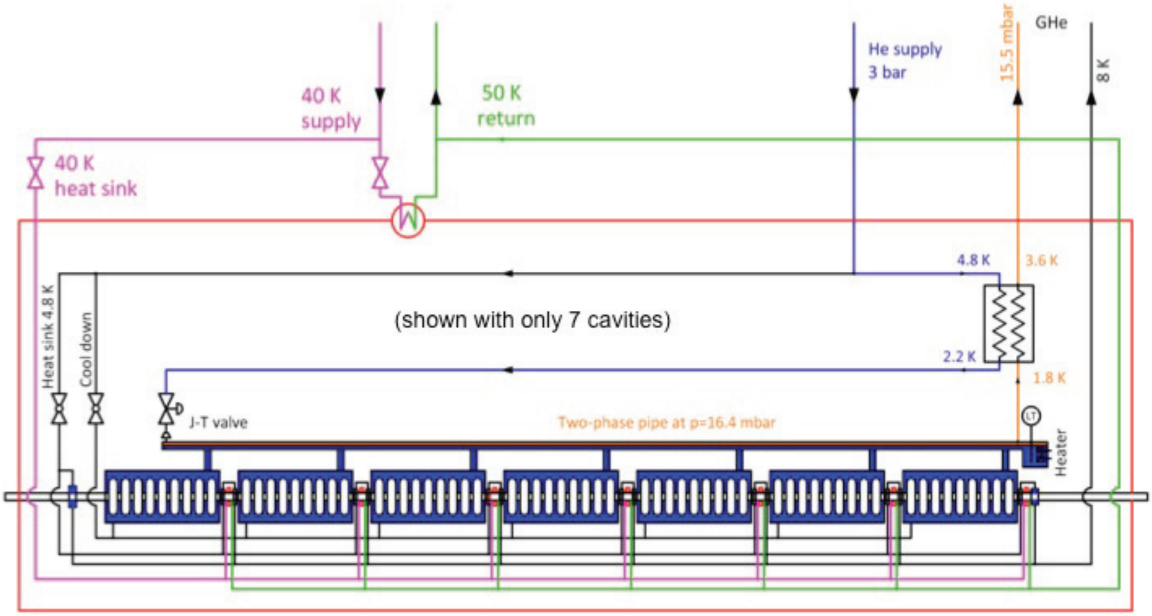

Figure 3: Schematic of the cryogenics distribution circuit.

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