A LINAC FOR THE SPALLATION NEUTRON SOURCE*

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Abstract

The Spallation Neutron Source Project (SNS), to be constructed at Oak Ridge National Laboratory, accelerates H^- ions to an energy of 1.0 GeV with an average current of 1-mA for injection into an accumulator ring that produces the short intense burst of protons needed for the spallation-neutron source. The linac will be the most intense source of H^- ions and as such requires advanced design techniques to meet project technical goals. In particular, low beam loss is stressed for the chopped beam placing strong requirements on the beam dynamics and linac construction. Additionally, the linac is to be upgraded to the 2- and 4-MW beam-power levels with no increase in duty factor. We give an overview of the linac design parameters and design choices made.

1 OVERVIEW

The SNS project is described in depth elsewhere [1,2]. Los Alamos is responsible for the design and construction of a linac suitable to meet project specifications. H^- beam enters the linac at an energy of 2.5 MeV with a peak current of 27.7 mA and a normalized rms emittance of 0.23 π-cm-mrad. The linac input beam is produced by a "front-end" assembly that sequentially consists of an ion source, RFQ, and transport line that contains a chopper. The chopper provides a gap in the beam as required by the accumulator ring extraction scheme. Lawrence Berkeley Laboratory is responsible for the front end [2] except for the chopper system that is to be constructed by Los Alamos. The linac output energy is 1.0 GeV with little emittance growth or current loss and will maintain the nominal time structure of the input beam. Beam then enters a transport line and is conveyed to an accumulator ring, to be constructed by Brookhaven National Laboratory [3]. It is also a Los Alamos task to construct and power a bunch rotator in the transport line. The ring, at constant energy, accumulates the nominal 1-ms-long linac macropulses to an intense proton pulse of 590-ns duration for impingement on the spallation target. The average beam power on the target is 1.0 MW with a pulse rate of 60 Hz. The beam-power is upgradeable to up to 4 MW by increasing the peak linac current.

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2 BASIS OF DESIGN

Requirements on the linac included cost effectiveness, high operational availability, low beam loss, upgradability, high beam quality, and insensitivity to chopping. We believe that the present design meets these criteria. A block diagram of the linac is shown in Figure 1.

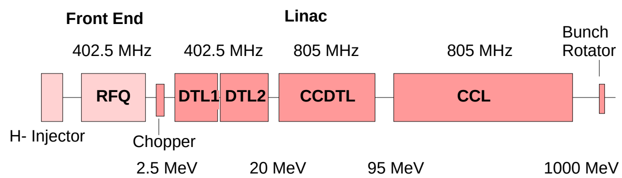

Figure 1. Block diagram of SNS linac

The linac consists of a drift-tube linac (DTL) up to 20 MeV, a coupled-cavity drift-tube linac (CCDTL) to nominally 95 MeV and a coupled-cavity linac (CCL) to the full energy. The DTL and the CCL are well known structures, appropriate to their energy ranges. The CCDTL, though a recent invention, has received cold-model testing and is considered a good intermediate structure between the DTL and CCL in terms of beam-dynamics matching and shunt impedance. This structure has other advantages and is believed to be the optimum choice in the given energy range.

In order to minimize cost, a tradeoff study was conducted early in the project that varied the linac gradient. On the basis of this study an average gradient (E_0T) of 2.7 MV/m was chosen. Later and more accurate costing showed this to be near the optimum value. The length arrived at was 493 m giving a real-estate energy gradient of 2.02 MeV/m. Although higher than many previous proton linacs, the peak field is everywhere less than 1.5 Kilpatrick, a safe value. Because of the high gradient, a relatively large amount rf power (slightly less than 100-MW peak delivered to the linac) is needed.

The linac rf frequency was similarly chosen; assessment of this and other design choices showed that frequencies near 800 MHz have best performance and lower cost. The exact frequency of 805 MHz was chosen because of our familiarity with the LANSCE linac and subsequent ease of technology transfer as well as an assessment of klystron cost and availability. The 402.5-MHz value for the structure frequency below

20 MeV was chosen to allow funneling in future upgrades.

Low beam loss and high availability are closely related. The linac structure must suffer only low levels of activation so that maintenance and upgrade can be done quickly. A spacious aperture and adequate steering are important in this regard and are part of the design. Furthermore, our calculations show that with good matching, halo formation will contribute negligibly to beam loss. However, it is expected that the predominant beam loss will occur by stripping of the negative hydrogen ions through collision with background gas. Calibration of the LANSCE-linac activation and loss-transport calculations are convincing that, at 1 GeV, a loss of 1 nA/m will cause activation of greater than 10 mrem/hr an hour after shutdown at a distance of 1 ft. To achieve this low-loss level at the 4 MW upgrade, a vacuum of $5x10^{-8}$ torr is required and, with proper design, is achievable.

A room-temperature structure was chosen over a superconducting structure largely to minimize technical and schedule risk. An assessment showed that if an R&D program were successful in addressing the issues of transient control and power coupling, the capital cost and schedule would be little affected and that the operating costs would be decreased by nearly 4 M$ per year. Nonetheless, if such an R&D program were to run into difficulties, the program schedule and cost would be strongly affected.

3 CHOPPING

A 35%-duty-factor chopping at 1.189 MHz (just slightly off the ring revolution frequency) is applied to the beam before entering the linac by a traveling-wave deflector. This decreases the average macropulse current to 18.8 mA for the 1-MW case. The chopper rise time should be under 2.5 ns to prevent partially chopped pulses from entering the linac and possibly creating additional loss downstream. R&D work [4] is in progress to define a deflecting structure and modulator that can provide the required 18-mrad deflection in a 0.5-m deflecting structure with such a challenging rise time. FET drivers with the required rise time are not commercially available; development work with a semiconductor manufacturer is scheduled. A device with 5-ns rise time is judged to be immediately feasible and construction of a prototype is underway. This decreased rise time may be adequate for the 1-MW scenario.

The chopper plays a secondary role in providing time-width modulation of the beam in order to maintain constant peak current during the 20-μs ramp up planned at the macropulse start.

Transient analysis has been done to evaluate the effect of chopping on the linac-cavity fields. Negligible excitation of high-order modes was found. The main effect predicted is a 3% field variation in the 4-MW case throughout the linac at the chopping frequency. The major effect is a broadening of the energy and phase width, small compared to the unperturbed parameters. The effect is inversely proportional to the accelerating field, thus further justifying the high linac gradient.

4 STRUCTURES

The 402.5-MHz DTL is 8.7-m long and uses a FOFODODO lattice with period 8 βλ (at 805 MHz). This was chosen over a FODO lattice to allow feasibility of permanent-magnet quads in the drift tubes. To achieve good field stabilization, the DTL is broken into two tanks at the 10-MeV point. The structure tune is maintained by regulating water temperature.

The 68.8-m long CCDTL uses a 12-βλ FODO lattice. Each of the 101 segments (structure between quads) contains two cells of length 3βλ/2, each with one drift tube. The space for quadrupole magnets, containing a coupling cavity is 6βλ/2, allowing sufficient room for quadrupole magnets and diagnostics but requiring a low acceleration gradient of 1.08 MeV/m. An adequate prototype quadrupole magnet has been made.

The CCL comprises the remaining 85% of the structure length and uses a 12-βλ FODO lattice. Up to 166 MeV the structure has eight cells per segment with 2-βλ quad spaces. The large intersegment spacing provides adequate space for quads and diagnostics. At higher energies, where βλ has increased sufficiently, a 10 cell segment is used with 1-βλ quad spaces.

The segments are joined by coupling cells to form isolated rf modules. Bridge couplers are not used; the modules are driven by from 1 to 3 klystrons in a symmetrical feed-point arrangement that minimizes field droop in a module. Partitioning of the modules has been chosen to facilitate upgrades. The choice of an even number of half βλ cells in the segments permits all segment couplers to remain on one side of the structure for simplified mounting, fabrication, and vacuum pumping. Structure tune is maintained by regulating the cooling water temperature for each module against cavity frequency offset.

5 BEAM DYNAMICS

The linac beam dynamics along with the physics design is discussed elsewhere [5]. We here note a few salient features. Variants of the code PARMILA were used to define and find a matched beam for each structure. The structures are joined and smooth matching done across structure transitions with appropriate phase and field ramping. There are no explicit matching sections; matching is done between structures by the quads and structure design. As well as matched beam studies, error studies and end-to-end simulations have been done using 10,000-particle sets starting from the RFQ output. We plan to increase the size of this particle set by using massively parallel processing.

The aperture size is maintained at 10 times the beam rms size to promote low beam loss; predicted halo growth will not intercept the aperture even with alignment errors and can be readily scraped in the transport line to the ring. A plot of aperture versus energy is shown in Figure 2.

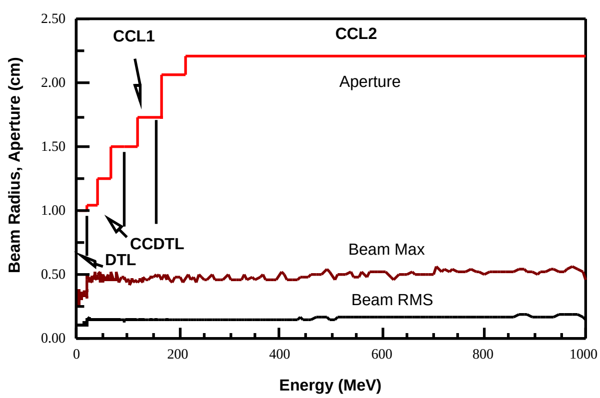

Figure 2. Aperture and beam size in the linac

6 RF SYSTEM

The rf system [6] will deliver approximately 99 MW peak power at 7.02% duty factor to the structure for an average power of 6.74 MW. The ac wall-plug power has been specified at 22 MW. Two 1.25-MW peak-power klystrons drive the DTL and a third klystron will be provided for the RFQ. The remainder of the structure uses 56 anode-modulated 805-MHz 2.5-MW klystrons in the baseline design. Allowing for control margin and system losses, 2-MW are available to the structures. Klystron size was determined from optimization of cost, technical feasibility, and relation to linac-structure. The anode modulation was judged to be the most technically feasible method of pulse switching. However, recent developments indicate that an IGBT switching system is likely feasible and will be substantially more cost effective; R&D work is planned for this approach. A two klystron modulator, developed in previous projects, is planned, also for economic reasons. The klystron modulators are located above and lateral to the linac tunnel in a gallery that contains the water systems, vacuum pump controls, low-level rf controls and beam-diagnostics electronics. The rf system will control the cavity fields to within ±1% and ±1° through a stable reference system and using sophisticated feedback techniques, including fast adaptive feed forward.

7 UPGRADES

The requirement that the SNS is to be readily upgradeable to beam powers up to 4 MW in a staged approach strongly affects the 1-MW design. An upgrade to 2-MW, with doubling of the ion-source current, could be accomplished by redefinition of the linac rf modules and the addition of rf power (14 klystrons). Upgrade to 4 MW requires beam funneling at 20 MeV because of likely ion-source limitations and the inability of the RFQ to accelerate the 108-mA current at 805 MHz. A second linac reconfiguration is then required along with addition of 14 more klystrons. The linac reconfiguration could be done without structure replacement by redefining the number of segments (half focusing periods) of the rf modules and terminating the module ends with special $\lambda/10$-cavity sections. Thus a module end could be defined by removing a CCDTL or CCL coupling cavity and terminating the two cells previously joined by the coupling cavity. Correspondingly a module could be extended by removing adjacent terminating cells and joining the terminating segments with a full coupling cell. Drive points and waveguide runs would have to be built into the design at initial construction. However, substantial effort would be required to effect the reconfiguration as well as in the initial design. A simpler scheme has recently been discussed that would use two klystrons for each of 26 rf modules and eliminate any structure reconfiguration in a direct upgrade from 1 to 4 MW. Here a third klystron would be added to the center of each module. and provision would be made for the appropriate (small) change in rf matching during the initial design.

8 REFERENCES

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