HIGH-POWER LINAC FOR A US SPALLATION-NEUTRON SOURCE

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Abstract

We present the status of the high-power linac-design studies for a proposed National Spallation Neutron Source (NSNS), based on a linac/accumulator-ring accelerator system. The overall project is a collaboration involving five national laboratories. The Oak Ridge National Laboratory will be responsible for the target, facilities, and the conceptual design; Brookhaven National Laboratory will be responsible for the ring; Lawrence Berkeley National Laboratory will be responsible for the injector, including the RFQ and a low-energy chopper located in front of the RFQ; Los Alamos National Laboratory will be responsible for the main linac, and the Argonne National Laboratory will be responsible for the instrumentation. The facility will be built at Oak Ridge. In the first phase, the dual-frequency linac with frequencies 402.5 and 805 MHz must deliver to the accumulator ring an H^- beam with nominal energy near 1 GeV, with a pulse length of about 1 ms at a repetition rate of 60 Hz, and with a nominal average beam power of at least 1 MW. The linac can be upgraded by a factor of four in beam power by increasing the dc-injector current, and by funneling the beams from two 402.5-MHz low-energy linacs into the 805-MHz high-energy linac. Requirements for low beam loss in both the linac and the ring have important implications for the linac design, including the requirement to provide efficient beam chopping, which is necessary to provide low-loss extraction for the ring. The linac-design options and initial parameters will be presented, together with initial beam-dynamics simulation results.

Introduction

In 1995 the US Congress commissioned Oak Ridge National Laboratory to conduct a two-year conceptual design study for a new pulsed spallation neutron source. Oak Ridge has formed a collaborative partnership with four other US national laboratories, LBNL, BNL, LANL, and ANL for the design and construction of the new facility. The design work builds on a strong base of recent studies for high-power spallation sources performed at ANL[1], LANL[2], BNL[3], and the European Spallation Source (ESS)[4] study. The conceptual design effort has been underway for about 8 months, and significant progress has been made in defining the reference design parameters.[5] The facility must initially deliver a beam in the 1-MW power range with high confidence, and must be upgradable to the 5-MW power range.

Two architectures for the accelerator were considered for the Reference Design, a full-energy linac plus an accumulator ring, and a lower-energy linac and a synchrotron ring. Based on consideration of the technical risks and the upgrade paths, the accumulator ring approach was chosen for the reference design. For the initial stage of the reference design the nominal parameters include a beam to target power of 1-MW, a beam energy of 1 GeV, and a repetition rate of 60 Hz.

Linac Reference Design

The main design requirements for the NSNS linac for the first phase of a 1-MW facility are 1) 1.1-MW average beam power at 1 GeV for the linac output beam (the extra 0.1 MW accounts for the minimum 90% injection efficiency into the ring), 2) 60-Hz pulse repetition rate, 3) linac beam losses below about 10^{-7}/m to avoid high accelerator radioactivation, so that remote maintenance is not necessary, and 4) chopped beam to allow low-loss extraction from the ring. Table 1 shows the main reference-design parameters, and Fig. 1 shows a block diagram of the NSNS-linac reference design.

Table 1: Linac Reference Design Parameters

Ion	H^-
RF frequency	402.5/805 MHz
Final energy	1000 MeV
Average beam power	1.1 MW
Average beam current	1.1 mA
Pulse repetition rate	60 Hz
Pulse period	1.03 ms
Beam duty factor	6.11%
Chopper transmission	0.65
Average pulse current	18.0 mA
Peak pulse current	27.7 mA
DC injector output current	34.6 mA
DC injector rms normalized emittance	0.14 mm-mrad
Peak beam power	18 MW
Peak structure-power losses	96 MW
Peak rf power	114 MW
Average rf power	8.0 MW
No. 1.2-MW, 402.5-MHz klystrons	3
No. 5.0-MW, 805-MHz klystrons	30
Total length	566 m

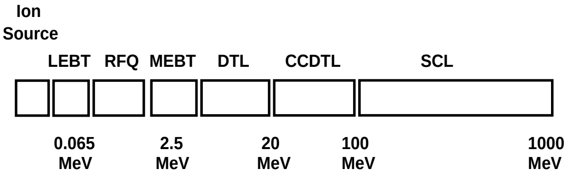

Fig. 1 Block diagram of the NSNS 1.1-MW linac

As the proton energy increases, different accelerating structures provide maximum power efficiency, while satisfying the beam focusing requirements. The H^- multi-cusp volume source delivers a nominal 65-keV 35-mA beam into a compact electrostatic Einzel-lens low-energy beam transport (LEBT), which transports the beam and matches it into the first linac structure, the radiofrequency quadrupole (RFQ). The RFQ is a 4-vane structure operating at 402.5 MHz with a vane length of 3.7 m, which bunches the dc beam with high transmission and accelerates it to 2.5 MeV, while focusing the beam using rf electric quadrupole fields. After the RFQ, the medium-energy beam transport (MEBT) matches the beam into the next structure, a drift-tube linac (DTL), and provides beam chopping, which will be described later. The ion source, LEBT, RFQ, and MEBT will be designed and manufactured by LBNL. The rest of the linac, as well as the 2.5-nsec chopper system in the MEBT will be designed and manufactured by LANL. The RFQ is designed to accommodate the full 55 mA required for the future upgrade, but will operate at 27.7 mA for the initial 1-MW operation. The all-electrostatic LEBT with chopping will be similar to one reported on at this conference[7]. The RFQ beam dynamics are conservative, and like the rest of the linac, an important engineering issue will be the thermal management at the high 6% duty factor operation. This requirement, and that of stabilizing an RFQ structure that is five wavelengths long, are the main design issues, which are currently being studied using extensive 3-D simulations.

A two-tank 402.5-MHz DTL, with SmCo permanent-magnet quadrupole lenses in the drift tubes, accelerates the beam to 20 MeV. This is followed by an 805-MHz linac, which is comprised of two sections. First is the coupled-cavity drift-tube linac (CCDTL)[6], which accelerates the beam to 100 MeV. The CCDTL consists of a chain of coupled accelerating cavities, each accelerating cavity containing a single drift tube. The accelerating cavities, which are $3\beta\lambda/2$ in length, are electromagnetically coupled through side cavities in the same manner as the familiar side-coupled linac (SCL), and therefore is really a side-coupled drift-tube linac. The CCDTL structure operates in a mode that is completely equivalent to the stable $\pi/2$ operating mode of the SCL. Transverse focusing is provided by electromagnetic quadrupoles that are periodically installed in spaces that would have been occupied by an accelerating cavity and that are easily accessible for alignment. The next and final accelerating structure is the SCL, which accelerates the beam to 1 GeV with focusing provided by electromagnetic quadrupoles installed between the tanks. The parameters of the initial SCL design are given in Table 2.

Table 2: Side Coupled Linac Parameters

Frequency	805 MHz
Cells per tank	14 to 11
Bore radius	2.2 cm
Axial accelerating field E_0T	2.8 MV/m
Effective synchronous phase	-30^o
Peak cavity-power loss	84 MW
Peak beam power	16 MW
Peak rf power	100 MW
Number of 5 MW klystrons	27
Total length	496 m

The linac must contain two frequencies which differ by a factor of two to allow an upgrade with beam funneling. Optimum choices range between about f/f_0 = 200/400 MHz to 500/1000 MHz. We have chosen f/f_0 = 402.5/805 MHz because of 1) compatibility with the 805-MHz system of rf and beam diagnostic hardware of the LANSCE linac, 2) immediate availability of existing 402.5-MHz klystrons and rf equipment from a previous project, and 3) immediate applicability of the results from the previous LANSCE upgrade study, which used exactly these frequencies.

The beam-chopping requirement is such that the linac must inject a beam with 278-ns current-free (to better than 10^{-4}) gaps every 795 ns to limit the beam spill in the ring, when the kicker magnets are energized for beam extraction. The chopping is most easily implemented at the low-energy end of the linac to facilitate the thermal management of the chopped beam. The reference design calls for three stages of chopping, so that most of the beam to be chopped is removed at the lowest energy, and the most effective chopping structure can be used at a high enough energy that space-charge effects do not degrade the beam quality. The three stages are 1) chopping in the ion source, 2) chopping in the 65-keV electrostatic LEBT, where each Einzel lens is split into four quadrants to add a pulsed transverse deflecting field to the constant focusing field, and 3) a chopping system based on a traveling-wave deflecting structure in the MEBT. The chopping in the ion source and the LEBT chopping will remove most of the beam to be chopped. In the 2.5-MeV MEBT the beam is focused in all three planes so that the beam is not allowed to debunch, and the chopping system in the MEBT provides the final clean chopping. The present MEBT design uses triplet quadrupole lenses to create three long drift spaces for the basic elements of the chopping system, 1) a traveling-wave deflecting structure for the chopping, 2) a collimator to remove the deflected beam, and 3) a traveling-wave deflecting structure to restore to the beam axis the beam that is not removed by the collimator, because it enters the chopping structure when the field is rising or falling.

The 805-MHz rf-system design is based on nominal 5-MW klystrons. For high reliability only 4-MW is supplied from each klystron to the accelerator. Because of power limitations of the rf windows, the total rf power per klystron is split into two parts of 2-MW each, which are then delivered through an iris coupler into the accelerating structures. The field distribution of the accelerating cavities is not sensitive to the exact placement of the drive points, because of the strong coupling (near 5%) of the cells and the stability of the $\pi/2$ operating mode.

The DTL focusing is provided by a FFDD lattice. For the CCDTL and the CCL, both singlet and doublet focusing lattices are being studied. Beam dynamics simulation studies including the effects of the space-charge forces will be an important tool for predicting the output beam emittances and the beam losses. Initial simulation studies have been carried out for the SCL structure assuming a doublet focusing lattice and using constant-length and constant-strength focusing quadrupoles. We have injected an input beam with uniformly charged ellipsoidal bunches and with an initial mismatch such that the initial beam projections are smaller than the matched values by 20% for the two transverse axes and by 50% for the longitudinal axis. For initial rms normalized emittances of 0.025 cm-mrad for x and y and twice as large for z, we find an emittance growth of less than 10% in x and y, and less than 5% in z. After the initial transient caused by the mismatch, the ratio of aperture radius to transverse rms beam size ranges from about 8 near 100 MeV to about 13 at 1000 MeV, values which should produce acceptably small beam losses, provided that errors such as misalignment of the quadrupoles are sufficiently small. Eventually, an end-to-end beam simulation from the ion source to the end of the linac will be needed to provide the expected values of the important emittances and aperture to rms beam size parameters that characterize the beam dynamics.

An upgrade for the linac to 4.4 MW can be achieved through the following steps: 1) doubling the ion-source output current to 70 mA, 2) installing a second 20-MeV linac, and a beam funnel at 20 MeV, which will fill all buckets of the 805-MHz linac, and 3) installing the additional rf power needed for the increased beam current.

Two important technical questions for the NSNS linac are: 1) how clean and effective the beam chopping can be made without degrading the linac-output-beam quality, and 2) how well the beam losses can be controlled for the H^- beam. The losses are expected to be lower than for the LANSCE linac for three reasons: 1) for LANSCE the beam tune is optimized primarily for the higher intensity H^+ beam, which results in missteering for the H^- beam, 2) the H^- emittance from the ion source is 50% larger than that expected for the NSNS source, and 3) the use of an RFQ promotes good low-energy bunching, which eliminates unwanted tails in longitudinal phase space.

Summary

We have presented a linac reference design for the NSNS linac. The initial beam dynamics simulations suggest that excellent beam-dynamics performance should be achievable. The next steps will be to study the chopping systems, and to produce end-to-end beam simulations from the ion source to the accumulator ring to study both chopping and beam loss.

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