HIGH-POWER OPTIONS FOR LANSCE*

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Abstract

The LANSCE linear accelerator at Los Alamos National Laboratory has a long history of successful beam operations at 800 kW. We have recently studied options for restoration of high-power operations including approaches for increasing the performance to multi-MW levels. In this paper we will discuss the results of this study including the present limitations of the existing accelerating structures at LANSCE, and the high-voltage and RF systems that drive them. Several options will be discussed and a preferred option will be presented that will enable the first in a new generation of scientific facilities for the materials community. The emphasis of this new facility is "Matter-Radiation Interactions in Extremes" (MaRIE) which will be used to discover and design the advanced materials needed to meet 21st century national security and energy security challenges [1].

INTRODUCTION

The LANSCE accelerator complex currently supports a broad user base including the neutron scattering community, isotope production, basic science, and national security programs by providing multiple beams to several diverse experimental areas. The LANSCE linac accelerates negative hydrogen ions (H^-) and protons (H^+) simultaneously. An 800-MeV H^- beam is delivered at 20 Hz to the proton storage ring/moderated neutron production target for a suite of neutron-scattering instruments. H^--beams are also delivered to other experimental areas at 800 MeV for proton radiography, ultra-cold neutron production, and for nuclear physics cross-section measurements. Protons are used for isotope production at 100 MeV. High-power operation using the 800-MeV, H^+-beam was halted in 1998. Historical high-power operation (10% total RF duty factor; 100 Hz x 625 µs; 16.5-mA peak proton beam current) resulted in 800-kW average beam power at an 800-MeV final energy.

At present, the linac is limited to 60-Hz operation due in part to degrading performance of the Burle 7835, 201.25-MHz power triode of the amplifier system for each module of the of the drift-tube linac (DTL). However, a plan to upgrade major components of the LANSCE accelerator complex that will ensure overall long-term reliability and enable a return to high-power 120-Hz operation (100 Hz H^+, 20 Hz H^-) has been funded recently [2] and is expected to be completed in FY2016.

The primary application of a high-power proton beam capability for LANSCE will be to generate neutrons for users of the planned Materials Test Station (MTS) [3] and the MaRIE Fission Fusion Materials Facility (FFMF). The concept for the FFMF irradiation area is based on the MTS spallation target design and an upgrade to the LANSCE proton beam power to 2.0-MW, although even higher beam powers are being considered (up to 5 MW). Experiments performed at MTS/FFMF are intended, for example, to address fundamental radiation damage phenomena with the goal of improving materials for future fission and fusion reactors. All upgrades must preserve beam delivery to the existing users.

Operation at an average beam power on target of 1 MW is the baseline requirement for the MTS, achieving 4.5% per calendar year fuel burn-up in highly enriched fuel and 18 dpa/year damage in steel. This assumes 4400 hours per calendar year full beam power on target and 800-MeV beam operations.

An average power upgrade to 2 MW would achieve neutron flux and irradiation volume equivalents similar to those expected to be achieved by the IFMIF [4]. Materials damage rates of 50 dpa per full-power year (fpy, assumes 100% availability for the entire year) and irradiation volumes of 0.3 liter with > 20 dpa/fpy are achievable with an expected 2.5×10^{15} n/cm^2/s peak neutron flux in the fuel irradiation region. Desired operational parameters are ≥ 100 Hz repetition rate, ≥ 0.75 ms pulse length, and beam energy in the range 800 MeV to 3 GeV.

A 5-MW power upgrade to the LANSCE accelerator would provide a world-class neutron irradiation environment allowing peak neutron fluxes of 5.0×10^{15} n/cm^2/s, equivalent to the peak fluxes in the JOYO reactor and exceeding BOR-60 (3.40×10^{15} n/cm^2/s) [5]. Besides providing the highest neutron flux in the world, this power level would allow fuel cladding to be taken to damage rates of 200 dpa in four years. This enables the development of higher burn-up fuels that would significantly reduce the life-cycle cost of the fuel cycle. Desired operational parameters are similar to the 2-MW case.

LANSCE LINAC LIMITATIONS

Achieving >800-kW beam power will require increasing either the duty factor, peak beam current, and/or final beam energy of the LANSCE linac beyond historical values. However, our ability to increase the LANSCE beam power by increasing duty factor is primarily constrained by known accelerating structure and high-voltage DC power system limitations. Table 1 summarizes these limitations.

DTL duty-factor limitations were estimated using RF electromagnetic field (RF-EM) and thermal/mechanical (T/M) models to investigate RF heating of the indirectly-cooled copper bellows that are located at the top of every drift-tube stem inside the tanks of the DTL while operating at design field levels. These bellows are believed to be the weak link in the DTL structure. Results

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indicate a maximum RF duty-factor limit of 15% when poor thermal contact of the bellows with both the tank wall and with the drift-tube stems is assumed. Other considerations that further degrade this upper limit include differences of up to ~ ±5% between measured and design fields at the location of the tuning slugs along the tanks, and an additional 5% margin of error to cover variations in the actual operating set points and other unknowns. These combined errors give a total field (power) error of ~10% (21%), reducing the DTL maximum safe operating RF duty factor to 12.4%. Post-coupler heating may also limit the RF duty factor, but at present these limitations are not known.

The LANSCE coupled-cavity linac (CCL) structure is cooled through water channels external to the cavities. Modelling results indicate that the operating duty factor for the CCL should stay below 15% to avoid plastic deformation, assuming uniform fields across each of the tanks of the CCL, however, bead-pull measurements of one CCL tank made during 2005 revealed variations in the accelerating cell field amplitudes across the tank of up to ~±6%. Combining this error with an additional 5% margin of error to cover variations in the actual operating set points and other unknowns gives a total field (power) error of ~11% (23%), reducing the maximum safe CCL operating RF duty factor to 12.2%.

Other systems that also limit the RF duty factor include the high-voltage DC power supplies (HVDC PS) that serve the final power amplifiers for the DTL and the klystrons for the CCL systems. Based on the LANSCE klystron peak-power rating, a range of klystron beam currents and efficiencies, and the average-current nameplate rating of the transformer-rectifier portion of the HVDC PS, limits the maximum RF duty factor to 11.8%, or equivalently a beam duty factor of 10%. A similar estimate for the new replacement 201-MHz Diacrode amplifiers for the DTL suggests that the final power amplifier HVDC PS can support an RF duty factor of 12.5% or a beam duty factor of 10.7%.

HIGH-POWER OPTIONS

Table 2 summarizes the upgrade options studied. The duty-factor limits discussed in the previous section have been assumed. In addition to these limits, impacts on facility power levels, reliability, and beam physics were also considered in the development of these high-power options.

Providing a 1-MW beam for MTS/FFMF while continuing to meet the beam requirements of our other users can be achieved through minimal efforts once the planned upgrade that will restore 120-Hz operation has been completed. See Table 2 for details.

Delivering a 2-MW beam will require nominal upgrades to the LANSCE linac, including replacement of the existing proton Cockcroft-Walton (CW) injector system with a radio-frequency quadrupole (RFQ) based injector to improve beam quality and eliminate additional beam losses associated with this high peak/high-average current operation. Option 1 assumes re-tuning of the DTL cavities to allow operation at slightly higher duty factors and operation of the ion source at a 27.5-mA peak beam current. The DTL high-power RF and HVDC systems are not presently adequate but could be upgraded to meet these new requirements. The 2-MW Option 2 assumes replacement of sections of the CCL with superconducting cavities to increase the final beam energy while operating at conservative peak beam currents and duty factors to deliver a 2-MW beam.

All high-power options beyond 2 MW require significant modification or replacement of existing accelerating structures as shown in Table 2. The 5-MW Option 1 was not considered viable due to the high peak beam current required and resulting excessive field droop between CCL cavities that are bridge-coupled together in an RF module.

A PREFERRED OPTION

Implementation of the discussed options to achieve 1-MW beam power will be straightforward after completion of the planned upgrade of major system components that will restore 120-Hz operation at LANSCE. The 2-MW Option 2 is our preferred option for doubling the beam power to meet future performance goals. It is also leads to a natural lower-risk upgrade path to even higher beam powers up to 5 MW by replacing or upgrading additional subsystems.

This option makes use of the existing 201.25-MHz DTL (0.75 MeV to 100 MeV) and the CCL up to approximately 500 MeV. The CW injector will be replaced with a 0.75-MeV 201.25-MHz RFQ and a new matching section for injection into the DTL. As a baseline, we propose replacing the last 18 CCL modules of the existing linac with 18 SNS-like high-β (β=0.81; E_0T=15.8MV/m) superconducting (SC) cryomodules to reach a final beam energy of ~1.5 GeV. This is a one-for-one replacement option that makes use of existing waveguide penetrations into the beam tunnel, but not optimized and leads to unnecessary space between cryomodules. Providing RF power to the SC cavities requires replacement of existing high-power RF systems with 72 (18 x 4; 4 cavities/cryomodule) lower-power klystrons. Other RF options, including feeding two SC cavities per klystron, are also being considered.

To continue to meet the requirements of the existing user programs, including injection of the 800-MeV H^- beam into the Proton Storage Ring (PSR), a special transport section will need to be added at the 800-MeV point within the SC linac. This transport would allow H^- beams to be extracted at 800 MeV and drifted to their destinations without additional energy gain. This would also require reconfiguring/rebuilding the existing LANSCE switchyard beam-transport system to accommodate the split beam lines as well as the higher-energy proton beam.

Much of this work is preliminary. A more in-depth study will be required to optimize the SC linac layout. Optimization of SC cavity/cryomodule parameters and reducing the number of klystrons per cryomodule will be investigated next since these can have significant cost impacts. Detailed beam dynamics simulations will also be performed.

REFERENCES

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[5] See www-frdb.iaea.org/fulltext/13_fastReactorDesigns.pdf#JOYO and www-frdb.iaea.org/fulltext/13_fastReactorDesigns.pdf#BOR-60.

Table 1: Summary of maximum safe RF duty-factor limits for the LANSCE linac structures and RF systems.

	DTL	**CCL**	**201.25 MHz (HVDC PS)**	**805 MHz (Klystron)**
RF Duty Factor	12.4% (structure limited)	12.2% (structure limited)	11.8% (10% beam) – Present 12.5% (10.7% beam) – Post LRM	12.0% (120 Hz, 1 ms)

Table 2: High-Power Upgrade Options (All options assume a 100-Hz repetition rate for H^+.)

Option	**Beam Power (MW)**	**Requirements**	**Beam Pulse Length (µs)**	**RF Duty Factor (%) DTL, CCL, SCL**	**E_{final} (GeV)**	**I_{peak} (mA)**	**I_{avg} (mA)**	**SC cryomodules/ klystrons**
1-MW Option 1	1	Increase duty factor	770	12.3, 10.8, N/A	0.8	16.5	1.25	N/A
1-MW Option 2	1	Increase duty factor & peak beam current	688	11.3, 9.8, N/A	0.8	18.5	1.25	N/A
Max. Beam Power	1.16	Increase duty factor & peak current	797	12.4, 11.0, N/A	0.8	18.5	1.45	N/A
2-MW Option 1	2	Fix DTL field errors, Increase duty factor & peak beam current, add 201.25-MHz RFQ, upgrade HPRF & HVDC	922	13.2, 12.3, N/A	0.8	27.5	2.5	N/A
2-MW Option 2	2	Increase duty factor & peak beam current, add 201.25-MHz RFQ, upgrade HPRF & HVDC, increase final beam energy	788	12.4, 10.9, 9.7	1.5	17.0	1.33	18/72
5-MW Option 1, Not Viable	5	Increase peak beam current, increased RF power to CCL	913	N/A	0.8	69.0	6.25	N/A
5-MW Option 2	5	Increase final beam energy, increase peak beam current, add 402.5-MHz RFQ & 402.5-MHz DTL, Upgrade HPRF, HVDC	913	TBD	1.5	37.0	3.3	18/72
5-MW Option 3	5	Increase final beam energy, increase peak beam current, add 402.5-MHz RFQ & 402.5-MHz DTL, Upgrade HPRF, HVDC	913	TBD	2.0	28.0	2.5	25/100