A CONCEPTUAL 3-GEV LANSCE LINAC UPGRADE FOR ENHANCED PROTON RADIOGRAPHY*

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Abstract

A conceptual design of a 3-GeV linac upgrade that would enable enhanced proton radiography at the Los Alamos Neutron Science Center (LANSCE) is presented. The upgrade is based on the use of superconducting accelerating cavities to increase the present LANSCE linac output energy from 800 MeV to 3 GeV. The LANSCE linac currently provides negative hydrogen ion (H^-) and proton (H^+) beams to several user facilities that support Isotope Production, NNSA Stockpile Stewardship, and Basic Energy Science programs. Required changes to the front-end, the accelerating structures, and to the RF systems to meet the new performance goals, and changes to the existing beam switchyard to maintain operations for a robust user program are also described.

INTRODUCTION

Proton radiography (pRad) at LANSCE has operated as a user facility since 2003 and has recently been designated as one of the three DOE user facilities at LANSCE. Each year a full schedule of experiments is executed after a formal proposal call and the submitted proposals are reviewed based on scientific merit by a program advisory committee, ensuring the highest ranked experiments are executed. Presently, the broad user community extends from the DOE-NNSA national laboratories (LANL, LLNL, SNL, and ORNL) to international users (AWE, CEA and VNIIEF) and has recently grown to include DOD laboratories (ARL and Eglin AFB) as well as university interest (Harvard, Imperial College, and the Technical University of Darmstadt).

In the past five years, an international community of scientists from the US, Russia, Germany, the UK, Italy and China have come together to collaborate on the development and applications of high-energy proton microscopy. This community now sponsors an annual high-energy proton microscopy workshop to define technology directions for improving the capabilities of proton radiography and to identify key science applications of this developing technique. The first and second workshops were held in Germany and Russia, respectively, and the third high-energy proton microscopy workshop was held in Los Alamos at LANSCE in October, 2011 [1].

The high-energy proton microscopy community has reached a consensus conclusion that the most effective way to extend the capabilities of proton radiography is through increasing the incident proton energy. This conclusion is the result of independent investigations into alternative and potentially less expensive improvement paths. The results of these studies have provided an independent peer review of LANL concepts, which has been used as a fundamental basis for the enhancements proposed here. Based on this community consensus new high-energy proton radiography systems are being designed, developed and utilized at GSI in Germany [2], ITEP [3] and IHEP [4] in Russia and in Lanzhou, China [5].

The spatial resolution of a proton radiography system is typically dominated by the combination of second-order chromatic aberration terms in the magnetic lens [6] with energy and angle spread of the protons due to energy loss and multiple Coulomb scattering within the object. Resolution is improved by increasing the energy and thus momentum, p, of the incident proton beam [7]. Increasing the proton beam energy from 0.8 GeV to 3 GeV increases the beam momentum by a factor of 2.6. The chromatic blur is reduced as $1/p^2$, while the in-object scattering blur diminishes as $1/p$. In this energy range, the radiographic penetrating power of the proton beam also increases linearly with momentum, thus object penetration also improves as the proton beam energy is increased. The proposed improvements would provide multiple-time radiography with unprecedented spatial, temporal and density resolution compared to the current capabilities at LANSCE.

A major trade study was performed to determine the appropriate accelerator format: linac or synchrotron. The costs of synchrotron accelerators were compared to the costs to increase the LANSCE linear accelerator beam energy. It was found the accelerator costs in this energy range were very comparable. However, the linac can be located in the existing tunnel structure, saving substantially in conventional facility costs over a synchrotron. The synchrotron has the advantage of storing a large number of protons per pulse however this large peak current comes at the expense of only providing four pulses or less per dynamic experiment in a rigid time structure. Linear accelerators do not provide the large peak current intensities, but they do provide many pulses per dynamic event with a very flexible time format. This flexibility in time was found to be a significant benefit for the range of experiments to be executed.

In addition to supporting pRad, LANSCE currently also supports a broad user base including the neutron scattering community, isotope production, basic science, and national security programs by providing multiple

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beams to several diverse experimental areas. The LANSCE linac accelerates two beams simultaneously (H^- and H^+). 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 (Lujan Center), at 40 Hz to an un-moderated spallation target for nuclear physics cross-section measurements and microchip irradiations for industry (WNR), and either on-demand at ~1 Hz for proton radiography (pRad) or 20 Hz for ultra-cold neutron production (UCN). Protons are used for isotope production (IPF) at 100 MeV. High-power operation (10% total RF duty factor; 100 Hz x 625 µs; 16.5-mA peak proton beam current) has provided 800-kW average beam power at 800-MeV but was halted in 1998 after shut-down of the nuclear physics mission that supported high-power beam operations. Upgrades currently underway will allow high-power operation in support of future new missions. Typical beam parameters for beams delivered to the five experimental areas are summarized in Table 1.

Table 1: Typical 60-Hz LANSCE beam parameters.

Beam/Area	Duty Factor	Chopping Specs
Lujan, H^-	20 Hz x 625 µs = 1.25%	290 ns burst every 358 ns
WNR, H^-	40 Hz x 625 µs = 2.5%	Single micropulse every 1.8 µs
pRad, H^-	1 Hz x 300 µs = 0.03%	20-30, 60 ns beam bursts, variable spacing
UCN, H^-	20 Hz x 625 µs = 1.25%	Variable
IPF, H^+	40 Hz x 625 µs = 2.5%	None

3-GEV LANSCE LINAC UPGRADE

The proposed 3-GeV pRad upgrade consists of a 750-keV, H^+ Radio-Frequency Quadrupole (RFQ) injector with beam chopper, a superconducting linac (SCL) upgrade to ~2.96 GeV, a rebuilt beam Switchyard (SY), a rebuilt Line-X (LX)/Line-C (LC) beam transport line, and upgraded pRad magnetic optics. This would provide ~30-mA peak current but low-average intensity (~1 Hz) chopped H^+ beam (up to one hundred 100-ns bursts with ~several µs inter-burst spacing over a 600-µs to 1000-µs macropulse) to pRad. Figure 1 shows a layout of the present LANSCE accelerator complex and the proposed upgrades. Table 2 summarizes the parameters for each component of the proposed upgrade.

The approach taken to implementing a 3-GeV pRad operation at LANSCE is to minimize the impact to existing beam operations and disregard any capability not presently used. Therefore, this scheme maintains delivery of a high-power 800-MeV H^- beam to Line-D facilities (PSR/Lujan and WNR) and high-power 100-MeV H^+ beam to IPF. The proposed scheme, however, does not preserve the capability to run high-average-power H^+ beam for future uses, nor does it preserve present Ultra-Cold Neutron (UCN) beam operations. To preserve these capabilities requires additional modifications and costs that are beyond the scope of this concept.

Table 2: Summary of 3-GeV upgrade parameters.

Upgrade Component	Description and Parameters
Injector - H^+ RFQ	Replaces existing CW; 4-rod, 201.25 MHz, 0.750 MeV, 30-mA peak
SCL	805-MHz, SNS style cryomodule; replaces existing CCL modules. No. of cryomodules = 24 No. of cavities/cryomodule = 4 Cavity Geometric $\beta_g = 0.81$ No. of cells/cavity = 6 E_{acc} = 30.6 MV/m (E_0=45.6 MV/m)
RF Systems (805 MHz)	*High Power* (598MeV-800MeV): SNS-like “4-pack” *Low Power* (0.8GeV-3.0GeV) uses 2, 1.25-MW klystrons + 8-way split.
Beam Transport	Introduction of a chicane at 800 MeV to separate H^- beam and bypass remaining SCL; beam switchyard modifications to redirect both beams; Magnet upgrades in transport line to pRad optics for higher momentum beam.
pRad Optics System	Upgraded magnets to maintain present field of view at higher beam momentum.

The heart of this upgrade is an SCL that replaces the last two sectors (G & H) of the existing coupled-cavity linac (CCL). The use of superconducting accelerating structures is new to LANSCE and will require the construction of a cryogenic plant to supply the required liquid helium to cool the cavities. Cost of the SCL may be reduced by taking advantage of previous design and engineering by using 24 Spallation Neutron Source (SNS) linac, high-beta (β_g=0.81) cryomodules operating at an accelerating gradient, E_{acc} = 30.6 MV/m (E_0=45.6 MV/m), which is twice the SNS design value. This aggressive accelerating gradient is based upon expected performance gains through cavity optimization [8]. This aspect of the upgrade holds the highest technical risk and would require an intensive multi-year R&D program of single- and multi-cell cavity testing to be realized. Each CCL module in Sectors G & H would be replaced with two cryomodules (CMs) to maximize the real-estate accelerating gradient. The first two CMs will require new high-power RF systems (assumes an SNS-like “4 Pack”) necessary to maintain the existing capability to accelerate both the H^- and H^+ beams up to 800 MeV [9]. The remaining 22 CMs will only accelerate the H^+ pRad beam to 3 GeV and can therefore be grouped into pairs and powered from the existing LANSCE 1.25-MW klystrons that presently reside in sectors G & H by using an 8-way split to deliver RF power to each of the four cavities in each CM. This approach maximizes the use of planned

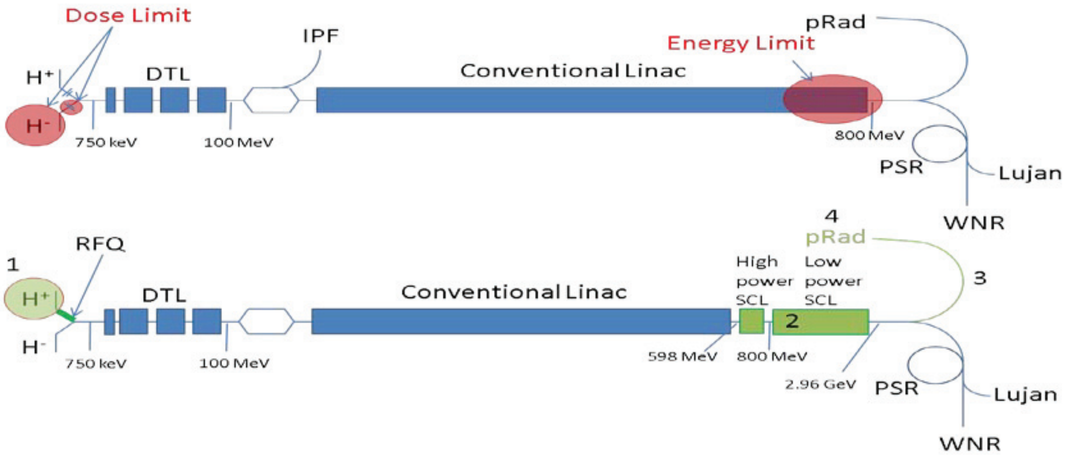

Figure 1: Top: layout of the existing LANSCE facility with injectors at the left and experimental areas at the right. The red regions are the locations of the present beam current (or dose) and energy limitations. Bottom: The four modifications (1-4) which allow the delivery of 30-mA peak current at 3 GeV. Instead of the existing H$^-$ source, a high-current H$^+$ source and RFQ would inject into the linac (1) and the last two sectors of conventional normal-conducting RF accelerating structures would be replaced with superconducting RF structures (2). Modifications are also required to the beam-transport lines (3) and the pRad optical system (4) to make use of the higher-energy beam.

LANSCE Risk Mitigation investments (new 805-MHz klystrons) [10] and significantly reduces the overall cost of the upgrade by minimizing the number of new RF systems required.

Replacement of the existing H$^+$ Cockcroft-Walton injector with a new 201.25-MHz, 750-keV RFQ is needed to meet the higher peak beam current requirement. The RFQ is expected to be of the 4-rod type and is considered low technical risk [11]. Similar RFQs are operating successfully world-wide. The RFQ would be combined with a slow-wave beam chopper to provide the 30-mA peak current in 100-ns bursts for pRad. An existing chopper structure may be appropriate, however, design of a new modern system should be considered.

The present SY and LX/LC are configured to deliver 800-MeV H$^-$ beam to pRad. Reconfiguration of the SY and LX/LC will be required to deliver a 3-GeV, H$^+$ beam. A conceptual layout of the SY and LX/LC reconfiguration has been completed. A beam-splitting dipole shortly after the end of the accelerator will be used to separate the 800-MeV H$^-$ beam from the 3-GeV protons. This magnet will be followed by additional magnets to capture the H$^+$ and H$^-$ beams and bend them into their respective beam lines. The existing magnets in LX were designed to have modest magnetic fields to avoid field-stripping of the H$^-$ ions. These magnets and their associated power supplies must be replaced (15 dipoles and 16 quadrupoles) to transport the higher-energy beam. To estimate the cost of the new magnets and power supplies, the field-length product (dipoles) or gradient-length product (quadrupoles) for each magnet was scaled up by a factor of 2.6 to take into account the increase in magnetic rigidity from 4.88 T-m at 800MeV to 12.74 T-m at 3 GeV required to preserve the existing bends in the beam line.

REFERENCES

[1] Barns, C. et al., “2011 High-Energy Proton Microscopy Workshop Summary Report,” LA-UR-11-06791, 2011.

[2] Merrill, F.E.et al., “Proton Microscopy at FAIR,” AIP Conf. Proc. 1195, 667, (2009).

[3] Golubev, A. A. et al., “Diagnostics of fast processes by charged particle beams at TWAC-ITEP accelerator-accumulator facility”, Technical Physics Letters, 36, 2, 177-180, YEAR.

[4] Antipov, Y. M. et al., “A radiographic facility for the 70-GeV proton accelerator of the Institute for High Energy Physics,” Nuclear Experimental Techniques, 53, 3, 319-326, YEAR.

[5] Wei, Tao et al., “A lattice scenario for a proton radiography accelerator,” Chinese Physics C, 34, 11, 1754-1756, (2010).

[6] Merrill, F. E. et al., “Magnifying lens for 800 MeV proton radiography,” Review of Scientific Instruments, 82, 103709, (2011).

[7] Morris, C. L., et al., “Flash Radiography with 24 GeV/c protons”, Journal of Applied Physics, 109, 104905, (2011).

[8] Rybarcyk, L., et al., “Technical Options for High-Power Beams,” LA-UR-10-07085, 2010.

[9] Bradley, J., et al., “Spallation Neutron Source High-Power RF Transmitter Design for High Availability, Ease of Installation, and Cost Containment,”

[10] Garnett, R. W. et al., “Progress towards an RFQ-based Font End for LANSCE,” IPAC2011 Proceedings.

[11] Garnett, R. W. et al., “Operational Status and Life Extension Plans for the Los Alamos Neutron Science Center,” LINAC10 Proceedings.