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HIGH-ENERGY BEAMLINE FOR DELIVERING H⁻ LASER STRIPPED PROTON BEAM TO LANSCE EXPERIMENTAL AREA*

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Abstract

A unique feature of the LANSCE accelerator facility is the acceleration of four H^- beams (differing in time structure) and one H^+ beam. This is achieved by the utilization of an injector system based on two ion sources (H^+/H^-), and a combination of chopper and RF bunchers in the Low Energy Beam Transports. Since the end of the 1990s, the large LANSCE experimental, Area-A, has been largely unused. In order to restore the usage of Area-A, we have been exploring the possibilities of bringing low-intensity power beams into Area-A. The proposal is based on the partial stripping of the 800 MeV H^- beam that is transported to the Weapons Neutron Research Facility and to deliver the resulting low-intensity proton beam to Area-A. The appropriate place for generating the proton beam was found to be the beginning of Line D after LANSCE Switchyard by first neutralizing the beam from H^- to the neutral hydrogen beam ahead of the bending magnet using a laser, and then by fully stripping the neutral hydrogen beam to protons utilizing a stripper foil. The paper discusses the design details of the proposed high-energy beamline and beam parameters.

INTRODUCTION

LANSCE linear accelerator (former Los Alamos Meson Physics Facility, LAMPF) consists of 201.25 MHz Drift Tube Linac (DTL) accelerating particles from 0.75 MeV to 100 MeV and 805 MHz Coupled-Coupled Linac (CCL), accelerating particles from 100 MeV to 800 MeV [1]. Proton 100-MeV beam is delivered to Isotope Production Facility (IPF), while 800-MeV H^- beams are distributed to four experimental areas: the Lujan Neutron Scattering Center, the Weapons Neutron Research facility (WNR), the Proton Radiography facility (pRad), and the Ultra-Cold Neutron facility (UCN). From the early 70's to mid-90s Area-A was a major experimental area for Medium-Energy Research Program which used the LAMPF accelerator. Since the conclusion of that research program in the late 1990's no beam has been transported to Area-A.

The proposed approach of delivering low-power beam into Area-A from the LANSCE accelerator switchyard assumes stripping of the fraction of WNR 800 MeV H^- beam to H^0 with subsequent stripping of H^0 to H^+ and to deliver the resulting several tens of nA proton beam to experimental area [2]. Realization of this idea will meet the needs of the radiation effects community and the basic science research community in low – power proton beam for basic research study.

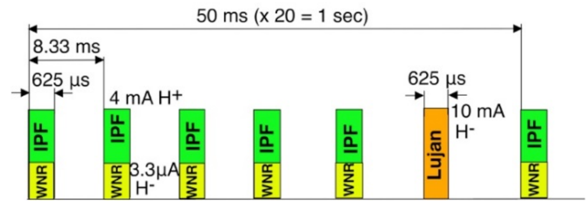

Figure 1: Time pattern of LANSCE Lujan/WNR/IPF beams. Beams delivered to pRad or UCN facilities, "steal" their time cycles from WNR beam.

THE THECHNIACL APPROACH

The time structure of LANSCE beams is illustrated by Fig. 1. The H^- beam, delivered to WNR facility, shares the same 625-µs-long macropulse (that is, both beams are accelerated simultaneously on different parts of the RF cycle) with the 100-MeV proton beam, delivered to the Isotope Production Facility (IPF). The WNR/IPF pulses occur on five out of every six of the 120 Hz accelerator macropulses, with beam for the Lujan Center delivered on the sixth pulse.

Figure 2 shows the time pattern of WNR Facility beam cycles. WNR bunches are created before DTL by the combination of a short 36 ns chopper pulse and the Low-Frequency Buncher (LFB) which operates at the frequency 201.25/12 = 16.77 MHz. Because of that specific combination, the WNR bunches typically contain $N_{H^-} = 6\cdot10^8$ ions per bunch, which is about 2.5 times more charge than that in other H^- bunches, created by a combination of two RF cavities operated at basic 201.25 MHz frequency. Since the WNR is run at frequency f_{WNR} = 201.25/360 = 0.559 MHz, the WNR bunches are separated by time interval $1/f_{WNR} = 1.7882$ μs . Each WNR bunch has a typicall pulse length of ~ 100 ps. WNR beam has the number of bunches per second: N_b = 100 [Hz] 625 [μs]/1.7882 [μs] = $3.49\cdot10^4$ bunch/sec. The average current of WNR H^- beam is $\overline{I_{H^-}} = eN_{H^-}N_b = 3.3$ µA.

The proposed approach to bringing low-power beam into Area-A from the LANSCE accelerator Switchyard is shown in Fig. 3, Fig. 4. In the proposed scheme a small fraction of the H^- beam is neutralized to H^0 upstream of the Line-D bending magnet LDBM00. For that purpose, the wire scanner section LDWS01 which is just before bending magnet LDBM00 is modified so that laser ports and laser alignment hardware share the vacuum chamber with the

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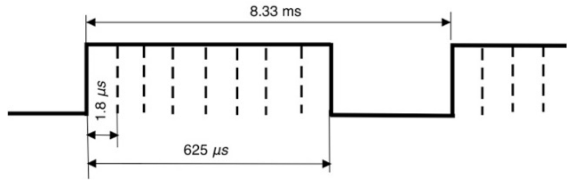

Figure 2: Time structure of LANSCE Weapons Neutron Research Facility beam. Vertical dotted lines illustrate single bunches.

wire scanner diagnostic. A similar setup was used in an Oak Ridge National Lab Spallation Neutron Source (SNS) experiment for their H$^-$ → H$^+$ beam laser stripping [3]. After photoneutralization in LDWS01, the H^0 fraction goes through bending magnet LDBM00 without deflection. Presently, LDBM00 magnet has a second exit port on the undeflected trajectory connected to Beam Stop 1DBS01, which is not used. This beam stop will be removed and replaced with a stripping foil to convert H^o beam to H$^+$ beam.

Two additional C-Bend magnets to be installed in a new beam line to direct the proton beam from the Switchyard into Line A (see Fig. 3). After the stripping foil, the proton beam travels around 6 m, and is bent towards Line A by the bending magnet C-Bend 1. A C-magnet shape is selected because space is only available for the magnet installation on one side of the new beamline. Along Line A, there is an empty region of 2.9 m after isolation valve LASV02 in which the second bending magnet C-Bend 2 is installed. The offset distance between axis of line A and that of the new beamline is d = 0.53 m. Assuming the longitudinal distance between centers of C-Bend 1 and C-Bend 2 is L ~ 4 m, the angle of deflection of both magnets is $\alpha = d / L \sim 0.13$, or 7.6^o. Selecting the magnetic field in bending magnets as 1 Tesla, the bending radius is $\rho = mc\beta\gamma / (eB) = 4.8\,\text{m}$, and length of the magnets is $L_m = \rho\alpha$ = 0.63 m. Additional detailed transport calculations will be done to determine if additional quadrupole magnets will be required along the new beamline.

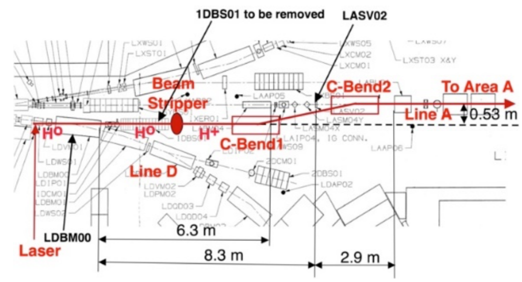

Figure 3: Layout of the proposed beamline in the Switchyard to transport the stripped beam to Area A.

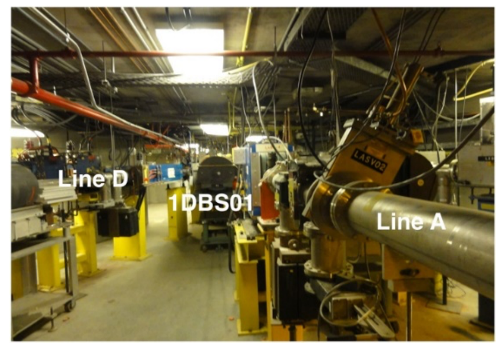

Figure 4: Elements of Switch Yard beamlines looking towards the linac: (center) Beam Stop 1DBS01 downstream of bending magnet LDBM00, which will be removed; (left) line D; (right) Line A.

STRIPPING OF H$^-$ BEAM BY PHOTODETACHMENT

Photodetachment of loosely attached electron in H$^-$ beams by laser beams is widely used in H$^-$ beam diagnostics. Consider laser beam crossing H$^-$ beam at angle θ (defined so that $\theta = \pi$ when collisions are head-on, see Fig. 5). According to invariant cross-section formula for two-beam collision [4], the number of events dN in the volume dV during time dt is given by

$$dN = \sigma\sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{[\vec{v}_1 x \vec{v}_2]^2}{c^2}}\rho_1\,\rho_2\,dV\,dt\,, \qquad (1)$$

where σ is the cross- section of the event in the rest frame of one of the beams, $\vec{v}_1$, $\vec{v}_2$ are particle velocities in laboratory frame, and ρ_1, ρ_2 are beam densities in laboratory frame. The cross-section of the photodetachment process in the rest frame of H$^-$ beam $\sigma = \sigma(E')$ is [5]:

$$\sigma(E') = 8\sigma_{BB}^{\max} E_o^{3/2}\frac{(E'-E_o)^{3/2}}{E'^3}\,, \qquad (2)$$

where $E' = \gamma E(1-\beta\cos\theta)$ is the photon energy in the H$^-$ rest frame, E is the laser photon energy in laboratory frame, $\sigma_{BB}^{\max}$ = $4.2\cdot 10^{-17}\,cm^2$ is the maximum black-body stripping cross-section, and E_o = 0.7543 eV is the electron binding energy for H$^-$ ion. Denoting H$^-$ beam velocity as $\beta = \beta_1$, and taking into account that laser beam velocity $\beta_2 = 1$, the square root factor, Eq. (1), is

$$\sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{[\vec{v}_1 x \vec{v}_2]^2}{c^2}} = c(1-\beta\cos\theta)\,. \qquad (3)$$

With Eq. (3), the number of photodetachment events dN in the volume dV during time dt becomes [6]:

$$dN = \sigma(E')c(1-\beta\cos\theta)\rho_b\,\rho_{ph}\,dV\,dt\,, \qquad (4)$$

where ρ_b, ρ_{ph} are beam densities of H$^-$ beam and laser beam in laboratory frame, correspondingly. Let us assume that both beams are round with radius R. The particle density of a continuous H$^-$ beam with current I is $\rho_b = I / (e\beta c\pi R^2)$, and the density of continuous laser

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beam is $\rho_{ph} = (dN_{ph}/cdt)/(\pi R^2)$, where $dN_{ph}/c\,dt$ is the linear density of photon beam along propagation direction. Substitution expressions for ρ_b, ρ_{ph} into Eq. (4) gives for number of photodetachment events dN in the volume dV during time dt:

$$dN = \frac{\sigma(E')(1-\beta\cos\theta)}{\pi^2 R^4}(\frac{I}{e\beta c})(\frac{dN_{ph}}{dt})dV\,dt\,. \quad (5)$$

The interaction volume of beams can be estimated as $V \approx \pi R^2(2R/\sin\theta)$ (see Fig. 5). The number of stripping ions N_{H^0} in the interaction volume V during time dt is obtained through integration of Eq. (5) over the volume of beams interaction:

$$N_{H^0} = \frac{2}{\pi}\frac{I\sigma(E')\,(1-\beta\cos\theta)}{e\beta cR\sin\theta}(\frac{dN_{ph}}{dt})dt\,. \quad (6)$$

Taking into account that H^- beam current is $I = eN_{H^-}/dt$, where N_{H^-} is the number of H^- ions propagating along z- direction during time dt, one can estimate the fraction of stripped H^- particles:

$$\frac{N_{H^0}}{N_{H^-}} = \frac{2}{\pi}\frac{\sigma(E')(1-\beta\cos\theta)}{R\beta c\sin\theta}(\frac{dN_{ph}}{dt})\,. \quad (7)$$

One of the possible candidate for neutralization of H^- beam is the Amplitude Satsuma HP3 laser [7] with photon's wavelength λ = 1030 nm, laser pulse width τ_L = 10 ps, which provides energy of W_L = 40 μJ/pulse at operation frequency ~ 560 kHz. At the 800-MeV interaction region with β = 0.84, γ = 1.85, the reasonable values for the parameters are R = 0.46 cm, θ = 85°. The energy of photon of the laser in laboratory frame is $E = hc/\lambda$ = $1.9\cdot10^{-19}$ J (1.2 eV), which provides dN_{ph}/dt = $W_L/(\tau_L E)$ = $2.1\cdot10^{25}$ photons/sec. The photon energy in the frame of H^- beam is $E' = \gamma E(1-\beta\cos\theta)$ = 2.06 eV. The cross-section of photodetachment of H^- ion by laser according to Eq. (2) is $\sigma(E')$ = 3.8 ×10^{-17} cm^2. Eq. (7) gives for stripping rate N_{H^0}/N_{H^-} = 0.04 of the input ion beams during the time the laser is on. Since the laser is only on for 10 ps for each ~100 ps long H^- bunch, this laser candidate photodetaches 0.4% of the beam, or the expected average current of stripped ions is $\overline{I_{H^-}} \times (N_{H^0}/N_{H^-})$ = 13.2 nA.

The laser, operating at the frequency of ~ 560 kHz will irradiate both WNR and Lujan beams (see Fig.1). The Lujan beam is operated with repetition rate 20 Hz, which is 5 times smaller than that of WNR beam, while the charge per Lujan bunch is roughly half of that of WNR bunch. Therefore, the expected intensity of stripped H^- Lujan beam is a factor of 10 smaller than that of WNR beam. The total H^+ beam current to the Area A in this configuration is expected to be I_{H^+} = 1.1×13.2 =14.5 nA.

The similar results are provided by the NeoLase externally-triggered MOPA laser [8] with photon's wavelength λ = 1030 nm, laser pulse width τ_L = 70 ps, energy per pulse W_L = 45 μJ/pulse, operating at frequency ~ 560 kHz, creating $dN_{ph}/dt = 3.3\cdot10^{24}$ photons/sec. The laser pulse length is 7/10 of the ion pulse length. Using Eq. (7) with correcting for the pulse length factor, the neutralization from H^- to H^0 photoneutralization fraction is 0.45 %, or the expected average current of stripped ions is $\overline{I_{H^-}} \times (N_{H^0}/N_{H^-})$ = 14.9 nA. Taking into account the extra 10% of neutralized H^- ions from the Lujan beam gives a final estimate of proton beam current to Area A I_{H^+} = 1.1×14.9 = 16.3 nA.

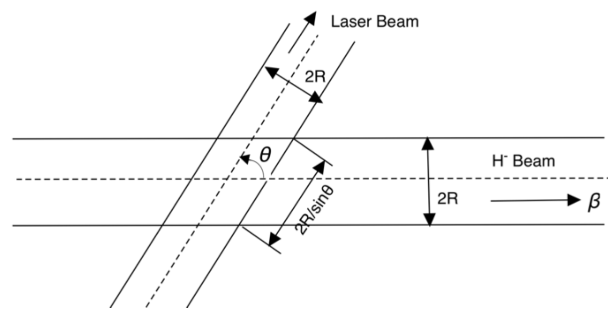

Figure 5: Geometry of laser photodetachment of H^- beam

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