H$^-$ BEAM LOSS AND EVIDENCE FOR INTRABEAM STRIPPING IN THE LANSCE LINAC*

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Abstract

The LANSCE accelerator complex is a multi-beam, multi-user facility that provides high-intensity H$^+$ and H$^-$ particle beams for a variety of user programs. At the heart of the facility is a room temperature linac that is comprised of 100-MeV drift tube and 800-MeV coupled cavity linac (CCL) structures. Although both beams are similar in intensity and emittance at 100 MeV, the beam-loss monitors along the CCL show a trend of increased loss for H$^-$ that is not present for H$^+$. This difference is attributed to stripping mechanisms that affect H$^-$ and not H$^+$. We present the results of an analysis of H- beam loss along the CCL that incorporates beam spill measurements, beam dynamics simulations, analytical models and radiation transport estimates using the MCNPX code. The results indicate a significant fraction of these additional losses result from intrabeam stripping.

INTRODUCTION

The LANSCE facility provides H$^+$ and H$^-$ beams to a diverse set of user programs. The beams are initially accelerated up to 750 keV in separate Cockcroft-Walton injectors before being merged in a common transport and directed to a 100 MeV drift tube linac (DTL). Following the DTL the two species are temporarily separated into different transport lines to allow independent matching, steering and phasing before being merged and injected into the 800-MeV coupled cavity linac (CCL). A kicker magnet located in the 100-MeV H$^+$ beam transport line is used to direct beam to the Isotope Production facility.

Previously, when LANSCE simultaneously delivered 800-MeV H$^+$ and H$^-$ beams to user facilities it was observed that the beam loss profiles along the CCL for the two species were distinctively different [1]. As seen in Fig. 1, the measured H$^-$ beam loss profile normalized to peak current shows a very strong trend toward higher values, which is significantly different in comparison to that of H$^+$. Since the two species have similar peak currents and emittances at 100 MeV, and are separately matched into the CCL, it was postulated that the higher H$^-$ losses were a result of additional stripping mechanisms, e.g. residual gas stripping, not present for H$^+$.

More recently, at the ORNL Spallation Neutron Source facility, higher than expected H$^-$ beam loss along the superconducting linac has been observed [2]. A subsequent study [3] found these additional losses to be consistent with estimates for intrabeam stripping (IBS), which results from collisions between ions in the same bunch.

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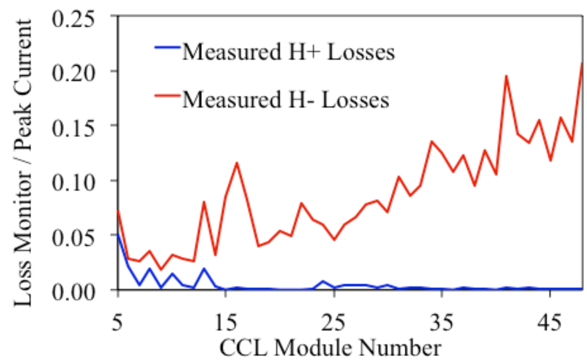

Figure 1: Measured loss monitor signals normalized to peak current for H$^+$ (blue) and H$^-$ (red) beams accelerated to 800 MeV in the CCL.

In light of this recent work, we have revisited the LANSCE linac beam-loss data to determine whether the IBS mechanism can help explain the observed H$^-$ beam losses in our room temperature CCL. In this work we consider three different mechanisms for stripped H$^-$ beam loss: 1) residual gas, 2) Lorentz field and 3) intrabeam. A simple beam envelope model was used to estimate the beam profiles along the linac. To relate the simulated particle losses to observed loss monitor signals, we employed the results of a radiation transport model calculation. These simulated results were then compared to measured loss profiles for both 800 MeV and ~366 MeV beams.

H$^-$ STRIPPING MECHANISMS

We considered three mechanisms that could contribute to the stripped H$^-$ beam losses along the CCL. Fractional loss rates for each process were estimated based upon typical operating conditions for a 10 mA$_p$ H$^-$ beam. For this study, we assumed that any H$^-$ ions that are stripped are immediately lost.

Residual Gas (RG) Stripping

This mechanism can remove of one or both electrons from an H$^-$ ion. It is a result of the H$^-$ beam particles scattering from gas atoms present within the high vacuum space inside the linac. The stripping rate depends upon the residual gas species, density and scattering cross section, which is beam energy dependent.

A simple model was used to estimate the fraction of beam loss due to residual gas stripping. The fractional loss per unit length is the product of the energy dependent cross-section, taken from [4][5] and scales like $1/\beta^2$, and the number density of gas atoms. The beam energy along the CCL was based upon a uniform acceleration rate. Due to the limited number of pressure measurements available along the CCL, an average of these values was used to represent the RG pressure everywhere in the structure. This average value combined with a residual gas analyzer measurement was used to estimate the partial pressure of the dominant species, H_2, H_2O and N_2/CO. Integrating the fractional loss per unit length gave an estimated total fractional loss of H^- ions from residual gas stripping of ~2.1×10^{-4}.

Lorentz Field Stripping

This mechanism, which is the result of combined relativistic and quantum mechanical effects, strips the weakly bound electron from the H^- ion. When an H^- ion moves through a transverse magnetic field in the lab frame, this field is transformed into an electric field in the rest frame of the ion. The additional electric field, transforms the potential well seen by the electron into a barrier, which the electron has a finite probability of tunneling through. The decay length of the ion in the lab frame changes rapidly due to the exponential dependence upon the electric field [6]. To estimate the fractional loss from field stripping by each quadrupole, we integrate the product of a centered beam shape (approximately Gaussian with $1\sigma = 0.25$ cm) and decay length over the field in each CCL doublet (~30 T/m, bore radius = 2.2 cm, length=20 cm). Combining the intermediate results gives a total fractional loss of approximately 4.5×10^{-11}, which is several orders of magnitude smaller than that from RG stripping, so we've chosen to ignore it.

Intrabeam (IB) Stripping

This mechanism contributes to single electron stripping and is a result of binary collisions between H^- ions in a bunch. Utilizing the work of Lebedev, et al. [3] we employed Ref. [3] Eqn. (7) for the fractional loss per unit length which depends upon several factors including beam intensity, energy, size and divergence and an estimate for the interaction cross section. For beam related information needed along the linac in the IB stripping model we used a TRACE3D [7] envelope calculation. The input beam was based upon transverse emittances extracted from an analysis of linac wirescanner data and longitudinal emittance based upon results of multiparticle beam dynamics simulations. Linac parameters were taken from standard operating values. Using this approach we estimated the total fractional loss from IB stripping along the CCL to be ~1.6×10^{-4}, which is comparable to that from RG stripping and therefore must be included in the final analysis. Shown in Fig. 2 are the H^- fractional loss rates per meter along the CCL for the RG and IB mechanisms.

RELATING SIMULATE LOSSES TO LOSS MONITOR PROFILES

The next step was to transform the calculated losses into the equivalent of observed loss monitor levels, which could then be compared to measurements. This required the use of a model to estimate the amount of radiation produced in each loss monitor located along the CCL by an H^- ion lost at a specified location and design energy.

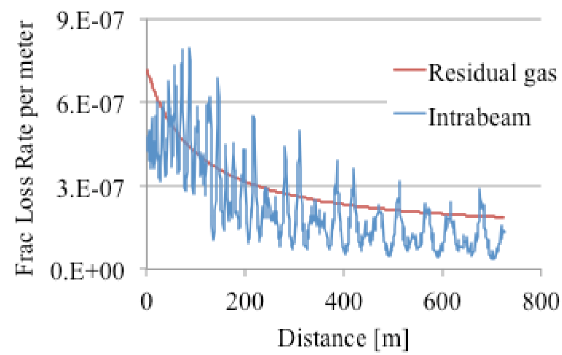

Figure 2: Calculated H^- fractional loss rates per meter along the CCL for residual gas (red) and intrabeam (blue) stripping of fully accelerated beam.

Each loss monitor along the CCL is comprised of a one-pint can of liquid scintillator with a photomultiplier tube attached. There are two per CCL module. They are gain adjusted to produce the same response to a standard gamma-ray source. Since their response to radiation is uniform, no additional corrections were applied to produce the simulated loss monitor profiles.

The model is based upon the Monte Carlo radiation transport code MCNPX [8] and uses a simplified representation of the linac structure. The linac, which is actually a quasi-regular array of copper accelerating cavities and iron quadrupole (doublet) magnets separated by short drift spaces (tens of cm), was represented in the model as a copper cylinder with a radius chosen to conserve copper mass per unit length. The model also included 30 cm thick concrete slabs to represent the tunnel enclosure around the linac. For these calculations, lost protons were started on axis at the design energy corresponding to their longitudinal location. Energy deposited in the loss monitor (represented as a one-pint container of toluene) from protons, neutrons, photons, electrons, and charged and neutral pions was tallied to estimate the total amount of energy produced in the device for a lost H^- ion. This data was then summarized for each CCL loss monitor device, as a distribution of charge-particle energy deposited versus location of lost proton along the linac, as shown in Fig 3. To simplify the analysis and remove some of the statistical scatter in the MCNPX results, each resultant distribution was fitted with a three parameter (amplitude, centroid, width) Lorentzian function. These functional representations of the loss monitor response to a lost proton were then convolved with the previously estimated fractional loss distributions to produce loss profiles for comparison to measured data.

COMPARISON TO H^- LOSS DATA

Results from simulated RG & IB stripping losses were compared to two measured H^- loss profiles. The first was a profile for 800-MeV beam. For this case the individual RG and IB calculated beam loss profiles were first

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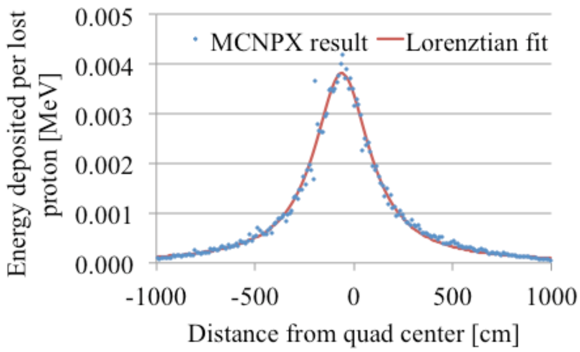

Figure 3: MCNPX results (blue points) showing energy deposited in CCL loss monitor 48LM01 per lost H$^-$ ion along CCL. The red line represents the Lorentzian fit to the data.

added together, then an overall scale factor was applied to achieve good overlap between it and the linearly increasing baseline of the measured profile. There is good qualitative agreement as shown in Fig. 4. The large spikes in the measured data at the beginning and near 150 m locations reflect additional losses due to transverse mismatch and longitudinal tails on the input beam and are usually present at some level in all the measurements. Although good qualitative agreement is seen, the solution is not unique. Since the trends of the RG and IB fractional loss for the 800 MeV beam are similar, good agreement could also have been achieved by excluding IB contribution altogether. So either a more quantitative comparison or a better signature is required to differentiate between these two dominant stripping mechanisms. This is where a lower final-energy data set allows us to distinguish between the presence of IB and RG mechanisms and provides a clear signature for the presence of IB stripping in the LANSCE linac.

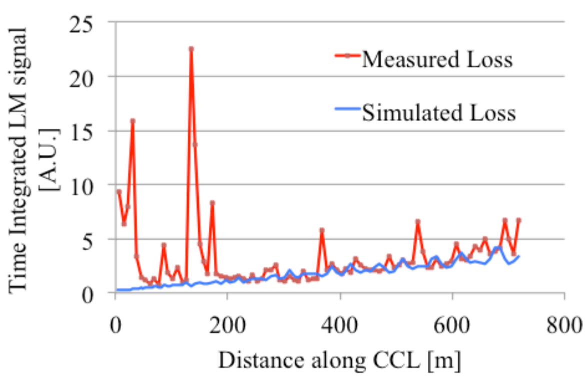

Figure 4: Comparison of measured (red) and simulated (blue) beam loss profiles for 800 MeV H$^-$ beam.

The second comparison was made to beam loss monitor profile data acquired for a lower final-energy beam, ~366 MeV. This beam is accelerated through the first 22 modules of the linac and then coasts through the remaining 26 modules. This data provides a means to discern the two mechanisms. At the point along the linac where the beam stops accelerating, the RG and IB loss rates diverge. The RG loss rate stops decreasing, since the stripping cross-section, which is energy dependent, remains constant. In contrast the loss rate for the IB mechanism, which depends on the beam size and divergence, diminishes rapidly following the last accelerating module. This is due to the expanding phase width of the beam, a result of removing the longitudinal focusing. Figure 5 shows the comparison between the calculated and simulated beam loss monitor data for an older, contemporaneous set of 800 and ~366 MeV data. These data were simultaneously compared to the simulated profiles by first applying a fraction of total scale factor, *f* and *1-f*, to the IB and RG profiles, respectively, then an overall scale factor. This resulted in good qualitative agreement between the calculation and measurement only when the IB contribution dominates (*f*~75%), which is evidence that this mechanism is present in the LANSCE CCL.

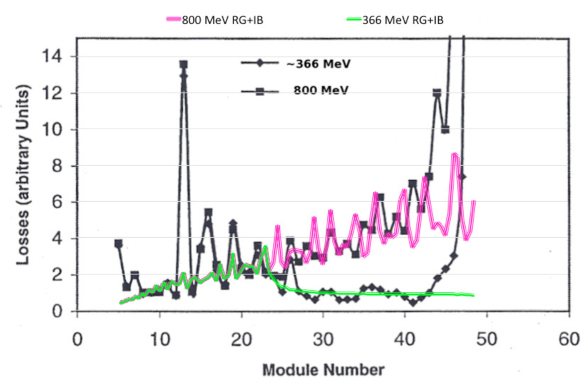

Figure 5: Comparison of measured (black) and simulated beam loss profiles for 800 (pink) and 366 (green) MeV H$^-$ beams.

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