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Research and Development of H⁻ Ion Source and LEBT for a Kaon-neutrino Factory

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A baseline H⁻ ion source and low energy beam transport system (LEBT) have been identified for Project X. The filament-discharge H⁻ ion source has been fabricated by D-Pace, Inc. and is now in operation at LBNL. The source is capable of delivering over 10 mA of H⁻ beam in cw operation with normalized 4 rms emittances less than 0.7 π mm mrad. A two-solenoid magnetic lens LEBT system has been design. The design has been validated with simulations of beam transport for 5 mA 30 keV H⁻ beams using various simulation codes.

I. Introduction

A high intensity proton facility is being proposed by Fermilab to support a world-leading program in neutrino and flavor physics over the next two decades. This proposed facility, Project X, will provide 3 MW of total beam power to the 3 GeV program, simultaneously with 2 MW to a neutrino production target at 60-120 GeV.¹

After evaluating various such as filament-discharge, RF-driven, and penning discharge negative H ion sources, we have identified a filament-discharge negative H ion source as a baseline ion source to produce 5 mA cw H⁻ ion beams for Project X. The low energy beam transport system has also been designed.

II. Project X front-end

The requirement for the front-end of Project X is to produce 5 mA DC H⁻ beam, which is bunched and accelerated by a cw normal-conducting RFQ to 2.1 MeV. The current RFQ design requires H⁻ ion beam to be injected at 30 keV. Figure 1 shows a schematic diagram of the proposed Project X ion source and low energy beam transport (LEBT) beamline, which includes two ion sources, a two-solenoid magnetic lens system, a bending magnet to switch beam between ion sources, and a chopper. Magnetic solenoids are inherently spark-free but they rely on a weak, second-order focusing effect provided by transverse fringe-field components. This fact makes it necessary to compensate the space charge of the ion beam by particles of the opposite charge, usually created by ion-impact ionization of the residual gas in the beamline. Two ion sources provide redundancy and the ability to replace one ion source while the other is in operation.² Each branch has diagnostics to measure the ion source performance before it is put on-line.

III. Filament-driven H⁻ Ion Source

To expedite R&D of the LEBT, a filament-discharge dc H⁻ ion source is currently chosen as a baseline ion source for Project X. It has been fabricated by D-Pace, Inc. and is now in operation at Lawrence Berkeley National Laboratory (LBNL). The source is non-cesiated and its design (filament materials, shape and location, cusp line confinement and magnetic filtering of electrons at the extraction region and extraction lens configuration) is based on the TRIUMF-type 15 mA direct current H⁻ multicusp source.³ As the lifetime for a filament-discharge ion source at 5 mA operation is limited to approximately 500 hrs,² the configuration of two ion sources with a
switching magnet facilitates fast source changes and minimizes down time due to ion source servicing.

Both beam current and emittance of this ion source have been measured at 20kV, 28kV, 30kV beam energy for beam intensities from 1mA to 10mA during the acceptance tests. Figure 2 shows the measured H' beam current at the Faraday cup as a function of arc power. At arc power of approximately 2500 W, the H' beam current produced by the ion source is over 10 mA. At beam energy of 20 keV, the measured beam current is slightly lower due to poorer ion optics at this reduced extraction energy.

The ion source has been installed and is in operation at LBNL (Figure 4). A magnet filter was installed in front of the water-cooled Faraday cup to prevent electrons from being detected in the Faraday cup. The measured current level didn’t change after the magnet filter had been installed, which indicated that the electrons, if there is any in the beam, was negligible.

Figure 3 summarizes the measured 4 rms normalized emittance as a function of beam current. At beam energies of 20kV, 28kV and 30kV for beam intensities from 1mA to 10mA, the normalized 4rms emittance of the ion source are all less than $0.7 \pi \text{mm-mrad}$. As the extraction system was optimized for 28 keV beam energy, the quality of the 28 keV beam is the best among the three energy levels.

Figure 5 compares the current measurement at LBNL with the acceptance test at the beam energy of 30 keV. At low power operation when the arc power is less than 1 kW, both results agree with each other quite well. When the ion source was operated at the arc power high than 1 kW, the current measured at LBNL was approximately 10% lower compared to the acceptance test. Due to the limitation of the available pumps at LBNL test stand, the pumping speed was lower and the downstream chamber pressure was higher compared to those in the acceptance test. More charge exchange is believed to result in the H-minus beam current reduction.
IV. LEBT simulation

A two-solenoid magnetic lens LEBT system has been designed to transport and focus 30 keV H\textsuperscript+-beam from the ion source and match the beam into the RFQ. The total length of the LEBT is approximately 1.3 meters. Simulations of 5 mA 30 keV beam transport have been carried out using various simulation codes. We used TRACE 3D, WARP and Astra to study the beam envelope, trajectories, dynamics, and space charge effects in the LEBT. Use of several codes allows cross checks and we found results from simulations with these different codes to be consistent. In these simulations, the fraction of space charge neutralization is assumed to be 90%. As an example, we show in figure 6 the beam envelope of the 5 mA 30 keV H\textsuperscript+-beam long the LEBT as simulated with Trace 3D.

![Beam envelope of the 5 mA 30 keV H\textsuperscript+-beam long the LEBT simulated by Trace 3D.](image)

The input twiss parameters ($\alpha = -3.05$, $\beta = 1.147$ m/rad) used in Trace 3D simulation were calculated from the emittance measurement. To match the beam into the RFQ ($\alpha = 2.0$, $\beta = 0.063$ m/rad), the two solenoids strength are at 3.1 kGauss and 4.5 kGauss respectively with an effective length of 11 cm. The bending magnet has an edge angle of 20 degrees.

Beam trajectories in the LEBT are also simulated using WARP. WARP is a multidimensional intense beam simulation program being developed and used at the Heavy Ion Fusion Virtual National Laboratory.\textsuperscript{3} Figure 7 is the beam distribution in $x'$-$x$ at the end of the LEBT generated by the WARP code. The derived twiss parameters ($\alpha = 1.47$, $\beta = 0.059$ m/rad) are in good agreement with the result of Trace 3D.

![Beam distribution in $x'$-$x$ at the end of the LEBT generated by WARP code.](image)

To reduce average beam dump power on the subsequent MEBT collimator, a high frequency LEBT chopper will be placed in front of the second solenoid lens. The emittance growth and neutralization time measurements of the chopped beam will be investigated in the near future.

V. SUMMARY

A filament-discharge H\textsuperscript+-ion source has been fabricated by D-Pace, Inc. and installed at LBNL. The source is capable to deliver over 10mA of H\textsuperscript+-beam at cw operation with normalized 4$rms$ emittance less than 0.7 $\pi$ mm mrad. A two-solenoid magnetic lens LEBT system has been design. Simulations of 5 mA 30 keV beam transport have been carried out using various simulation codes, showing minimal emittance growth in the magnetic LEBT and beam properties that will allow efficient coupling of the H\textsuperscript+-beam into the RFQ.

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