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LAMP FRONT-END RFQ OPTIMIZATION FOR MICROPULSE PRODUCTION*

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Abstract

The LANSCE Accelerator Modernization Project (LAMP) aims at upgrading the front end of the LANSCE accelerator, involving one single radio-frequency quadrupole (RFQ) at 201.25 MHz for simultaneously accelerating both proton (H+) and negative hydrogen ion (H-) beams from 100 keV to 3 MeV. To meet the diverse set of beam requirements at various user stations, the RFQ must be capable of accelerating a continuous-wave-like beam as well as a pulsed input beam. We introduce the design optimization of the LAMP conceptual design RFQ, ensuring that all LAMP key performance parameters are satisfied. The optimization of the overall configuration of the low energy beam transport (LEBT) beamline for shaping the phase spaces of the WNR beam pulse at the entrance to the RFQ is also addressed.

INTRODUCTION

At Los Alamos National Laboratory (LANL), the Los Alamos Neutron Science Center (LANSCE) accelerator system has been in operation for over fifty years, and modernization is now essential to ensure continued support for future experiments. The LANSCE Accelerator Modernization Project (LAMP) aims to upgrade the front end of the LANSCE accelerator system, highlighting an injector system based on a 201.25-MHz radio-frequency quadrupole (RFQ) [1]. The scope of LAMP upgrade is from the ion sources to the exit of the Drift-Tube Linac (DTL). The LAMP project will lead to enhanced reliability and improved beam quality at LANSCE.

At LANSCE, both proton (H+) beams and negative hydrogen ion (H-) beams are produced. The proton (H+) beam is provided for the Isotope Production Facility (IPF) at 100 MeV. For the negative hydrogen ion (H-) beam, several distinct timing structures are established. Short beam pulses with a period of 1.8 μs are provided to the Weapons Neutron Research (WNR) facility; each short pulse (also referred to as a "micropulse") is formed by H- particles captured within one 201.25-MHz RF period (5 ns) by the end of the DTL at 100 MeV, which is further accelerated by the Coupled-Cavity Linac (CCL) to 800 MeV. The H- beam for most other experimental facilities are continuous-wave-like (CW-like) [2].

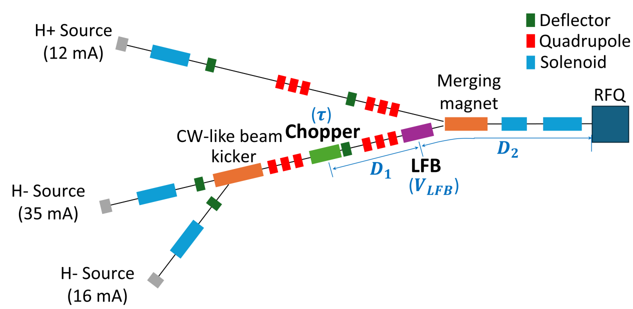

Figure 1: Schematic of the LAMP front end beamline, from the ion sources to the RFQ. The medium-energy beam transport beamline and the DTL sections of the LAMP beamline are not shown.

The LAMP front end must produce identical beam species and timing structures as those currently available at LANSCE. A schematic of the LAMP conceptual design beamline from the ion sources to the RFQ is provided in Fig. 1. One H+ ion source and two H- ion sources are involved. The 16-mA H- source provides the input beam for the CW-like time pattern, and the 35-mA H- source provides the input beam to be shaped into the WNR timing structure. To form the WNR beam pulse for input into the RFQ, the low-energy beam transport (LEBT) uses a chopper to produce a 20–30 ns H- pulse, which is then modulated by a subharmonic (low-frequency) buncher (LFB) to velocity-bunch the beam, providing an increased instantaneous current at the center of the pulse. The merging magnet deflects the H+ and H- beams to be merged before they enter the RFQ. In particular, the H+ beam and the WNR H- beam are accelerated simultaneously by the RFQ.

During the conceptual design stage of LAMP, the most significant challenge was to ensure that the WNR beam (micropulse) should contain sufficient beam charge within a single bunch. Now, the LAMP conceptual design has been developed and all requirements imposed by the key performance parameters (KPPs) have been met. An overview of the conceptual design parameters of the LAMP RFQ is provided in Table 1.

RFQ PARAMETRIC STUDY

As mentioned above, the LAMP RFQ is used for bunching and accelerating both the H+ and H- beams, and for all timing patterns. Therefore, when designing the RFQ, the parametric optimization was multifaceted. Three major factors were considered: CW-like H- beam transmission, its emittance at

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Table 1: LAMP RFQ conceptual design parameters.

Parameter	Value	Unit
Operating frequency	201.25	MHz
RFQ tank internal length	5.400	m
Ohmic RF power loss	0.8	MW
Input beam energy	0.100	MeV
Output beam energy	3.00	MeV
Shaper end beam energy	0.110	MeV
H+ source current	12.0	mA
H- WNR source current	35.0	mA
H- CW-like source current	16.0	mA
H+ RFQ-entr. rms ϵ_x^N	0.0035	π·cm·mrad
H+ RFQ-entr. rms ϵ_y^N	0.0043	π·cm·mrad
H- WNR RFQ-entr. rms ϵ_x^N	0.067	π·cm·mrad
H- WNR RFQ-entr. rms ϵ_y^N	0.080	π·cm·mrad
H- CW-like RFQ-entr. rms ϵ_x^N	0.012	π·cm·mrad
H- CW-like RFQ-entr. rms ϵ_y^N	0.014	π·cm·mrad
H+ transmission	98	%
H- WNR bunch charge	223	pC
H- CW-like transmission	98	%
H+ RFQ-exit rms ϵ_x^N	0.019	π·cm·mrad
H+ RFQ-exit rms ϵ_y^N	0.016	π·cm·mrad
H- WNR RFQ-exit rms ϵ_x^N	0.087	π·cm·mrad
H- WNR RFQ-exit rms ϵ_y^N	0.091	π·cm·mrad
H- CW-like RFQ-exit rms ϵ_x^N	0.021	π·cm·mrad
H- CW-like RFQ-exit rms ϵ_y^N	0.027	π·cm·mrad

the RFQ exit, and the WNR micropulse beam charge at the RFQ exit.

An overview of the LAMP RFQ optimization we performed using both the LANL RFQCodes (especially PARMTEQM) [3] and the CST Solvers [4] is provided in Fig. 2. The beam transmission (blue) and RFQ-exit normalized rms emittance in x- and y-direction (green) are plotted for the CW-like beam as functions of the RFQ shaper-end beam energy W_s, calculated using the RFQCodes. LAMP will start with a source current of 16 mA for the H- CW-like beam production, with future upgrade capability up to 35 mA. The WNR micropulse beam charge at the RFQ exit (red) was calculated using the CST Particle-in-Cell Solver.

The RFQ shaper-end beam energy (W_s) is a key design factor affecting the WNR bunch charge. The LAMP RFQ used $W_s = 0.110$ MeV. This small increment over the injection energy results in the shaper section of the RFQ being shorter than in more traditional designs. This is beneficial for capturing the WNR micropulse bunch charge: when the LFB-compressed H- pulse enters the RFQ, a short shaper section allows the RFQ to rapidly impose an RF energy modulation sufficiently high to stall the longitudinal debunching, "freezing" the WNR micropulse bunch charge within a single 201.25-MHz RF period. In comparison, if such an RFQ should be dedicated for the CW-like H- beam production, the optimized design should use $W_s = 0.140$ MeV for minimized output beam emittance and higher transmission.

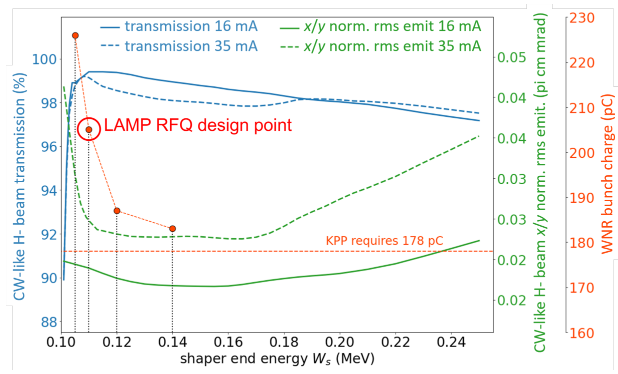

Figure 2: Parametric study of the LAMP RFQ, focusing on the CW-like beam transmission and transverse emittances and the WNR micropulse beam charge, at the RFQ exit.

The LAMP conceptual design RFQ operating point (207 pC) annotated in Fig. 2 represents a downselect prioritizing sufficient beam charge for the WNR bunch, while allowing sufficiently high transmission and appropriately low RFQ-exit transverse emittances of the CW-like beam. In a later CST PIC simulation of dual-species propagation through the RFQ, with the space charge force mitigation effect provided by the H+ beam, the WNR bunch charge was further enhanced to 223 pC. In comparison, at the RFQ exit, the WNR bunch charge must be at least 178 pC to meet the KPP.

WNR BUNCH PHASE SPACE SHAPING

We optimized the LEBT for shaping the 6D phase space of the WNR H- pulse at the RFQ entrance to ensure maximal WNR bunch charge at RFQ exit, minimized number of satellite bunches, and minimized WNR bunch transverse emittances.

The transverse phase spaces of the WNR H- beam pulse were adjusted by the setup of the LEBT magnets, ensuring high transmission of the pulse beam, and minimized WNR bunch emittance. The longitudinal phase space optimization of the WNR H- beam involved the RF voltage (V_{LFB}) and positioning (D_1 and D_2) of the LFB (see Fig. 2). The optimized longitudinal phase space distribution of the WNR H- pulse at the RFQ entrance is shown in Fig. 3.

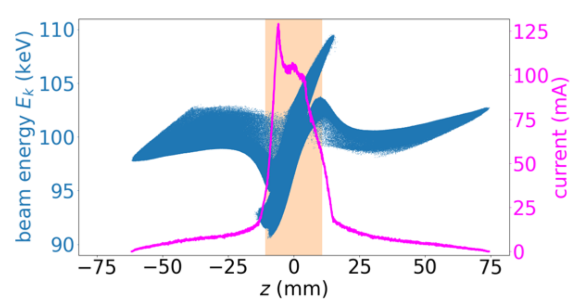

Figure 3: Longitudinal phase space distribution of the WNR H- pulse at RFQ entrance, with the central 5-ns (201.25-MHz period) highlighted.

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At the exit of the RFQ, the input WNR beam pulse shown in Fig. 3 produced the bunch train shown in Fig. 4. The central bunch is defined as the WNR bunch, and all other bunches, referred to as "satellites" bunches, in the train are removed by choppers in the medium-energy beam transport (MEBT) beamline.

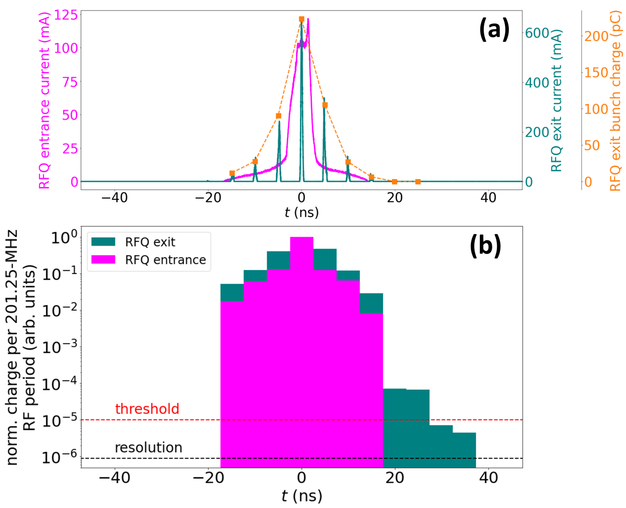

Figure 4: Longitudinal phase space distribution of the WNR H- bunch train at the RFQ exit. Only the central bunch with the highest beam charge is defined as the WNR bunch. All other bunches ("satellites") are removed by the chopper in the MEBT.

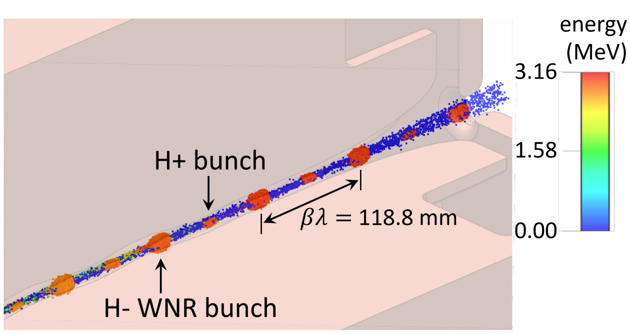

Figure 5: 3D beam distribution at the LAMP RFQ exit in the CST PIC Solver, for the WNR H- beam pulse propagating together with the H+ beam.

RFQ 3D MODELING

The VANES program of the RFQCodes generated refined vane profiles. A PYTHON script was developed for generating a Visual Basic macro for building the 3D vane tip solid models in CST. The CST Electrostatic Solver was run to acquire the 3D electrostatic electric field, which was then converted to an RF electric field distribution for the CST 3D PIC simulations. Later, the entire RFQ tank was modeled and the CST Eigenmode Solver was used to directly generate the RF electric as well as magnetic field distributions for the CST PIC simulations. The PIC simulation results using the direct, electromagnetic fields and using the manually converted RF electric field agreed very well.

The dual-species beam 3D distribution (CST PIC result) at the RFQ exit is shown in Fig. 5, with the three-quarter cross section view of the RFQ drawn accordingly in the background.

CONCLUSIONS

A 201.25-MHz radio-frequency quadrupole (RFQ) was developed for the LANSCE Accelerator Modernization Project conceptual design. The RFQ was intended to simultaneously bunch and accelerate the proton beam and the input, pulsed negative hydrogen ion beam to be shaped into the micropulse beam for the Weapons Neutron Research (WNR) facility. The RFQ also bunches and accelerates a continuous-wave-like negative hydrogen ion beam for most other target stations, such as those at Lujan Center. The RFQ conceptual design presented in this paper met the requirements driven by the LAMP key performance parameters.

For ensuring the WNR bunch production, the phase spaces of the input WNR beam pulse to the RFQ were optimized by adjusting the low-energy beam transport beamline, especially the chopper and the low-frequency buncher.

To model the RFQ performance with high fidelity, an entirely 3D workflow was developed to simulate the dual-species transmission of the proton beam and the WNR beam.

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