

ELECTROMAGNETIC AND BEAM DYNAMICS MODELING OF LANSCE FRONT-END ELEMENTS WITH CST STUDIO

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Abstract

The front end of the 800-MeV proton linac at the Los Alamos Neutron Science Center (LANSCE) is still based on Cockcroft-Walton (C-W) voltage generators that bring proton and H⁻ beams of various flavors to 750 keV. We have developed 3D CST models of the LANSCE front-end elements including low-frequency and 201.25-MHz RF bunchers. The fields in these elements are calculated with MicroWave and ElectroMagnetic Studio. Beam dynamics is modeled with Particle Studio for beams with realistic charge distributions using the CST calculated fields. The modeling results provide insight into linac operations and a guidance for designing a modern, RFQ-based front end for the LANSCE linac.

INTRODUCTION

Realistic 3D models of accelerator structures proved to be useful for studying various EM effects, mechanical tolerances, and beam dynamics; some examples are referenced in [1]. Here we apply modeling with CST Studio [2] to the front end (FE) of the LANSCE 800-MeV linac. The linac delivers both proton and negative hydrogen ion (H⁻) beams of different flavors (time patterns, bunch charges) to five user facilities simultaneously. We built simplified CST models of the FE elements: low frequency buncher (LFB), pre- and main RF bunchers, merging dipole, and quadrupoles in the beam transport lines. The focus of our study is on a special flavor of H⁻ beam, which consists of single bunches with increased bunch charge, about 300 pC, separated by long intervals of 1.8 μ s – the so-called MPEG beam. The MPEG bunches are delivered from the linac at 800 MeV directly to targets, mainly for time-of-flight experiments. Compared to regular H⁻ bunches (called LBEG) which are injected into the Proton Storage Ring (PSR) at 800 MeV and follow at 201.25-MHz repetition rate (~5-ns period), the higher charge in MPEG bunches is achieved by chopping about 25-30 ns of continuous H⁻ beam at 750 keV and applying an energy tilt in LFB for velocity bunching. LFB effects on beam parameters were studied experimentally in [3]. One should note that MPEG bunches are not well matched to the linac, which is tuned to beam flavors with higher average power, and a significant fraction of the MPEG beam is lost before it reaches its target.

Below we describe CST models of FE elements, present their calculated fields and results of Particle-in-Cell (PIC) simulations of MPEG beam in the LANSCE front end. The CST PIC simulations of this beam in the first two tanks of the Drift-Tube Linac (DTL) are also presented. We use the FE settings (buncher voltages, quad gradients) recorded during a 2012 MPEG beam run. The CST results are compared with those from the beam dynamics code Beampath [4] for the same parameters.

CST MODELING OF FRONT END

Initial Beam Distribution from Beampath

The MPEG beam is formed by chopping about 25 ns of continuous H⁻ beam at 750 keV with the LANSCE traveling-wave chopper. The chopper system has the rise and fall times of 7-10 ns. The beam dynamics was modeled with Beampath. We use a macro-particle distribution generated by Beampath and recorded at TBEM3 plane, just before the low frequency buncher. This initial distribution for CST simulations contains 18,639 H⁻ macro-particles with total charge of -325 pC.

Low Frequency Buncher (LFB)

The LANSCE LFB is an RF device driven by an external LC circuit at frequency of 16.77 MHz (1/12 sub-harmonic of the DTL RF frequency 201.25 MHz). The device itself looks like a coaxial structure, see a simplified model in Fig. 1. Its inner beam pipe has two narrow transverse gaps, with the central piece supported by an isolated radial rod (not shown). The LC circuit voltage is fed via rod to this central piece, while the end pieces and cylindrical enclosure are grounded. The LFB enclosure length is 45.085 cm, the beampipe inner radius is 1.5875 cm, and the gap widths are 0.9525 cm. The gap edges are rounded. The gap centers are separated by the distance $\beta\lambda/2 = 35.72$ cm, where $\beta = 0.04$ for 750-keV protons and $\lambda = 17.877$ m is the wavelength at 16.77 MHz. The LFB electric field is calculated either in electrostatics or by an eigensolver as a quasi-static mode. The calculated field is the same; the on-axis field is plotted for the applied potential of 15 kV in inset of Fig. 1.

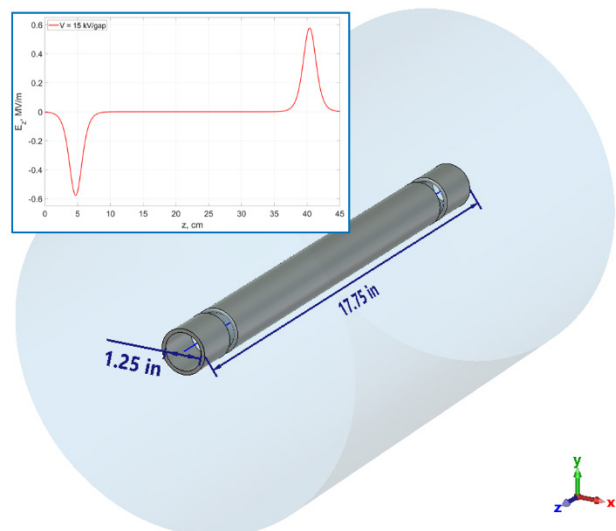


Figure 1: Vacuum volume in CST model of LFB (outer enclosure walls not shown).

The LFB potential for the MPEG run under consideration was 15 kV/gap. A snapshot of PIC simulation with CST Particle Studio (PS) when the bunch is between the gaps is shown in Fig. 2. The particle energy is indicated by color; see scale on the right. The energy tilt along the bunch length is noticeable: particles in the bunch tail have higher energy than those in the head. The beam distribution after LFB is recorded and used as an input for the next simulation step. The inset in Fig. 2 plots the particle energy vs time at the LFB exit. A few particles outside the main bunch are from the initial Beampath distribution.

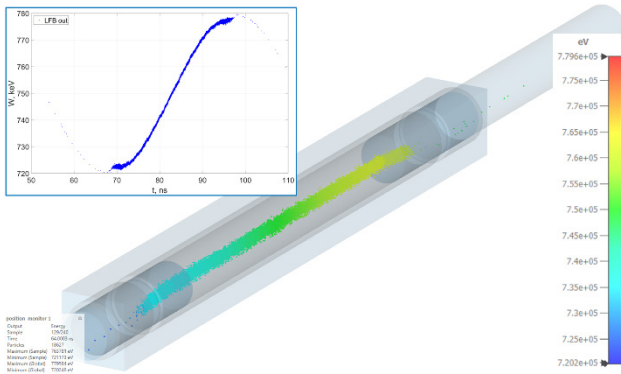


Figure 2: Snapshot of macro-particles in LFB volume, cut for PIC simulations; beam longitudinal phase space (inset).

Pre-Buncher and Transport to Bending Magnet

The pre-buncher (PB) is a re-entrant TM_{010} -type RF cavity with a narrow beam pipe aperture of 1-cm radius near the gap, the same as the main buncher [5]. It operates at the DTL RF frequency of 201.25 MHz and imposes on the beam a 201.25-MHz structure with voltage amplitude of 4 kV, see inset in Fig. 3 (after bending magnet). The PB is followed by a 3.88-m long transport line, which contains two quadruplets of quadrupoles, to a bending magnet.

Bending Magnet

The 9-degree bending magnet (BM) is a dipole used to merge proton and H^- beams, see in Fig. 3. The inset shows the particle energy vs time recorded at 20 cm after BM exit.

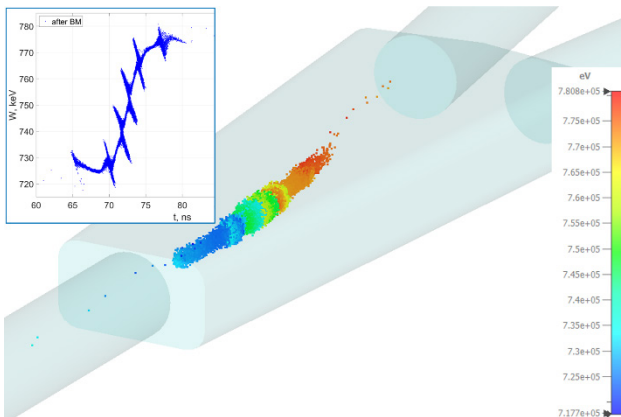


Figure 3: Snapshot of MPEG H^- bunch in BM vacuum chamber; particle energy is indicated by color.

The BM vertical dipole field was calculated with CST EM Studio. Some emittance increases after PB-BM transfer and BM become noticeable, see in Table 1.

Main Buncher and Transport to DTL

The main buncher (MB) is used to compress the beam longitudinally for injection into DTL. It operates at the RF frequency of 201.25 MHz with voltage amplitude of 13 kV. Figure 4 illustrates a cut volume around the MB gap used for PS simulations; its left inset shows the bunch longitudinal phase space after MB.

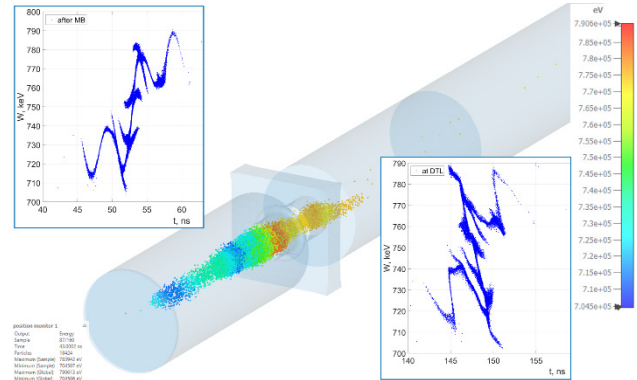


Figure 4: MPEG bunch passes through MB; particle energy is indicated by color.

The transport line TD from MB to the entrance into the first tank of DTL (T1) is 1.64-m long. It contains four quadrupoles, which are used to match the beams to DTL. The right inset in Fig. 4 shows the bunch longitudinal phase space after TD, at the entrance to the DTL tank 1 (T1). The MPEG bunch is noticeably compressed longitudinally.

Comparison of CST PS and Beampath Results

The beam parameters after each FE element described above are summarized in Table 1. It compares normalized rms emittances, in π mm-mrad, from CST (C) and Beampath (B) calculations. The longitudinal emittance values, especially after they increase in LFB, are much larger than the transverse ones.

Table 1: FE Beam Parameters from PS & BP Simulations

Element	ϵ_x , C/B	ϵ_y , C/B	ϵ_z , C/B
Input	0.188/0.188	0.208/0.207	0.95/0.95
LFB	0.186/0.187	0.216/0.215	6.83/5.20
PB	0.191/0.194	0.220/0.219	9.41/7.59
PB-BM	0.276/0.245	0.235/0.275	7.78/6.22
BM	0.353/0.299	0.251/0.298	7.44/5.98
MB	0.330/0.303	0.300/0.322	10.8/8.19
MB-T1	0.586/0.524	0.363/0.417	10.7/7.96

The beam losses are small: a fraction of per cent until MB, $\sim 1\%$ in MB, and $2\%(C) / 1\%(B)$ in transport TD from MB to DTL. Overall, the CST PS and Beampath results are

in agreement. Some differences can be attributed to Beam-path using approximate transit time factors for RF gaps, while CST uses the calculated fields.

The MPEG beam is not well matched to DTL, and its calculated transverse emittances are about twice as large as those for the regular (LBEG) beam. It is important to check how this beam is captured and accelerated in the DTL.

MPEG BEAM IN DTL

We previously developed 3D CST models [6] of DTL tanks in the LANSCE linac. The RF fields of tank modes were calculated with CST MicroWave Studio, quadrupole magnetic fields with EM Studio. We use these models to study beam dynamics of MPEG beam from the above FE simulations in DTL with CST PIC solver. The PS run with MPEG beam shows that out of 18,078 macro-particles at T1 entrance only 7,686 exit T1, others are lost on drift tubes. Only 6,276 of exiting particles are captured in RF buckets and accelerated to the nominal energy of 5.4 MeV. Figure 5 gives a particle snapshot just before the main accelerated bunch with 6,214 particles (red blob) exits T1. There are still 8,056 particles inside T1 at this moment. The inset shows the accelerated particles: main bunch and two small satellites: first with 51 particles, one RF period (~5 ns) ahead, and second with 9 particles, one period behind the main bunch. Two more tiny satellites contain one particle each. The transmission of this MPEG beam distribution into accelerated particles in T1 is 34.7%. For comparison, about 81% of input particles for regular LBEG beam are captured and accelerated in T1 [6]. Out of the initial charge -325 pC only -108.4 pC is left in the main bunch. The normalized rms emittances of the main bunch after T1 are 0.83, 0.37, 4.37π mm-mrad in x, y, z, correspondingly.

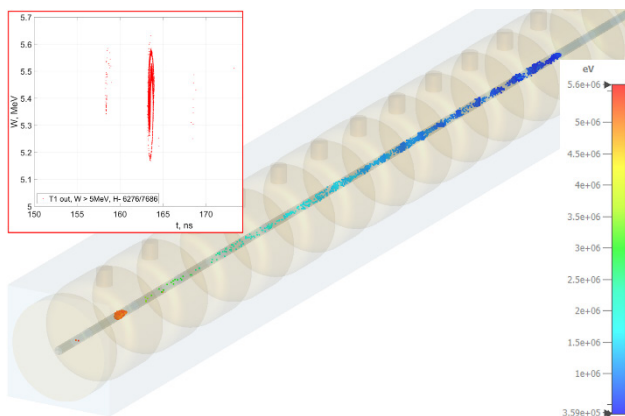


Figure 5: MPEG beam in cut volume of DTL T1: the main bunch (red blob, 6,214 particles); particles with lower energies (green, blue) form the beam tail.

We checked how the accelerated in T1 bunches propagate through T2. There were no losses except for 2 particles from the main bunch. All particles bunched in T1 reach the nominal T2 energy of 41.3 MeV. This is consistent with our results in Ref. [6]: no losses were observed in DTL T2-4 from bunches captured and accelerated in T1. The calculated normalized rms emittances of the main bunch after

T2 are 0.8, 0.38, 4.16π mm-mrad in x, y, z, very close to the emittance values after T1. Based on previous results [6], the particles in the beam tail after T1 will not be further accelerated in the DTL and eventually will be lost.

CONCLUSION

We developed simplified 3D CST models of the front-end elements in the LANSCE linac. The RF and magnetic fields are calculated with CST. Beam dynamics is modeled using the PIC solver in CST Particle Studio for the special type of H⁻ beam consisting of high-charge bunches, about 300 pC, separated by long intervals of 1.8 μ s. Such MPEG bunches are formed in FE by velocity bunching of chopped chunks (25-30 ns) of continuous H⁻ beam at 750 keV.

The CST modeling results are compared with those from Beam-path for the same settings of the FE elements and found in good agreement. Further CST PIC simulations of MPEG beam in DTL using CST tank models [6] found that about 2/3 of the MPEG bunch charge is lost in the first tank of DTL, T1. No losses of the accelerated in T1 bunch were observed in the following DTL tanks. Overall, this result is consistent with the LANSCE accelerator complex operation: typical MPEG bunch charges delivered by linac to the target are near 100 pC, about 1/3 of the initial MPEG bunch charge in the front end. Some experiments would benefit from higher bunch charges. The modeling approach presented here provides more details on the MPEG beam dynamics in the LANSCE front end and can help exploring options for improving delivered MPEG beam parameters.

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