BEAM DYNAMICS MODELING OF DRIFT-TUBE LINACS WITH CST PARTICLE STUDIO

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Abstract

The CST Studio provides convenient tools for self-consistent 3D modeling of accelerators, even large ones. Here we demonstrate this approach for the LANSCE drift-tube linac (DTL) taken as an example. The RF fields in 3D models of full DTL tanks are calculated and tuned with MicroWave Studio (MWS). Beam dynamics in the DTL is modeled with Particle Studio for bunches and bunch trains with realistic initial beam distributions using the MWS-calculated RF fields and quadrupole magnetic fields. The output beam parameters and locations of particle losses are calculated and compared for different beam distributions. Our main emphasis is on the formation of low-energy tails (longitudinal halo) and their interaction with regular bunches. Such effects are usually not taken into account in standard multi-particle phase-space codes.

INTRODUCTION

The drift-tube linac (DTL) structure, proposed by Alvarez in 1946, became the most popular type of low-energy proton linac for many decades. The DTL structure employs long cylindrical resonators (tanks) operating in the TM_{010} mode and containing a sequence of drift tubes (DTs) installed along the beam axis. DTL accelerators achieve their best efficiency for particle velocities from approximately 10% to 35% of the speed of light, i.e. $\beta = v/c$ = 0.1-0.35. The Los Alamos Neutron Science Center (LANSCE) 201.25-MHz DTL covers a wide velocity range from β = 0.04 to 0.43, which corresponds to the proton energies from 750 keV to 100 MeV. The LANSCE DTL consists of four tanks. Some relevant parameters of the DTL tanks are listed in Table 1, where N_{DT} is the number of full DTs and N_{pc} is the number of post-couplers in the tank.

Table 1: LANSCE DTL Design Parameters [1]

Parameter	Tank 1	Tank 2	Tank 3	Tank 4
Energy in, MeV	0.75	5.39	41.33	72.72
β, in-out	0.04	0.107	0.287	.37-.43
Length L, m	3.26	19.688	18.75	17.92
N_{DT}	30	65	37	29
N_{pc}	0	65	37	29
Aperture r_b, cm	0.75	1-1.5	1.5	1.5
Grad. E_0, MV/m	1.6-2.3	2.4	2.4	2.5
Aver. ZT^2, MΩ/m	26.8	30.1	23.7	19.2

FIELDS IN DTL TANKS

We have built 3D models of all four DTL tanks using CST Studio [2]. The RF fields in the full tank models were calculated with the CST MicroWave Studio (MWS) [3], mainly using the MWS tetrahedral eigensolver. For accuracy, the meshes were refined locally, especially inside the DT apertures; details can be found in [4]. The shortest tank of the DTL, tank 1 (T1), does not have post-couplers, and its accelerating field is ramped: the average on-axis cell field E_0 increases along the tank from 1.6 to 2.3 MV/m. In T2-T4, the accelerating gradient E_0 is constant. The field flatness was tuned in the CST models by adjusting spacing between post-couplers and DTs [3, 4]. The MWS-calculated RF fields of the tuned operating mode in the tanks are used to study beam dynamics. The fields in the beam region were exported from MWS as text files in a format that can be imported into various multi-particle codes. We use the CST Particle Studio (PS) particle-in-cell (PIC) solver. The static magnetic fields of the focusing quadrupoles, produced in Matlab as text files based on the hard-edge quad design values, were also imported into PS as external fields. One should emphasize that both the calculated RF fields and magnetic focusing fields are idealized: they do not include machine errors caused by misalignments, etc.

BEAM DYNAMICS

PIC Simulation Approach

Our initial simulations of beam dynamics in DTL with PS PIC were performed in [3] using an input beam of 10K macro-particles that was one RF period long. We traced only particles exiting T1 in a well-formed bunch, to speed up simulations in T2-T4, and ignored low-energy particles after the T1 exit, assuming that they will be lost anyway. Later we found [5] that a noticeable fraction of particles that are not captured in a bunch by RF in T1 still manage to propagate through T2-T4, though they are not accelerated as efficiently as the main bunch. To study how the following bunches interact with such a longitudinal tail (halo) when they pass it, and vice versa, in PS PIC simulations [5] we included tracking of the low-energy tails. Some results of PIC simulations with 10 RF periods injected in DTL are in [5]; see [4] for more details. The bunch-tail influence was small in both directions, and the results [3] for the main bunch remain valid. Here we continue PIC modeling of the DTL with more bunches, larger numbers of particles per bunch, and denser meshes.

Two realistic initial particle distributions at the T1 entrance from PARMILA [6] runs (L. Rybarcyk) were studied. The first distribution (case A) started as 100K macro-particles (24-mA current) propagated through the

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future LANL RFQ [7] and the following long beam transfer; 95899 particles (23 mA) reached the T1 entrance. The second considered initial distribution (case B) was traced from the Cockcroft-Walton (CW) injector through the existing transport lines that include a pre-buncher; 100K macro-particles at the entrance of tank 1 correspond to the 18-mA current injected into T1. At the T1 entrance the average beam energy $W = 0.75$ MeV. The same two distributions were used in [3] but with 10K initial particles. For the case A, with RFQ, the beam is better bunched, though its transverse emittances at the T1 entrance are larger.

The PS PIC solver runs the input distribution through a tank with RF and quadrupole fields and records the particles in the exit plane. This exit distribution serves as an input for the next simulation, in a drift space between two tanks, then in the next tank, and so on. To ensure the correct RF phases, φ_s = -26° in all tanks, the input distributions are time-delayed so that the bunch center reaches the middle of the first RF gap exactly at -26°. To reduce the mesh size for the PS runs, we cut the tank volume in the transverse directions x and y to just outside the DTs, but at the same time refine the mesh within the DT apertures.

Most beam parameters do not depend on the mesh size for PS runs with meshes from a few million to 70M mesh points in a tank model. The transverse emittances initially increase as the mesh size increases and then stay nearly constant. The PS results presented here were obtained using meshes 35-70M points. Many of the PIC runs at larger meshes were performed on a PC with Tesla K40c GPU. One should add that GPU computation in PS PIC was implemented in CST2015 but there were problems with recording exiting particles using 2D plane monitors, fixed in CST2016. A typical speedup due to GPU is by factor 6-8 for meshes 40-50M and 100K particles.

Simulation Results

Figure 1 shows the particle energy versus arrival time at the T1 exit for case B when only one RF period is injected into T1. This PS run was performed with a mesh of 69M points. Out of 100K injected particles, 85008 make it through T1: 80643 in the core bunch (top left) and 4365 with lower energies. Each blue dot corresponds to one macro-particle; many dots overlap in the bunch, see its expanded view in the inset. The results are similar to [3-5]: the T1 capture in the bunch is 80.6%, while additional 4.4% of injected particles exit T1 in the low-energy tail; 15% is lost on drift tubes (DTs). The bunch and tail components of the beam are separated in energy; the following bunches will overlap the tail in space. The average bunch energy is 5.36 MeV (β = 0.106) and that for the low-energy tail is 1.26 MeV (β = 0.052, i.e. about two times slower than the bunch). For comparison, in case A the total T1 transmission is 96.3% of the initial 95899 particles, with 94.5% (90649) in the core bunch and only 1.8% (1735) in the tail; the beam loss on DTs is 3.7%.

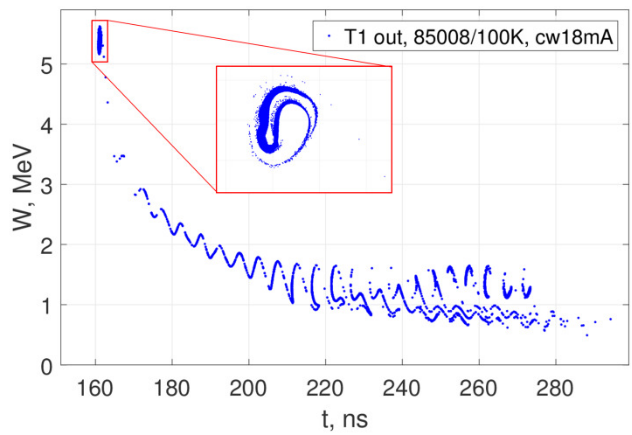

Figure 1: Energy of particles exiting DTL T1 versus time for case B (CW injection, 18 mA, 100K in 1 RF period).

The LANSCE linac macro-pulses are typically longer than the largest number of RF periods (30, ~150 ns) used in our simulations. The following bunches, which are formed from RF periods injected later, will go through the low-energy tail left by the leading bunches. To take that into account, we modify the input distributions in T2-4 by shifting the bunches from the head of the distribution to its back so that they pass through the tails while moving in the tank. After that the time delay is adjusted for the center of the first bunch to arrive to the middle of the first RF gap at the right RF phase. The procedure was used in [3-5]; it is repeated after each tank. In one case, we modified the T4 input distribution for case B not only by shifting 10 bunches from the head of the distribution to its tail, but also by repeating these 10 bunches four more times, with additional time shift of $10T_{rf}$. The resulting 50 bunches continually pass through the tail, which was produced by the first 10 RF periods, during all the time it moves in the tank. The result is shown in Fig. 2. Here each of 50 bunches contains 8066 particles while all the tail (from the first 10 bunches) has 773.

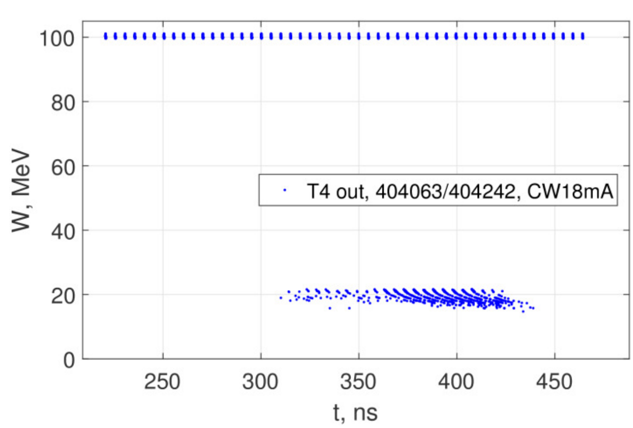

Figure 2: Energy of particles exiting DTL T4 versus time for case B (CW 18 mA, 10 RF periods) with 50 bunches.

As was noticed in [4-5], starting after T1 the ratio of the average particle energy in bunches and the tail is close to 4, or more exactly, the average velocity ratio is m = 2.

This pattern is seen especially well after T2 and T3. One can also observe it in Fig. 2 though less clearly due to the increased energy spread in the tail. This effect is usually not observed in phase-space codes (tail particles are too far in energy from synchronous ones and thus discarded) but it has a simple explanation. The tail particles that survive are accelerated with multiplicity $m = 2$: it takes them two RF periods to move from one RF gap to the next, while the main bunch particles are accelerated during every RF period ($m = 1$).

Our PS simulations results for the beam transmission (fraction of the initial number of particles) through the tanks for two distributions (A and B) with one 100K RF period injected are summarized in Table 2.

Table 2: Beam Transmission Fraction, %%

	T1 out	T2 out	T3 out	T4 out
Case A, total	96.3	94.9	94.7	94.7
Case A, tail	1.80	0.39	0.18	0.15
Case B, total	85.0	82.2	81.5	81.3
Case B, tail	4.37	1.60	0.85	0.67

One should emphasize that after the beam bunches are formed in T1, practically all beam losses come from the low-energy tail (longitudinal halo). The bunch population remains unchanged in our idealized PIC simulations (no misalignments, RF errors, etc.). For the RFQ injection (case A), 94.5% of initial 23 mA is transmitted in bunches exiting the DTL at 100.16 MeV and only 0.15% exits it in the longitudinal halo, at ~20 MeV. For C-W injection (case B), 80.4% of 18 mA is fully accelerated and 0.67% exits DTL as a 20-MeV halo. The difference is due to better bunching of the RFQ beam at the DTL entrance.

The transverse normalized (ε_x, ε_y) and longitudinal (ε_z) rms emittances for two initial distributions (A and B) are summarized in Table 3.

Table 3: Beam Emittances, π µm

	T1 in	T1 out	T2 out	T3 out	T4 out
A, ε_x	0.29	0.37	0.43	0.44	0.44
A, ε_y	0.28	0.37	0.33	0.37	0.38
A, ε_z	0.62	2.26	1.98	2.09	2.19
B, ε_x	0.12	0.31	0.37	0.38	0.37
B, ε_y	0.10	0.25	0.25	0.29	0.32
B, ε_z	2.38	2.06	1.76	1.92	2.22

Though the initial transverse emittances for case B are much smaller than for A, they increase noticeably more in T1. For longitudinal emittance the situation is reversed. These results are similar to those in [3-5].

Particle Losses

Particle loss distributions inside the DTL tanks are extracted from the PS results; see details and pictures in [4]. The beam losses in T1 are larger in the downstream part of the tank. In T2 the losses are mainly on DTs 1-29 with smaller bore. The losses in T3 are mostly on the first 6 DTs. The total average power at 100% duty deposited in each of the four DTL tanks by beam losses for the two cases is listed in Table 4. These values are small compared to the RF power losses on the DTs, which range from 65 kW in T1 to 813 kW in T4 [4].

Table 4: Average Power from Beam Losses, kW

	T1	T2	T3	T4
Case A (23 mA)	0.77	0.45	0.47	0.09
Case B (CW 18 mA)	1.72	0.74	1.66	0.55

CONCLUSION

We built 3D full-tank CST models of the 100-MeV LANSCE DTL to calculate the RF fields of the operating mode in the tanks. The calculated fields are used for Particle Studio PIC simulations of beam dynamics in the DTL. The PIC results elucidate interesting details of the longitudinal halo and particle loss in the DTL. As one can expect, the RFQ injection provides better transmission and lower losses compared to that from the existing Cockcroft-Walton injector. Our results indicate the presence of low-energy particles with energies around 20 MeV at the DTL exit. The low-energy tail amounts to about 0.7% of the regular 100-MeV beam with the existing injection scheme, and 0.15% for the future RFQ injection. We hope to verify these results experimentally.

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