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# CST MODELING OF THE LANSCE COUPLED-CAVITY LINAC

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*Abstract*

The 800-MeV proton linac at LANSCE consists of a drift-tube linac, which brings the beam to 100 MeV, followed by 44 modules of a coupled-cavity linac (CCL). Each CCL module contains multiple tanks, and it is fed by a single 805-MHz klystron. CCL tanks are multi-cell blocks of identical re-entrant side-coupled cavities, which are followed by drifts with magnetic quadrupole doublets. Bridge couplers – special cavities displaced from the beam axis – electromagnetically couple CCL tanks over such drifts within a module. We have developed 3D CST models of CCL tanks. The models are used to calculate electromagnetic fields in the tanks. Beam dynamics is modeled in CST for bunch trains with realistic beam distributions using the calculated RF fields and quadrupole magnetic fields. Beam dynamics results are crosschecked with other multi-particle codes and applied to evaluate effects of CCL misalignments.

## INTRODUCTION

Realistic 3D models of accelerator structures proved to be useful for studying various EM effects, mechanical tolerances, and beam dynamics. One example is CST models of LANSCE drift-tube linac (DTL) tanks [1]. On various occasions, they were used to calculate details of DTL element heating, tuning sensitivities, fine features of beam dynamics and particle losses. Another example is CST modeling of the FNAL 4-rod RFQ. We received a CAD model of this RFQ from its manufacturer, Kress GmbH, to help us evaluate a 4-rod RFQ option for LANL. The CAD model was imported into CST [2] and simplified for EM analysis. Our EM calculations revealed unexpected longitudinal fields in the end gaps, which are purely 3D effects and were not (and could not be) taken into account in the RFQ designed with standard codes. The beam dynamics study with CST Particle Studio showed that the end-gap field reduced the beam output energy. This incidental discovery helped our FNAL colleagues to understand the reason for the incorrect RFQ output energy, which puzzled them for over a year before that, and showed how to correct it [3]. Fortunately, the fix was easy: just removing an end-wall plug in the RFQ outer box.

Here we apply a similar approach to the LANSCE coupled cavity linac (CCL). As a first step, we build a simplified CST model of the first CCL tank (T1) in the module 5 (M5T1). The model is fully parametrized and applicable for all tanks in the CCL modules. More details and pictures can be found in the report [4]. All geometrical and design electromagnetic parameters of CCL cavities are summarized in the original 1968 document [5].

## CST MODELING OF CCL

### *EM Model of Module 5 Tank 1 (M5T1)*

The first module of CCL, module 5 (M5; the count includes four preceding DTL modules), starts at beam energy of 100 MeV and consists of four tanks. Each tank in M5 contains 36 identical re-entrant accelerating cavities (cells, AC), which are side coupled by 35 coupling cavities (CC). The coupling cavities are located off axis (side-coupled structure) and alternate their transverse positions on both sides of the beam path. Drifts after each tank contain a doublet of two EM quadrupole magnets. For M5T1, the AC length is 8.0274 cm and inner radius 12.827 cm. The tank total length is 289 cm, and the drift after T1 is 72.3 cm.

The CST model of the AC cavity starts with creating a parametrized profile curve for a quarter of the cavity vacuum volume, making a figure of rotation, and its mirroring. The CC vacuum volume is then added to the AC, and the edges of the coupling slot formed by the AC-CC intersection are rounded. After that, the cavity frequency is tuned to the operating mode frequency, 805 MHz, by adjusting the AC gap. In practice, some additional metal was left on the drift-tube noses of manufactured half-cavities, and it was scraped by a special tool to adjust the frequency before cavity brazing. We follow a similar procedure in our CST model by adjusting the AC gap width, using an optimizer in the CST eigensolver. To find all the tank modes, we need to consider bridge couplers. The end cells are tuned such that the field amplitudes there for operating mode are the same as in inner cells, so it is sufficient to calculate fields in one structure period, shown in Fig. 1.

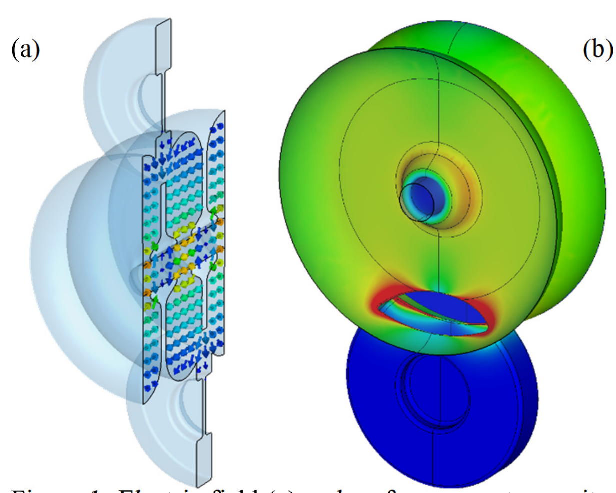


Figure 1: Electric field (a) and surface-current magnitude on the cavity inner surface (b) in one period of M5T1. Red color indicates higher values, blue – lower ones.

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Table 1: Calculated EM Parameters of M5T1

| Parameter | Value | Units |
|---|---|---|
| Quality factor $Q$ | 17630 | |
| Transit-time factor $T$ ($\beta = 0.4311$) | 0.862 | |
| Energy gain per AC | 0.110 | MeV |
| Cavity shunt impedance $R_{sh}$ | 3.398 | MΩ |
| Effective impedance $Z_{eff} = R_{sh}T^2/L$ | 31.45 | MΩ/m |
| Averaged power dissipation per AC | 4.79 | kW |
| Maximum peak electric field | 8.3 | MV/m |
| Max peak surface magnetic field | 27.4 | kA/m |

Calculated parameters of this CCL tank are summarized in Table 1. The field and power (100% duty) values in Table 1 are scaled to the nominal accelerating gradient of $E_0T$ = 1.37 MV/m and assume ideal copper surface with conductivity $\sigma = 5.8{\cdot}10^7$ Sm/m.

### *PIC Modeling of M5T1 with Particle Studio*

Using the calculated RF fields, we model beam dynamics in M5T1 with CST Particle Studio (PS) Particle-in-Cell (PIC) solver. The RF fields are extracted from eigensolver in the beam region, scaled to the T1 nominal gradient, and imported into PS. Since the operating mode fields are periodic, we could use the results for one period and repeat such an import 18 times with proper shifts along the beam line. It is more convenient to calculate and extract RF fields for a longer section of T1. We take a section with 12 AC, one-third of M5T1, for field computations. Because of the structure vertical symmetry and the operating mode symmetry in the longitudinal direction, one can restrict the computational domain to one-quarter of the section. Adaptive mesh iterations in the eigensolver increase the mesh density in regions with higher field energy density. The resulting mesh after three adaptive iterations contains 2.7M tetrahedra for one-quarter of the considered section (1/3) of T1. The solution takes about 45 minutes total on a PC with 40 cores but requires 140 GB of RAM.

The initial macro-particle distribution for Particle Studio (PS) Particle-in-Cell (PIC) runs consists of one bunch of 50K particles with the average energy of 100 MeV. It is matched to M5T1 and corresponds to 10-mA proton beam current; it was generated by Beampath [6]. The total bunch charge is 49.7 pC. The bunches in the CCL follow with the repetition frequency 201.25 MHz provided by the DTL, so that only one out of every four RF buckets at 805 MHz contains a bunch. This distribution was reformatted with Matlab for PS input and imported into CST. All particles are injected into the structure in the transverse plane located at $z = -1$ cm ($z = 0$ is the tank entrance) at different times corresponding to their positions along the bunch and move in the positive z-direction. The bunch injection time is adjusted to ensure that the bunch center reaches the middle of the first AC cavity at the correct RF phase, –36°. The magnetic fields of the quadrupole doublet after T1 are generated in Matlab in the hard-edge approximation. These quadrupole fields, as well as the properly scaled calculated RF fields, are imported into PS, see [4] for details.

For Particle Studio (PS) runs the simulation volume was cut transversely in both $x$ and y to [–3 cm, 3 cm], somewhat larger than the cavity aperture radius of 1.5875 cm, to reduce the required hexahedral mesh size. The cut volume for PS simulations and imported fields are shown in Fig. 2.

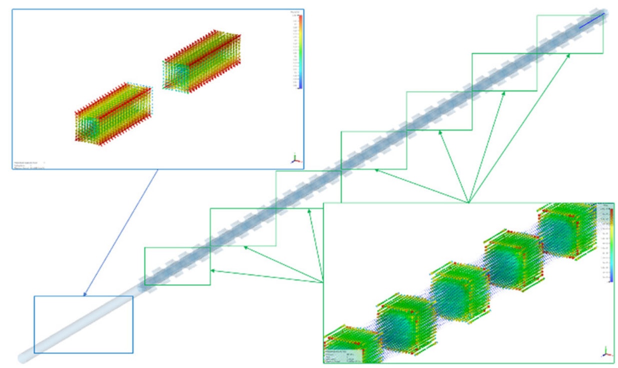

Figure 2: Calculation volume for PS runs. Insets show imported RF electric field (part; bottom) and magnetic field of the quadrupole doublet (top left). Thin blue and green arrow lines indicate locations of imported fields.

PIC simulations were performed on hexahedral meshes ~20M points with steps 0.066 cm in $x$, $y$, and 0.05 cm in the longitudinal ($z$) direction. The PS run with 5 bunches of 50K macro-particles takes 36 minutes on a PC with GV100 GPU; see Fig. 3. The simulated time in this case is 50 ns; it takes ~28 ns for a bunch to pass through M5T1.

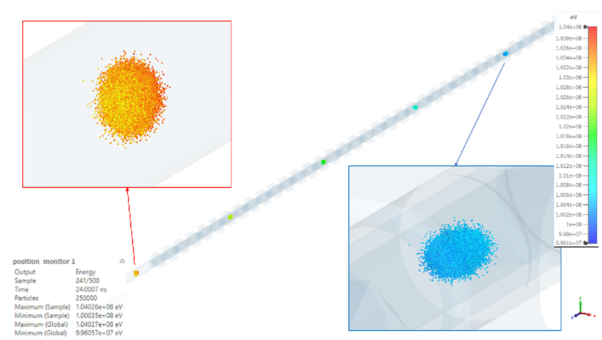

Figure 3: Snapshot of 5 bunches of 50K particles in M5T1 at $t$ = 24 ns. Color indicates particle energy; the scale is on the right. Particles move from top right to bottom left.

Our PIC simulations show no particle losses. This is because the initial distribution is well matched to the tank and contains only 50K macro-particles. It is somewhat idealized compared to realistic beams coming to M5T1 from the DTL-CCL transition region. Moreover, the simulated structure is short, less than 4 m out of the 700-m CCL. The input and output beam parameters are summarized in Table 2. It lists transverse normalized rms and longitudinal rms emittances, in π mm·mrad. The column "Out/In" lists ratios

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of final to initial parameters without misalignments; column "Out1/In" gives these ratios with misalignments included in PS simulations as described below.

Table 2: M5T1 Beam Parameters from PIC Simulations

| Parameter | In | Out/In | Out1/In |
|---|---|---|---|
| Particles | 50,000 | 1 | 1 |
| Average energy, MeV | 100 | 1.0342 | 1.0341 |
| Tr. emittance $\varepsilon_x$, π µm | 0.3687 | 1.0081 | 1.0098 |
| Tr. emittance $\varepsilon_y$, π µm | 0.3589 | 1.0093 | 1.0213 |
| Long. emitt. $\varepsilon_z$, π µm | 1.7464 | 1.0033 | 1.0036 |
| rms bunch length, deg | 6.460 | 1.153 | 1.144 |
| rms energy spread, MeV | 0.2455 | 0.920 | 0.926 |

An important observation is that the exit beam parameters are independent of the number of bunches. They are the same for all bunches and coincide with those from PIC runs with a single bunch. This means that there is no influence of one bunch on the others, which is not surprising considering that the bunches are separated by four 805-MHz RF periods. The results in Table 2 agree well with those obtained using code Beampath [6] with the same initial beam distribution.

A few more PS runs with different initial macro-particle distributions were performed to evaluate dependence on beam current and effects of beam mismatch. For example, we used the above initial macro-particle distribution: one bunch of 50k macro-particles with the average energy of 100 MeV, matched for 10 mA, but changed the beam current to 15 mA. There were no particle losses, but the transverse emittance increases at the exit of M5T1 were higher: 1.1-1.3% instead of 0.8-0.9% for the matched case of 10 mA in Table 2. The longitudinal emittance increase remained practically the same as in Table 2, about 0.33%. More examples and details can be found in [4].

### *Including Measured Misalignments of M5T1*

Misalignments of LANSCE linac elements were measured a few years ago, see references in [7]. For CCL modules, the measured misalignments are transverse shifts at the tank entrance and exit points and transverse shifts of the quad boxes. For M5T1, these values are: $(x, y) = (0.261, 0.178)$ cm at the entrance and (-0.071, 0.223) cm at the exit; (-0.046, -0.019) cm for quads. It translates into the tank tilt angles of -1.138 and 0.154 mrad in $x$ and $y$, respectively. The tank tilts are very small, so the RF fields can be obtained by simple linear transformations of the RF fields calculated in CCL tanks without misalignments, see in [7]. The quad displacements are added by shifting quadrupole magnetic fields.

The results of M5T1 PS modeling with misalignments are summarized in Table 2, last column. Comparing to the previous column, one can see that the misalignments add to the emittance increase. The added emittance growth is small except that in $y$-direction: 2.1% increase instead of 0.9% without misalignments.

The misalignment effects in the LANSCE CCL have already been studied with Beampath [7]. The Beampath results for this tank, M5T1, are in a very good agreement with the CST results presented in Table 2.

## CONCLUSION

We developed simplified 3D CST models of CCL tanks of the LANSCE linac. The CST model for Tank 1 of Module 5 (M5T1), the first tank in the CCL linac, is presented. The 3D RF fields of the operating mode in M5T1 are calculated with CST MicroWave Studio. Beam dynamics is modeled with the PIC solver in CST Particle Studio for bunch trains with a matched initial beam distribution. The PIC simulations of M5T1 use imported CST calculated RF fields and quadrupole magnetic fields. The output beam parameters agree with results from other beam dynamics codes. The beam emittance growth in M5T1 is rather small, cf. Table 2, which can be expected since the structure is relatively short, the initial particle distribution was well matched and contained only 50k particles. The measured misalignments were added to our CST model. They contribute to the emittance growth, see in Table 2. Our results for M5T1 are in good agreement with the results of Beampath simulations [7], both with and without misalignments.

## REFERENCES


[1] S. S. Kurennoy, "Beam Dynamics Modeling of Drift-tube Linacs with CST Particle Studio", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 689-691. doi:10.18429/JACoW-IPAC2016-MOPOR042

[2] CST Studio, Dassault Systemes: www.3ds.com/products-services/simulia/products/cst-studio-suite/

[3] J. S. Schmidt *et al.*, "Investigations of the output energy deviation and other parameters during commissioning of the four-rod radio frequency quadrupole at the Fermi National Accelerator Laboratory," *Phys. Rev. ST-AB*, vol. 17, p. 030102, 2014..doi:10.1103/PhysRevSTAB.17.030102

[4] S. S. Kurennoy, "EM and Beam Dynamics Modeling of CCL with CST Studio," LANL, Los Alamos, NM, USA, Rep. LA-UR-22-27127, Jul. 2022.

[5] L. N. Engel, "Geometrical and Electromagnetic Parameters of the Accelerating and Coupling Cells of the 805 MHz Linac for LAMPF", LANL, Los Alamos, NM, USA, Rep. MP-3-58, 1968.

[6] Y. K. Batygin, "Particle-in-cell code BEAMPATH for beam dynamics simulations in linear accelerators and beamlines," *Nucl. Instr. Meth. A*, vol. 539, pp. 455–489, 2005. doi:10.1016/j.nima.2004.10.029

[7] Y. K. Batygin and S. S. Kurennoy, "Effect of Lattice Misalignment on Beam Dynamics in LANSCE Linear Accelerator," presented at NAPAC'22, Albuquerque, NM, USA; paper TUPA48.