

THE FERMILAB UPGRADE LINAC: DYNAMICS DESIGN PROCESS

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Abstract

The Fermilab Coupled Cavity Linac requires dynamics design procedures that predict 805 MHz rf synchronization, non-linear emittance dilution and system error aspects of the device. Full 3-D beam simulations using three separate codes have shown the need for a central orbit monitor to detect desynchronization implicit in the longitudinal dynamics of coupled cavity devices. The new linac section accepts a 116 Mev (200MHz) DTL beam, requiring a transition matching section, before actual 805Mhz acceleration begins. This requirement places significant constraints on phase space acceptances of the side coupled structure.

We describe special aspects of the design codes used to verify these system attributes, with particular attention to the effect of system errors and RF noise on the beam performance. Results of beam loss simulations, using a PIC model of beam halo based on current knowledge of the 200 Mev beam is discussed.

Introduction

To raise the Fermilab Booster space charge limited beam (50ma) brightness an increase in injected beam energy is being implemented. ¹ An optimized upgrade of the existing 200 Mev DTL linac indicated that a side coupled CCL with operating frequency at 805 Mhz, and average axial fields of 7.5 Mev/meter would interface with the upstream DTL at 116 Mev. Replacing the last 4 DTL structures with a CCL system consisting of a longitudinal bucket matching section, for bunch size matching, and a 28 cavity accelerating section could provide a 400 Mev injected beam for the Booster.

Project goals for the 400 Mev beam required both the ability to be debunched with a tolerable energy

spread and little emittance dilution in all planes, and an axial allotment of 67 meters to keep the original Booster transport line length constant. These goals required careful attention to the bunch compression (transition) section, where space charge equipartition effects were expected to appear.

A tight radial dimension (1.50 cm.) for the cavity bore radius required beam loss simulations with all construction and drive errors included, using realistic beam halo simulations. The choice of 805 Mhz vs. 1307.5 Mhz was made to lower the risk of beam emittance dilution(1) predicted for abrupt changes in structure parameters.

The dynamics design required a 3 stage effort. First a trial segmentation of the cavity array was generated with a 'genlin' code that used SUPERFISH (2) data ($ZT^{**2}, T, E_{max}/E_0$) to constrain the selection of cavity average fields (E_0) consistent with rf drive power choices (12 MegWatt klystrons) and peak cavity fields.(37 MV/m)

The second stage required finding the matched Twiss parameters for the maximum space charge (50 ma.) beam conditions using the linear space charge beam matrix methods of TRACE3D. A known limitation in TRACE3D is its inability to recognize CCL travelling wave synchronization conditions implicit in the bridge coupler elements. For rf drive error studies in which several cavities are linked together in a single rf pathway, synchronous particle definitions require the ability to recognize the desynchronizing effects that may occur within a given drive module.

The third stage of the design involved a CCL specific PIC code that has a 2 1/2 D space charge (elliptical transverse charged rings) capability with many error simulating functions. This code (CAVDYN) utilized the same TRACE3D data sets used in stage 2 to assemble a CCL system and incorporated the same longitudinal linear dynamics, but included non-linear terms as well. In addition, a central orbit monitor developed for this code (3) was able to

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recognize any desynchronization within a complete CCL system, including all contributing errors. The key ingredient was the recognition of the rf drive boundaries by the PIC code. An extra 'tank' parameter has been imbedded in the TRACE3D code (TRACEX at Fermilab) to implement the z-plane central orbit data transfer to CAVDYN. This parameter provides check data for the internal consistency of the CCL tank, in TRACEX, and the downstream bridge coupler, in CAVDYN. It also provides the structure defined synchronous energy used to form the central orbit monitor in CAVDYN. CAVDYN will detect improper drive boundaries, and flag these as data failures before system simulation can be run.

System Overview

The synthesis of the new high gradient CCL started with defining the space charge matched beam Twiss parameters predicted from the operating DLT tank 5 design parameters. This beam matrix would be then transformed by a matching section to reduce the bunch size by 1/2, a result of the tighter rf focusing in the CCL dynamics, and expand the transverse beta functions up by a factor of 2.3, corresponding to the a 50ma. space charged matched conditions entering the CCL quadrupole FODO channel. The 7 module (28 tank) acceleration segment of the CCL design was chosen, satisfying the 37 MV/m field maxima and uniform rf power distribution. By selecting 16 cell cavities, with 3-cell bridge couplers a uniform tank array was produced that simplified the quadrupole tune design. Larger (5-cell) bridge couplers produced significant bunch shape oscillation from the debunching.

The transition section design(4) uses 7 quadrupoles (3DTL, 4 CCL) to provide the FODO matching. Bunch compression is accomplished by two bunching cavities, sized to allow a 200 Kw klystron for rf drive. The transition section, because of the magnification of input energy swings, together with a 10 degree phase slippage off the travelling wave in the low energy cavities, produces a tighter input acceptance for DTL beam energy swings. A smaller initial cell segmentation (ie 11 cell cavities) would alleviate this constraint, but was not deemed necessary.

Error Studies

The simulation of CCL system errors has been layered at 3 levels. Level 1 allows major detunes of the TRACE3D data set to simulate major detunes or crashes for loss analysis. Level 2 allows correlated random alignment and drive errors to be inserted into the dynamics to assess emittance degradation, and beam centroid swings. Level 3, not reported here, is simulation of cavity phasors disturbances arising from real cavity conditions such as stopbands, power droops and coupling errors. This requires phase and amplitude errors resolved in individual cells.

The level 2, random correlated errors, have been simulated for 2 independent correlation groups, corresponding to rf drives, for z-plane dynamics, and transverse displacements for correlated groups of quadrupoles and cavities, for the transverse plane. The rf drive errors (phase and amplitude) were run for the 7 drives, using independent random errors in each drive. Because a central-orbit is established for a given TRACE3d file, rf drive error disturbances are superimposed on any central orbit swing, and give realistic assessment of non-linear dynamics. Level 3 disturbances to the central orbit, will eventually be taken into account, to produce a working central orbit.

Figure 1 shows the 400 Mev longitudinal phase space for a nominal CCL with ideal DTL input beam and with a random error in the 7 accelerating drives of +/-1.0 percent amplitude, 1.0 deg phase, uniformly distributed. At twice this tolerance band, significant non-linear dilutions occur in the phase-energy space. Figure 2 shows the effect of the same drive errors when the DTL beam is 0.5 Mev off the CCL synchronous input energy. This sensitivity to input energy error is related to the dynamics of the bunch compression (transition) section, which doubles the central orbit energy swing. Here, the central orbit swing produced by the DTL energy offset, is added to the klystron random errors, producing a significant non-linear z-plane disturbance, at the design tolerance band.

Transverse beam centroid swings had been simulated for the CCL girder design, which carries 4 cavity-quad pairs. Correlated displacement tolerances for girders and individual quadrupoles were set at 0.25 and .10 mm.(5) respectively, correspond-

ing to rms centroid swings of 4.5 and 2.7 mm respectively. These require 1.5 mrad dipole steering for each girder. Quadrupole field harmonics have also been simulated to check the harmonic tolerance band.

Loss Studies

The beam loss simulations were carried at both level 1 and level 2 error modes. The operating knowledge of current DTL 200 MeV transverse emittance permitted a realistic transverse halo model to be employed, which was described by a 4D-gaussian whose 95% limits were well established. The crash modes investigated were loss of trim steering, single quadrupole crash, and a single rf drive modulator crash. Single rf drive losses were catastrophic in the low energy modules, as expected from phase slip arguments. Loss simulations were useful in providing strategies for interlock and alarm (6) provisions for initial safety system designs.

Summary and Conclusions

The design of the new CCL system at Fermilab has been studied using linear and non-linear dynamics. Simulations have predicted no significant emittance dilutions for the space charge 50 ma average beam current. 400 MeV beam centroid motion resulting from construction and rf drive errors appear to be acceptable to the Booster requirements. Required DTL stability in energy is estimated to be 0.2 MeV, to control z-plane emittance dilution from non-linear bucket excursions in the CCL.

Further studies, using level 3 errors (intra-cavity phasor error distributions) will show realistic working central orbits. This will aid in the commissioning strategies for finding the working points of the klystron drive controls, typically for such methods as the delta-t process.

References

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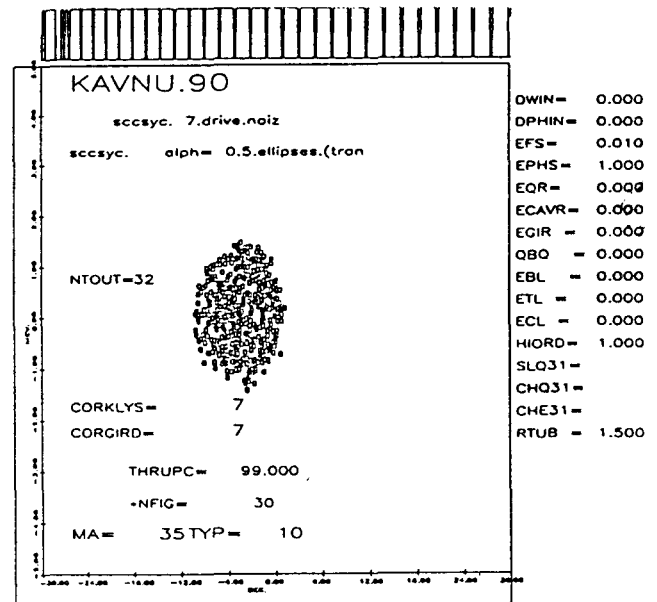


Figure 1: 400 MeV z-plane dw-dphi for 1 deg/% drive noise

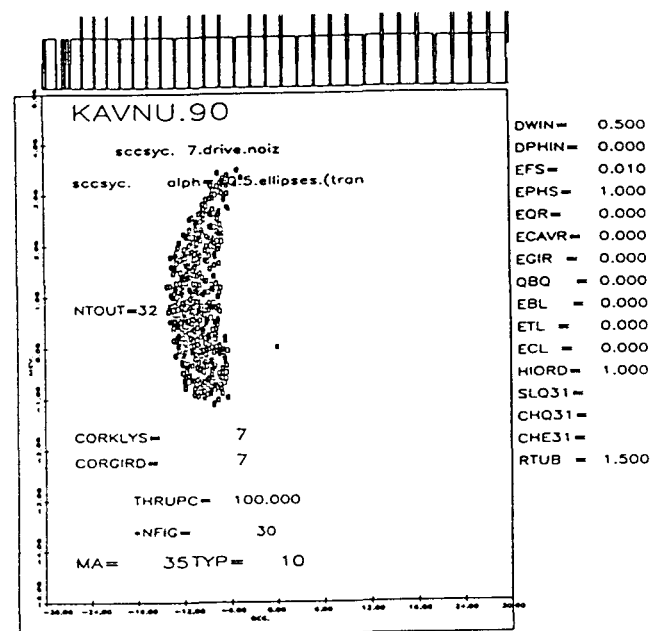


Figure 2: 400 MeV z-plane dilution from 0.5 MeV DTL error