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**Summary of the Workshop Session for Wakefields
During the Linear Accelerator and Beam Optics Codes
San Diego, January 19-21, 1988.**

The computational tools for calculating wakefields are well developed and are currently complemented with experimental measurement.

There are various computer codes used in calculating wakefield effects nowadays. Among them, the most notable and complete one is the MAFIA group of codes. This code group is being supported by a collaboration between the Deutsches Elektronen-Synchrotron (DESY) and the Los Alamos National Laboratory (LANL). It consists of codes that are used for time-domain and frequency-domain calculations. Calculations with 3D and 2D geometries are possible. An introductory talk on 3D calculations using MAFIA codes was given by R. K. Cooper of LANL showing the present capabilities of the codes. Up-to-date information was reviewed during discussions with T. Weiland of DESY.

At the Argonne National Laboratory (ANL), an Advanced Accelerator Test Facility (AATF) has been commissioned that will allow the measurement of wakefield effects of beamline components up to a length of 1 m. The transverse and longitudinal electromagnetic fields induced by a primary electron bunch are probed using a second collinear electron bunch that trails the primary bunch at a variable time delay. This facility will be extremely useful for benchmarking results from computer codes. A talk introducing the facility was given by P. Schoessow of ANL. During the talk, the measured transverse and longitudinal wake effects of several iris-loaded RF-structure were presented, showing good agreements with calculations made with TBCI, a code from the MAFIA code group.

LTRACK — BEAM-TRANSPORT CALCULATION INCLUDING WAKEFIELD EFFECTS *

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ABSTRACT

LTRACK is a first-order beam-transport code that includes wakefield effects up to quadrupole modes. This paper will introduce the readers to this computer code by describing the history, the method of calculations, and a brief summary of the input/output information. Future plans for the code will also be described.

INTRODUCTION

LTRACK is a simple first-order beam-transport code that has the special feature of including wakefield¹ effects of a beam bunch. When a beam bunch traverses beamline elements, it interacts with the elements and generates electromagnetic fields called wakefields. The wakefields induced by the front of the bunch will provide additional forces for the latter part of the bunch, and different parts of the bunch will be transported differently. At the end of the beam transport, there will be variations of beam parameters along the beam bunch. When the beam parameters of the whole bunch are considered, these variations become effective growths in energy spread and transverse emittance. When the beam current is increased, this deterioration of beam qualities increases and becomes significant.

Beam-transport codes, including wakefield effects, began to appear in the last few years for two reasons. Firstly, the introduction of computer codes like TBCI² has allowed the calculation of wakefield effects in the time domain, and including wakefield effects in beam-transport codes then becomes a straightforward task. Secondly, while people try to design accelerators with high peak currents and demand good beam qualities, they need codes of this kind to treat wakefield effects properly. There are two important examples of this type of design. The first example concerns injector for free electron lasers. The light conversion efficiency of a wiggler increases with the peak beam current and with better beam qualities. It is imperative that wakefield effects be considered when the injector is designed. The second example concerns TeV colliders, where high current and good beam qualities are necessary to produce high luminosity for the high-energy physics community. In the Workshop of New Developments in Particle Acceleration Techniques held at Orsay, France, this past summer, people believed that a high-frequency rf linac is the way to build tomorrow's etc.

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colliders.³ With wakefield effects scaling up as the powers of rf frequency, these colliders have to be designed with beam-transport codes including wakefield effects.

HISTORICAL BACKGROUND

LTRACK is a by-product of the design effort of the Stanford Linear Collider (SLC). In 1983, Chao and Cooper wrote LTRACK to investigate the transverse quadrupole wakefield effects in the SLC.⁴ Around 1984, Bane adapted LTRACK for use in investigating the effectiveness of Landau damping for curing single bunch beam breakup caused by the dipole wakefield in the SLC.⁵ Currently we have incorporated LTRACK as a part of the wakefield code set being developed in AT-6 of the Los Alamos National Laboratory. This development effort is being supported with Institutional Supporting Research and Development (ISRD) funds aiming to build a set of beam-transport codes available for the design of high-energy electron linacs with high bunch-charge density, where wakefield effects are important. At the present time, this set of codes includes: LTRACK, a first-order code used for quick preliminary designs; and PARMELA,⁶ a particle tracking code used for final designs with all the higher-order beam-optics considerations.

METHOD OF CALCULATIONS

At the present time, LTRACK is used in conjunction with TBCI, which produces wakefield information. Figure 1 shows the running sequence of these codes and the associated files. The wakefield information is produced by TBCI in the form of wake functions and are contained in the output file TBCIWAK of TBCI. Using a small program called WORK1, these wake functions are processed and output to a file called LTRAKWAK, in a form useful to LTRACK. If analytical forms of the wake functions are available, LTRAKWAK can also be replaced by a user-defined subroutine in LTRACK that contains these analytical forms. The rest of information required by LTRACK, i.e., beamline arrangement, beam parameters, etc., are specified in LTRAKIN, the principal input file for LTRACK.

During a calculation using LTRACK, a beam bunch is divided into a number of slices longitudinally. Each slice is characterized with the following parameters:

1. number of particles in the slice;
2. longitudinal position of the slice relative to the bunch center, i.e., z ;
3. energy of the slice;
4. parameters describing the location and divergence of the centroid of the slice, i.e., (x, x', y, y') ; and
5. parameters describing the transverse phase-space distribution of particles in the slice, i.e., a 4×4 Σ -matrix.

Fig. 1. Operation sequence of LTRACK and the associated files.

LTRACK has been designed for particles that are travelling at the speed of light; therefore, the numbers of particles in the slice and the relative positions of the slices (parameters in 1 and 2) are assumed to be unchanged during the transport. The other parameters (parameters in 3 to 5) are changed when the slices are transported through the beamline under two influences: the beamline elements and the wakefield forces.

The treatment of the beamline elements is similar to that of the computer code TRANSPORT.⁷ The elements are represented by transfer matrices **T**. The centroid of a slice is tracked according to

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{out} = \mathbf{T} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{in} , \quad (1)$$

and the transverse distribution of particles in the slice according to:

$$\Sigma_{out} = \mathbf{T} \Sigma_{in} \tilde{\mathbf{T}} , \quad (2)$$

where Σ is the 4 x 4 matrix describing the transverse phase space and the tilde indicates the transpose of a matrix. The transfer matrix **T** is allowed to depend on the energy of the slice being tracked. Types of beamline elements currently available are

drift,
bending magnet with edges,
quadrupole,
accelerating section, and
solenoid.

The treatment of monopole, dipole, and quadrupole wakefields, respectively, is explained as follows. Using the impulse approximation, wakefield effects are applied at regular intervals during beam transport.

The monopole wake has the effect of changing the energy of the slices. The k^{th} slice suffers an energy change of ΔE_k , which is given by

$$\Delta E_k = -L \sum_{i=1}^{k-1} N_i W_0(z_i - z_k) , \quad (3)$$

where

- L : the length over which wake effect is to be considered,
 N_i : the number of particles in the i^{th} slice,
 $W_0(s)$: the monopole wake function per unit length, and
 $\sum_{i=l}^{k-1}$: sum over all slices ahead of the k^{th} slice.

The dipole wakefield causes energy loss and deflections of particles. The energy loss is not taken into account in LTRACK because it is usually small compared to that caused by the monopole wake effect. The dipole transverse forces for all the particles in a slice are the same; therefore, they will only introduce a deflection of the centroid of the slice without affecting the Σ -matrices of slices. These deflections are represented by changes of divergences of x' and y' for the centroid of the k^{th} slice:

$$\begin{bmatrix} \Delta x'_k \\ \Delta y'_k \end{bmatrix} = \frac{r_e L}{\gamma_k} \sum_{i=l}^{k-1} N_i W_1(z_i - z_k) \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \quad (4)$$

- where $W_1(s)$: the dipole wakefunction per unit length,
 r_e : classical electron radius, and
 γ_k : energy of the k^{th} slice in units of the electron rest mass.

The quadrupole wakefield changes the energy, the centroid parameters, and the Σ -matrices of the slices. As in the case of the dipole wakefield, the energy changes are not taken into account in LTRACK. The quadrupole transverse wake force is in a form very similar to that of a quadrupole. The force induced by the i^{th} slice at distance z behind is given by

$$e^2 W_2(z) [Q_{1i}(x\hat{x} - y\hat{y}) + Q_{2i}(y\hat{x} - x\hat{y})], \quad (5)$$

where

$$Q_{1i} = \Sigma_{11i} - \Sigma_{33i} + x_i^2 - y_i^2,$$

$$Q_{2i} = 2\Sigma_{13i} + 2x_i y_i, \text{ and}$$

$W_2(s)$: to the quadrupole wake function per unit length.

The terms Q_{1i} and Q_{2i} are the regular and skewed quadrupole moments, respectively. These moments contain contributions from both centroid displacements and beam shapes. A transfer matrix $T_{\text{quad wake}}$ similar to those for a beamline element can be constructed as

$$T_{\text{quad wake}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ q_1 & 1 & q_2 & 0 \\ 0 & 0 & 1 & 0 \\ q_2 & 0 & -q_1 & 1 \end{bmatrix}, \quad (6)$$

where

$$q_{1,2} = \frac{r_e L}{\gamma k} \sum_{i=1}^{k-1} N_i W_2(z_i - z_k) Q_{1,2i}.$$

The quadrupole transverse wake effects on the k^{th} slice are treated by operating with this matrix on the k^{th} slice as in Eqs. (1) and (2).

INPUT/OUTPUT INFORMATION

Figure 2 shows a summary of the input to LTRACK contained in the input file LTRAKIN. It is shown in a form as echoed in the LTRACK output file, called LTRAKOUT and is very much self-explanatory. The input information can be classified into three types. Firstly, there are initial beam parameters. Secondly, there are parameters specifying the options, which include the choice of positrons and electrons, including alignment errors for the accelerator, the beam-position monitor (BPM), and the quadrupoles and (2) the simulation of the BPM and the corrector pair as in automatic beam-position controls. Thirdly, there is information on the beamline lattice, which takes the same form as in the computer code TRANSPORT (not shown in Figure 2). In LTRAKOUT, after echoing the information from LTRAKIN, the wake function information as supplied via LTRAKWAK will be echoed. After reading in all the input information, LTRACK will start transporting the bunch and printing out the bunch parameters averaged over all the slices at each of the beamline elements. These parameters include the centroid and first moment of the transverse bunch positions and divergence, the transverse emittance growth, the bunch energy, and the energy spread. LTRACK also prints out the parameters of individual slices after the last beamline element.

FUTURE PLAN

There are three major areas in which LTRACK will be improved in the near future. First, a graphic package convenient to the user will be added. Second the capability of using more than one set of wake functions corresponding to different beamline elements will be implemented. At the present time, LTRACK only accepts one set of wake functions, which are used at accelerator sections. Third, a more complete User's Guide will be written.

```

*****
*input parameters*
*****

wakefield existence flag, monopole : lwak0 = t
                                dipole : lwak1 = f
                                quadrupole : lwak2 = f
acc sect. slice length / m (if wake) : aclens = 3.7500e-02
initial ztot (no scraping for ztot<0) : ztot0 = 0.0000e+00
flag for scattering at each element : lthrua = f
flag for scraping at naper= lca : lscrap = f

bunch, total number of particles : qntot = 1.0000e+11
      rms length / m : sigz = 3.8300e-03
      trunc. num. of sigz in front : nsgfro = 3
      trunc. num. of sigz in back : nsgbak = 3
      number of transverse slices : nsll = 37
      flag for positrons : lpost = f
      flag for electrons : lelec = t
      slice retention limit / m : rcut = 1.0000e+03

orbit correction, flag x : lcorx = f
                   flag y : lcoy = f
                   scale factor : rcor = 1.0000e+00
                   scat.-for-corr.flag : lcosca = t
                   mon.s/block forward : nmofo = 20
                   mon.s/block bakward : nmobak = 4

errors, accelerator, generation flag : lacgen = f
      rms error x / cm : sigacx = 0.0000e+00
      rms error y / cm : sigacy = 0.0000e+00
monitor, generation flag : lmoen = f
      rms error x / cm : sigmax = 1.0000e-02
      rms error y / cm : sigmay = 1.0000e-02
quadrupole, generation flag : lqugen = f
      rms error x / m : sigqux = 1.0000e-02
      rms error y / m : sigquy = 1.0000e-02
generation seed : lseedg = 878348

card enabling flags, corrector kicks : lcorrt = f
      accelerator errs : lacert = f
      monitor errs : lmoert = f
      quadrupole errs : lquert = f

bunch, initial energy / gev : e0 = 1.0000e-02
      initial energy spread / gev : sige0 = 0.0000e+00
      initial x offset / m : cen0(1) = 1.0000e-04
      initial x prime / mr : cen0(2) = 0.0000e+00
      initial y offset / m : cen0(3) = 1.0000e-04
      initial y prime / mr : cen0(4) = 0.0000e+00

bunch, initial sigma matrix for e+ : 1.5329e-08 1.4452e-08 0.0000e+00 0.0000e+00
                                     1.4452e-08 2.0440e-08 0.0000e+00 0.0000e+00
                                     0.0000e+00 0.0000e+00 1.5329e-08 -1.4452e-08
                                     0.0000e+00 0.0000e+00 -1.4452e-08 2.0440e-08

random number generator seed for scat : lseed = 13579
number of points to scatter : nscat = 2000
flag for echoing the input : lecho = t
index for printing at each element : ltabl = 2
indicator for printing at the end : lprint = 6
plotting, flag : lplot = t
      plot selection string : splot = 1111111111
debugging, flag : sdebug = 0011001000

initial emittances:
gam = 1.9589e+01
ga*2*eps_xy = 4.0000e-10
gam*eps_x = 2.0001e-08
ga*eps_y = 2.0001e-08

```

Fig. 2. Input information to LTRACK as echoed by LTRAKOUT.

REFERENCES

1. Reviews of wakefield effects can be found in the following two references:
A. W. Chao, Coherent Instabilities of a Relativistic Bunch Beam, SLAC-PUB-2946 (1982), also Physics of High Energy Accelerators (SLAC Summer School 1982), AIP Conf. Proc. 105.
P. B. Wilson, High Energy Electron Linacs: Applications to Storage Ring RF Systems and Linear Colliders, SLAC-PUB- 2884 (1982); also Physics of High Energy Particle Accelerators (Fermilab Summer School, 1981), AIP Conf. Proc. 87.
2. T. Weiland, Transverse Beam Cavity Interaction, Part I: Short Range Forces. DESY 82-015, March 1982.
3. G. Coignet and S. Turner, Foreword to the Proceedings of the Workshop of the New Developments in Particle Acceleration Techniques, CERN 87-11, October (1987) pp. vii.
4. A. W. Chao and R. K. Cooper, Transverse Quadrupole Wake Field Effects in High Intensity Linacs, Particle Accelerators, Vol. 13, pp. 1-12 (1983).
5. K. L. F. Bane, Landau Damping in the SLAC Linac, IEEE Trans. Nucl. Sci. **32** (5), 2389 (1985).
6. PARMELA, particle tracking code for electrons written by K. R. Crandall. For further information consult Computer Codes used in Particle Accelerator Design, Los Alamos National Laboratory report LA-UR-86-3320. (1987).
7. D. C. Carey, TRANSPORT Manual, Stanford Linear Accelerator Center report SLAC-91, 1973 revised.