

Phase space simulation program for main linacs of future linear colliders

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Tracking simulation programs have been developed for main linacs of future linear colliders. The primary concern of the simulation is preservation of emittance. Sources of emittance dilution are wakefield effect and dispersive effect due to injection error and misalignment of quadrupole magnets and accelerating structures. Longitudinal and transverse wakefield are included. Both single bunch and multibunch effect can be taken into account. Several kinds of correction schemes can be simulated, e.g.. one-to-one correction, DF(dispersion free) type corrections and fast kicker for individual bunch.

Part 2 explains how to use the program.

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1. Beam

The beam consists of bunches. Each bunch is divided into slices and each slice contains macro particles. Each macro particle is identified by three numbers, bunch number (n_b), slice number (n_s) and particle number (n_p). Macro particles having the same bunch number are considered to be in the same bunch. Macro particles having the same bunch number and the same slice number are in the same slice, having the same longitudinal position. Relative longitudinal position of each macro particle depends on n_b and n_s as;

$$z(n_b, n_s) = (n_b - 1)s_b + (n_s - N_s / 2 - 1 / 2)s_s \quad (1)$$

where s_b is bunch spacing and s_s is slice spacing N_s total number of slices in a bunch. Macro particles having the same slice number and the same particle number have the same charge ($q(n_s, n_p)$).

A simulation can be chosen as 'first order' or 'second order' according to the purpose. In the 'first order' simulation, each macroparticel is treated as a point charge and its status is described by parameters as follows.

E : energy
x : transverse position
p : transverse momentum

In the 'second order' simulation, each macro particle is treated as an ellips in phase space with center position x and center momentum p. Each macro particle is monochromatic (energy E) and has additional parameters as follows.

σ_{11} : average of square of transverse offset
 σ_{12} : average of transverse offset times transverse momentum
 σ_{22} : average of square of transverse momentum

Emitance is defined in different ways in second order simulation and first order simulation.

$$\varepsilon = \left[\left(\langle x^2 \rangle - \langle x \rangle^2 \right) \left(\langle x'^2 \rangle - \langle x' \rangle^2 \right) - \left(\langle xx' \rangle - \langle x \rangle \langle x' \rangle \right)^2 \right]^{1/2} \quad (2)$$

In the second order simulation

$$\langle x^2 \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \sigma_{11}(n_b, n_s, n_p)}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (3)$$

$$\langle x'^2 \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \frac{\sigma_{22}(n_b, n_s, n_p)}{E^2(n_b, n_s, n_p)}}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (4)$$

$$\langle xx' \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \frac{\sigma_{12}(n_b, n_s, n_p)}{E(n_b, n_s, n_p)}}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (5)$$

$$\langle \mathbf{x} \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) x(n_b, n_s, n_p)}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (6)$$

$$\langle x' \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \frac{p(n_b, n_s, n_p)}{E(n_b, n_s, n_p)}}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (7)$$

in first order simulation, $\langle x^2 \rangle$, $\langle xx' \rangle$ and $\langle x'^2 \rangle$ are defined as

$$\langle x^2 \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) x^2(n_b, n_s, n_p)}{N_b \sum_{n_s, n_p} q(n_s, n_p)}, \quad (8)$$

$$\langle x'^2 \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \frac{p^2(n_b, n_s, n_p)}{E^2(n_b, n_s, n_p)}}{N_b \sum_{n_s, n_p} q(n_s, n_p)} \quad (9)$$

$$\langle xx' \rangle = \frac{\sum_{n_b, n_s, n_p} q(n_s, n_p) \frac{x(n_b, n_s, n_p) p(n_b, n_s, n_p)}{E(n_b, n_s, n_p)}}{N_b \sum_{n_s, n_p} q(n_s, n_p)} \quad (10)$$

N_b and N_s are total number of bunches and slices respectively.

2. Elements of Linac

A linac consists of series of elements of five kinds as follows.

- (a), Drift space
- (b), Dipole magnet
- (c), Quadrupole magnet
- (d), Accelerating structure
- (e), Beam position monitor

(a) Drift space

Each drift space has one parameter, length (l). Beam parameters (see section 1) of each macro particle will change as ;

$$\begin{aligned} \begin{bmatrix} x \\ p \end{bmatrix} &\rightarrow R_D \begin{bmatrix} x \\ p \end{bmatrix} \\ \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} &\rightarrow R_D \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} R_D^T \end{aligned} \quad (11)$$

where

$$R_D = \begin{bmatrix} 1 & l/E \\ 0 & 1 \end{bmatrix}, \quad (12)$$

(b) Dipole magnet

Dipole magnets are located at the center of quadrupole magnets as orbit correctors. The length is zero. Each dipole magnet has one parameter, integrated strength (B). Beam parameters of each macro particle change as ;

$$\begin{aligned}
 x &\rightarrow x \\
 p &\rightarrow p + B \\
 \sigma_{11} &\rightarrow \sigma_{11} \\
 \sigma_{12} &\rightarrow \sigma_{12} + xB \\
 \sigma_{22} &\rightarrow \sigma_{22} + 2pB + B^2
 \end{aligned} \tag{13}$$

(c) Quadrupole magnet

Each quadrupole magnet has two primary parameters, integrated strength (Q) and length (I), and one parameter of transverse offset (misalignment, d_q). If the length is not zero, it is treated as thin (zero length) magnet between two drift spaces of a half length of the magnet. Beam parameters of each macro particle will change at a thin quadrupole magnet as ;

$$\begin{aligned}
 \begin{bmatrix} x \\ p \end{bmatrix} &\rightarrow R_Q \begin{bmatrix} x \\ p \end{bmatrix} \\
 \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} &\rightarrow R_Q \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} R_Q^T
 \end{aligned} \tag{14}$$

where

$$R_Q = \begin{bmatrix} 1 & 1 \\ Q & 1 \end{bmatrix}. \tag{15}$$

If the transverse offset is not zero, at first the beam parameters are shifted as ;

$$\begin{aligned}
 x &\rightarrow x - d_q \\
 p &\rightarrow p \\
 \sigma_{11} &\rightarrow \sigma_{11} + d_q^2 \\
 \sigma_{12} &\rightarrow \sigma_{12} - pd_q \\
 \sigma_{22} &\rightarrow \sigma_{22}
 \end{aligned} \tag{16}$$

and at last shifted again opposite side ($d_q \rightarrow -d_q$ in above equations).

(d) Accelerating structure

Parameters of an accelerating structure are length, parameters of RF accelerating field and parameters of wake field and transverse misalignment(d_c). Parameters of

accelerating field are amplitude (E_{acc}), frequency (f_{rf}) and offcrest angle (ϕ_{off}). Parameters of wake field are total effect of longitudinal wake field for each macro particle ($W_{l,sum}$) and transverse wake function at the bunch-slice positions ($W_{t,p}$).

Acceleration and kick by wake field are done at the center of a structure which is between two drift spaces of a half length of the structure. At the center of the structure, beam parameters change as;

$$\begin{aligned}
E &\rightarrow E + \Delta E \\
x &\rightarrow x \\
p &\rightarrow p + \Delta p \\
\sigma_{11} &\rightarrow \sigma_{11} \\
\sigma_{12} &\rightarrow \sigma_{12} + x\Delta p \\
\sigma_{22} &\rightarrow \sigma_{22} + 2p\Delta p + \Delta p^2
\end{aligned} \tag{17}$$

where ΔE and Δp depend on bunch number n_b and slice number n_s of the macro particle,

$$\Delta E = \left(E_{acc} \cos(\phi_{off} + \omega_{RF} z(n_b, n_s) / c) + W_{l,sum}(n_b, n_s) \right) \times l \tag{18}$$

$$\Delta p = \sum_{\substack{m_b, m_s, m_p \\ (z(m_b, m_s) < z(n_b, n_s))}} q(m_s, m_p) [x(m_b, m_s, m_p) - d_c] W_{t,p}(n_b - m_b, n_s - m_s) \times l \tag{19}$$

m_b and m_s are the bunch and slice index of the preceding macro particles, $q(m_s, m_p)$ $x(m_b, m_s, m_p)$ are charge and offset of the macro particle respectively.

If the transverse offset is not zero, at first the beam parameters are shifted as ;

$$\begin{aligned}
x &\rightarrow x - d_c \\
p &\rightarrow p \\
\sigma_{11} &\rightarrow \sigma_{11} + d_c^2 \\
\sigma_{12} &\rightarrow \sigma_{12} - p d_c \\
\sigma_{22} &\rightarrow \sigma_{22}
\end{aligned} \tag{20}$$

and at last shifted again opposite side ($d_c \rightarrow -d_c$ in above equations).

(e) Beam position monitor

BPMs are at the center of quadrupole magnets and, in some cases, at the head of some accelerating structures. Parameters of a BPM are offset (transverse misalignment, d_{BPM}) and resolution (σ_m). The averaged position of all macro particles is recorded with the offset and random gaussian error.

$$X_{mon} = \frac{\sum q(n_s, n_p) x(n_b, n_s, n_p)}{\sum q(n_s, n_p)} - d_{BPM} + rnd(\sigma_m) \quad (21)$$

where $rnd(\sigma_m)$ is random number with gaussian distribution and summations are taken over n_b , n_s and n_p .

3. Misalignment

(a) Quadrupole magnet

Quadrupole magnets are aligned with respect to an identical streight line (called 'the center line'). Misalignment is assumed to be 'truncated gaussian distribution', $rnd_{tr}(\sigma_q, \lambda_q)$, which is identical as gaussian distribution with r.m.s. of σ_q in the region $(-\lambda_q, \lambda_q)$ and zero out of this region.

(b) Accelerating structure

Misalignment of accelerating structure is combination of misalignment of (a) girder, (b) structure and (c) piece. Some structures are assumed to be set together on one 'girder'. One structure can be divided into some 'piece' in order to simulate fabrication error of a structure. Each girder is misaligned independently. Each structure is misaligned on a girder and each piece is misaligned in a structure independently. All distributions are truncated gaussian. In the tracking, each piece is treated as an individual element.

It can be chosen whether girders are aligned with respect to (1) the center line or (2) line connecting quadrupole magnets. In the case (1), misalignment of a piece is

$$d_a = rnd_{tr}(\sigma_g, \lambda_g) + rnd_{tr}(\sigma_{as}, \lambda_{as}) + rnd_{tr}(\sigma_{ap}, \lambda_{ap}) \quad (22)$$

where (σ_g, λ_g) , $(\sigma_{as}, \lambda_{as})$ and $(\sigma_{ap}, \lambda_{ap})$ are distribution parameters of girders, structures on a girder and pieces in a structure. In the case (2),

$$d_a = \frac{s_+ d_{q-} + s_- d_{q+}}{s_- + s_+} + rnd_{tr}(\sigma_g, \lambda_g) + rnd_{tr}(\sigma_{as}, \lambda_{as}) + rnd_{tr}(\sigma_{ap}, \lambda_{ap}) \quad (23)$$

where d_{q-} and d_{q+} are misalignment of the previous quadrupole magnet and the next magnet respectively, s_- distances from the previous quadrupole magnet to the center of the first structure on the girder and s_+ distances from the center of the first structure on the girder to the next quadrupole magnet.

(c) BPMs

Misalignment of a BPM at a quadrupole magnets has truncated gaussian distribution with respect to the magnet as

$$d_{BPM} = d_q + rnd_{tr}(\sigma_{BPM}, \lambda_{BPM}) \quad (24)$$

where d_q is misalignment of the magnet.

A BPM at an accelerating structure is aligned with respect to the structure as

$$d_{BPM} = d_a + rnd_{ir}(\sigma_{BPM}, \lambda_{BPM}) \quad (25)$$

where d_a is misalignment of the structure.

(d) Arbitrary alignment

Regardless of setting of random misalignment as described above, misalignment of several elements can be set to arbitrary amounts.

4. Wakefield

(a) Longitudinal wakefield

Short range wakefunction is given as a file of a set of numbers as

$$(z_i, W_{l,S}(z_i)), i = 1, 2, 3, \dots$$

$W_{l,S}(z_i)$ is the wakefunction at z_i . Wakefunction at every slice position (z) is calculated as

$$W_{l,S}(z) = \frac{(z_{i+1} - z)W_{l,S}(z_i) + (z - z_i)W_{l,S}(z_{i+1})}{z_{i+1} - z_i}, \quad (z_i \leq z \leq z_{i+1}). \quad (26)$$

Long range wakefield from single mode can be included. Wake function is calculated from the frequency (f_{wl}), Q-value (Q_l) and amplitude (W_{l0}) as

$$W_{l,L}(z) = W_{l0} \exp(-2\pi f_{wl} z / 2cQ_l) \cos(2\pi f_{wl} z / c). \quad (27)$$

Sum of wakefield effect to each slice which is used as a parameter of accelerating structures (see 2-(d)) is

$$W_{l,sum}(n_b, n_s) = \sum_{m_b < n_b, m_s, m_p} q(m_s, m_p) W_{l,L}[(n_b - m_b)s_b + (n_s - m_s)s_s] + \sum_{m_s \leq n_s, m_p} q(m_s, m_p) W_{l,S}[(n_s - m_s)s_s] \quad (28)$$

(b) Transverse wakefield

Short range transverse wake function is assumed to be linear as

$$W_{t,S}(z) = zW_t' \quad (29)$$

where Wt' is a constant parameter, slope of the wakefunction.

Long range wake function is calculated from parameters of dipole modes of accelerating structures,

$$(i, f_{wt,i}, W_{t0,i}, n_{cell,i}), i = 1, 2, \dots, N_m,$$

$f_{wt,i}$ and $W_{t0,i}$ are frequency and kick factor of i-th mode respectively. $n_{cell,i}$ is the cell number to which i-th mode is assumed to belong, usually set as the cell in which the field of the mode is strongest. The same Q-value (Q_t) is given to all modes. Wake function is calculated for each piece (see sec.3) of accelerating structure as

$$W_{t,L}(z) = \sum_{n_{cell,i} \in piece} W_{t0,i} \exp(-2\pi f_{wt,i} z / 2cQ_t) \sin(2\pi f_{wt,i} z / c) \quad (30)$$

Wake function at bunch-slice positions which is used as parameters are as follows.

$$W_{t,p}(n_b, n_s) = \begin{cases} W_{t,L}(n_b s_b + n_s s_s) & (n_b \geq 1) \\ W_{t,S}(n_s s_s) & (n_b = 0 \text{ and } n_s \geq 1) \\ 0 & (\text{other cases}) \end{cases} \quad (31)$$

In some cases, random error of mode frequencies of transverse wakefield, $f_{wt,i}$, can be introduced. Each mode is assumed to have independent error and the distribution of the error is constant in the region from $(1 - \delta_f) f_{wt,i}$ to $(1 + \delta_f) f_{wt,i}$ where δ_f can be set as a parameter.

5. Correction

(a) Estimated transfer matrix

For some kinds of correction schemes, it is necessary to know transfer matrixes from correctors (usually angle x' is changed at these point) to BPMs (transverse position x is measured). Because actual beams have energy spread and get different effect of wake field, we use transfer matrixes for centroid of a bunch.

A matrix is calculated as multiplication of matrixes of elements; drift space, quads and accelerating structures. Matrixes of the elements are as follows.

$$\text{Drift space: } \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix}, \quad (32)$$

where l is the length of the space.

$$\text{Quads: } \begin{bmatrix} 1 & l_q / 2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ K_q & 1 \end{bmatrix} \begin{bmatrix} 1 & l_q / 2 \\ 0 & 1 \end{bmatrix}, \quad (33)$$

where l_q is the length of the magnet and

$$K_q = Q / E_0 \quad (34)$$

is thin lens kick where Q is the strength and E_0 is estimated beam energy.

Accelerating structure for one-to-one correction:

$$\begin{bmatrix} 1 & l_a / 2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & E_0 / (E_0 + \Delta E) \end{bmatrix} \begin{bmatrix} 1 & l_a \\ 0 & 1 \end{bmatrix}, \quad (35)$$

l_a is the length, E_0 estimated beam energy and ΔE estimated acceleration. Estimated acceleration is designed accelerating field multiplied by the length. Beam energy at certain place is calculated from initial energy and summation of acceleration at all structures before the place.

For DF/WF type corrections, usually matrixes between long distance are needed, more precise estimation is used. Matrix of an accelerating structure includes effect of short range wake field as

$$\begin{bmatrix} 1 & l_a / 2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ K_a / 2 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & E_0 / (E_0 + \Delta E) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ K_a / 2 & 1 \end{bmatrix} \begin{bmatrix} 1 & l_a / 2 \\ 0 & 1 \end{bmatrix} \quad (36)$$

where

$$K_a = Aq\sigma_z l_a W' / E_0 \quad (37)$$

is the kick of bunch centroid by wake field where q is bunch charge, σ_z bunch length, W' slope of short range transverse wake function and E_0 estimated energy. Parameter A is a constant usually set to be

$$A = 1 / \sqrt{\pi} \approx 0.564 \quad (38)$$

because averaged kick of gaussian bunch by wake field in passing through a structure with offset of x (assuming a whole bunch has the same offset) is,

$$\begin{aligned} & \int_{-\infty}^{\infty} dz \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \int_{-\infty}^z dz' \frac{x l_a W'(z-z')}{E_0} \frac{q}{\sqrt{2\pi}\sigma_z} \exp\left(-\frac{z'^2}{2\sigma_z^2}\right) \\ & = \frac{xq\sigma_z l_a W'}{E_0 \sqrt{\pi}} \end{aligned} \quad (39)$$

E_0 and ΔE estimation includes dependence on bunch length and bunch charge assuming that we know the shape of the RF field and longitudinal wake field.

Note that the estimated matrixes for quads and accelerating structures are not exact. If there is a correlation between energy and transverse positions in a bunch, K_q and K_a will not represent the exact average of kick. And, if there is a correlation between longitudinal positions and transverse positions, K_a will not be exactly correct.

Fortunately, these approximations will be acceptable in cases that internal transverse distortion of a bunch is small compare with transverse offset of bunch centroid with respect to quadrupole magnets and accelerating structures through the linac.

(b) One-to-one correction

Beam trajectory is corrected with respect to **BPMs** at focusing quads using dipole correctors at the previous focusing quads. **BPMs** and correctors at defocusing quads are not used because the effect of BPM errors is bigger where beta function is smaller. The correction is done one by one from upstream to downstream of the linac.

The strength of a dipole corrector (B, see 2-(b)) is set as

$$B = \left(-m_{21}^{-1} + \frac{m_{11}^{-1}}{m_{12}^{-1}} \right) X_{mon} E = \left(\frac{m_{12}}{|M|} - \frac{m_{22}}{m_{21}} \right) X_{mon} E \quad (40)$$

where X_{mon} is the measured position at the BPM (see 2-(e)) at the next focusing quad, E is estimated beam energy at the dipole corrector,

$$M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad \text{and} \quad M^{-1} = \begin{bmatrix} m_{11}^{-1} & m_{12}^{-1} \\ m_{21}^{-1} & m_{22}^{-1} \end{bmatrix} \quad (41)$$

are estimated transfer matrix from the corrector to the BPM and its inverse. In this case, effect of wakefield is not considered for estimation of the transfer matrix. Because transfer matrixes only over a short distance (from a focusing quad and the next focusing quad) are used, usually wake field effect can be ignored compared with errors of **BPMs**.

(c) DF/WF (dispersion free/wake free) type correction

In this type of correction, basically differences of trajectories with different parameters (strength of quads, beam current and bunch length) are minimized. Because different strength of magnets simulates different beam energy, to minimize difference of trajectories means to minimize dispersion at every BPM position. Different beam current and bunch charge give different wake field, then to minimize the difference means to minimize the effect of wake field.

In a correction of this type, several trajectories with different strength of focusing quads, different strength of defocusing quads, different bunch length and different bunch charge are measured by all **BPMs**. And

$$\chi_d^2 = \sum_j \left[\sum_i (m_{j,i} + X_{j,i})^2 / (\sigma_{BPM}^2 + \sigma_{pre}^2) + \sum_{i < k} (\Delta m_{j,ik} + \Delta X_{j,ik})^2 / \sigma_{pre}^2 \right] \quad (42)$$

or

$$\chi_m^2 = \sum_j \sum_{i < k} (\Delta m_{j,ik} + \Delta X_{j,ik})^2 / \sigma_{pre}^2 \quad (43)$$

is minimized using dipole correctors or moving accelerating structures. j is index of BPMs i and k are index of trajectories. $m_{j,i}$ is measured offset at j -th BPM of i -th trajectory, $\Delta m_{j,ik}$ measured difference of offsets at j -th BPM between trajectories i and k . σ_{BPM} estimated misalignment of BPMs and σ_{pre} estimated resolution (measurement to measurement error) of BPMs. $X_{j,i}$ is change of offset at j -th BPM of i -th trajectory and $\Delta X_{j,ik}$ change of difference of offset at j -th BPM between i -th and k -th trajectories. These depend on amount of corrections (change of strength of all dipole magnets or change of alignment of all accelerating structures at upstream of the BPM). Dependence of $X_{j,i}$ and $\Delta X_{j,ik}$ on the correction is calculated from estimated transfer matrixes from correctors (dipole magnets or moving structures) to BPMs. Minimization uses a least square fitting algorithm.

To use χ_d or χ_m and using dipole corrector or moving accelerating structures can be chosen. Moving structures is effective for correction of wakefield effect changing bunch length and/or bunch charge with the same magnet strength. In the cases using dipole correctors, χ_d should be chosen in order to prevent divergence of the trajectories.

In the case of moving structures, at most one structure between two quads can be used. Number of quads per one moving structure can be set. BPMs are located at all moving structures in addition to ones at all quads.

A linac can be divided into sections and measurement and fitting is performed for each section at a time from the upstream. Sections next each other can have a overlapping. Length of a section and length of an overlapping are decided as number of BPMs including a section and an overlapping. All sections have the same number of BPMs except the last section which has remaining BPMs. Measurement and fitting can be iterated for each section and number of iteration is the same for all sections.

It is possible to perform two sequential corrections. For example, set dipole correctors measuring trajectories with different strength quads at first, and second, move accelerating structures measuring trajectories with different bunch charge. In this example, the first stage corrects dispersive effect and the second stage correct wake field effect. Bunch length, bunch charge, ratio of strength of quads and parameters of the fitting can be changed between two stages.

(d) Re-alignment of accelerating structures vs. beam

In this correction, every accelerating structure has a BPM and a mechanical mover and is aligned respect to the beam. BPM is attached at the head of every accelerating structure and the structure (all pieces of the structure) is moved according to position measurement, the misalignment changes as

$$d_a \rightarrow d_a - X_{mon,s}$$

where $X_{mon,s}$ is beam position measured by the BPM at the structure.

(e) Fast kickers

This correction is for multibunch beams. Individual bunch is kicked by special fast dipole kickers. Amount of kicks by a pair of kickers are decided from measurement of

BPMs to minimize position differences from the first bunch. There can be several diagnostics stations in a linac and each station has two bunch-by-bunch kickers and several bunch-by-bunch BPMs which measure averaged position of individual bunch. The fast kickers are located at centers of quadrupole magnets. The bunch-by-bunch BPMs are at following focusing quadrupole magnets.

For n-th bunch.

$$\chi^2(n) = \sum_j \left(X_{bmon,j}(n) - X_{bmon,j}(1) + \Delta X_j(n) \right)^2 / \sigma_{bpre}^2 \quad (44)$$

is to be minimized by fitting where $X_{bmon,j}(n)$ is bunch position measured by j-th BPM, σ_{bpre} resolution of BPMs for each bunch. $\Delta X_j(n)$ predicted change of position at j-th BPM due to the kicks as

$$\Delta X_j(n) = R_{12}(1 \rightarrow j) \Delta x'_1(n) + R_{12}(2 \rightarrow j) \Delta x'_2(n) \quad (45)$$

where $R_{12}(1 \rightarrow j)$ ($R_{12}(2 \rightarrow j)$) is (1,2) element of estimated transfer matrix from first (second) fast kicker of the pair to j-th BPM and $\Delta x'_1(n)$ ($\Delta x'_2(n)$) ideal kick by the first (second) kicker. For the first bunch,

$$\Delta x'_1(1) = \Delta x'_2(1) = 0 \quad (46)$$

Number of stations per linac positions of them and number of BPMs to be use in each station are chosen arbitrarily. But betatron phase difference between a paired kickers should not be close to $n\pi$. And number of BPMs per station should be more than one.

Limited speed of kicker system can be also simulated. Ideal strength (integrated strength) of a kicker when n-th bunch is passing is

$$\overline{\Delta p}((n-1)t_b) = E_0 \Delta x'(n) \quad (47)$$

where t_b is bunch spacing, E_0 estimated beam energy and $\Delta x'(n)$ is from fitting for n-th bunch. Time origine is chosen at the center of the first bunch. With given parameters representing the speed of the kickers, f_{low} and f_{up} , lower and upper frequencies of the kickers, actual strength is to be expressed in the form of

$$\Delta p(t) = \sum_{m=1}^{f_{up}/f_{low}} [a_m \sin(2m\pi f_{low} t)] \quad (48)$$

a_m are calculated as

$$a_m = \sum_{n=1}^{N_b} \left[\overline{\Delta p}((n-1)t_b) - \sum_{k=1}^{m-1} a_k \sin[(n-1)k\phi_b] \right] \frac{\sin[(n-1)m\phi_b]}{N_b/2 - \sin(2mN_b\phi_b) / 4m\phi_b} \quad (49)$$

where

$$\phi_b = 2\pi f_{low} t_b \quad (50)$$

If f_{low} is chosen as

$$f_{\text{low}} = \frac{\pi}{N_b t_b}, \quad (51)$$

this process is equivalent to a Furrier expansion up to the frequency f_{up} .

Part 2. How to use

There are three programs for different purposes,

- | | | |
|-----|--------|--|
| (A) | linaca | one-to-one correction and
re-alignment of accelerating structures |
| (B) | linacb | fast kicker |
| (C) | linacc | WF/DF type correction |

To execute these programs, type

linaca *'name of a file'*
linacb *'name of a file'*
linacc *'name of a file'*

The name of a file which gives names of input and output files should follow the program name.

Executable files and examples of some input files are in the directory /a/juno/u3/r1/kubo/public. Source programs are also in this directory. See 'README' and 'makefile' in this directory. Some examples of output files are in /nfs/laslett/u1/kubo3/exempl.

Program (A) One-to-one correction Re-alignment of accelerating structures

1. Input Data

(a) Names of files

All input data are given from files. A file which consists of a set of names of files in three namelists 'CNTRL' 'CNTLAT' and 'DTWAK' should be prepared. When execute the program, the name of this file should be the argument of the command while the name of the program is the command. This file is sometimes called as 'filenames-file' in this document.

Namelist CNTRL

Input

inpara : general input parameters
incav : wakefield for every slices
inl : parameters of elements of linac

output

outpara : general parameters
outpl : top-drawer data for plots in phase space etc.
outdr : top-drawer data for emittance along the linac etc.
result : final emittance etc.
outcav : wakefield for every slices
outl : parameters of elements of linac

Namelist CNTLAT (Input)

inlin : lattice of linac

Namelist DTWAK (Input)

datwaki : longitudinal short range wakefield
datwakt : transverse long range wakefield

If inl is not 'new', inlin is ignored and if incav is not 'new'
datwaki, datwakt and outcav are ignored.

(b) General input parameters

Most input parameters are given from a file whose name is given to 'inpara' in the filenames-file.

Namelist NDIV

NB : number of bunches
NS : number of slices in a bunch
NP : number of macro particles in a slice

Total number of macro particles is $NB*NS*NP$. Limit of numbers are temporarily set as $NB \leq 150$, $NS \leq 20$ and $NP \leq 10$.

Namelist BUNCH

NBUCKT : number of RF buckets between bunches
 ZSIG : bunch length σ_z in m.
 ZCUT : maximum slice position with respect to the bunch center, in σ_z
 E00 : initial averaged energy in eV
 ESIG : initial energy spread σ_E in eV
 ECUT : maximum energy deviation from the center energy in σ_E
 CTOTL : number of electrons per bunch
 X00 : initial transverse position in m
 PX00 : initial transverse momentum in eV/c
 EMIO : initial emittance in rad*m
 BET0 : initial beta as a parameter of beam shape in m
 ALP0 : initial alpha as a parameter of beam shape
 IORD : =1 for first order, =2 for second order simulation
 FRF0 : Nominal frequency of accelerating RF which gives bunch spacing

Bunch spacing is $NBUCKT*c/FRF0$

Slice spacing is $2*ZCUT*ZSIG/(NS-1)$, if $NS > 1$.

If $NS=1$, ZSIG and ZCUT are ignored.

The last (first) slice has position $(-)ZCUT*\sigma_z$ with respect to the center.

The last (first) slice has initial energy $E00 + (-) ECUT*\sigma_E$, if $NP > 1$.

If $NP=1$, ESIG and ECUT are ignored.

Charge of each macro particle is decided to make both longitudinal distribution and energy distribution be gaussian like.

All macro particles have the same initial transverse condition.

In the case $IORD=2$, EMIO, BET0 and APL0 give initial transverse shape of bunches. If $IORD=1$, EMIO, BET0 and APL0 are ignored.

Name list PLOT

NPLOT : limit of number of sets of phase space data recorded in 'outpl'
 SPLOT(n) : s (distance from the beginning of the linac) where phase space data are recorded in 'outpl'
 IBDRAW : bunch number of which x, px and E are recorded in 'outdr'.
 If 0, averaged x, px and E of all bunches are recorded.
 ISDRAW : slice number of which x,px and E are recorded.
 If 0, average of all slices are recorded.
 If IBDRAW is 0 this parameter is ignored.
 IPDRAW : particle number of which x,px and E are recorded.
 If 0, average of all particles are recorded.
 If ether IBDRAW or ISDRAW is 0 this parameter is ignored.
 NSKIP : Parameter to save disk space of file 'outdr'.

Namelist CORREC

MCOR : Flag for one-to-one correction. =1 correction on. =0 off.
 RESMON : Resolution (r.m.s.) of BPMs at quads in m.
 MCALIG : Flag for structure re-alignment. =1 on. =0 off.
 RESCBP : Error (r.m.s.) of BPMs at accelerating structures in m.

Namelist RANDM

NRAN : Used for changing seeds of random numbers
NRNDC : Number of randomly different types of wakefield of accelerating structures.
NROLD : Information on 'inl', see description of 'inl'

If 'incav' is not 'new', NRNDC is ignored.
If 'inl' is 'new' NROLD is ignored

Namelist RFLAT

FRF : Actual frequency of accelerating RF
EWAKE : Additive amplitude of RF to compensate longitudinal wakefield.
PHRF(n) : Phase of RF with respect to the bunch center.
EPH(n) : Designed beam energy where phase of RF is changed.

If 'inl' is not 'new' all parameters in this namelist are ignored.

Namelist CTYPE

NTYPE : Number of designed types of accelerating structures with different transverse long range wakefield.
NPIECE : Number of pieces per accelerating structure.

If 'inl' is not 'new' all parameters in this namelist are ignored.

Namelist ALIGN

NAL : Number of linacs with different seeds of misalignment to be simulated
XQSIG : Misalignment of quads, σ_q , in m
XQCUT : Maximum misalignment of quads (for truncation) in σ_q .
XCSIG : Misalignment of accelerating structures, σ_{as} , in m
XCCUT : Maximum misalignment of accelerating structures in σ_{as} .
XNSIG : Misalignment of BPMs, σ_{BPM} , in m
XMCUT : Maximum misalignment of BPMs in σ_{BPM} .
XPSIG : Misalignment of pieces of accelerating structures, σ_{ap} , in m
XPCUT : Maximum misalignment of pieces in σ_{ap} .
XCTSIG : Misalignment of girders of accelerating structures, σ_g , in m
XCTCUT : Maximum misalignment of girders in σ_g .
NCTABL : Number of structures on a girder
IAMOD : Mode of alignment of accelerating structures.
=0 ; align with respect to lines connecting quads
=1 ; align with respect to 'the center line'

If 'inl' is not 'new' all parameters in this namelist are ignored.

Namelist ALSET

NALSET : Number of elements of which misalignment are to be set arbitrarily
IALST(n) : Sequential number of each element to be set.

DXALS(n) : Misalignment of each element

Namelist WAKE

WLL0 : Amplitude of longitudinal long range wakefield in V/C/m
FRLG : Frequency of longitudinal long range wakefield in Hz
QL : Q of longitudinal long range wakefield
QT : Q of transverse long range wakefield
DFR : Ratio of random error of frequencies of modes of transverse long range wakefield
WTS 1 : Slope of transverse short range wake field in V/C/m³
IFLS : Flag for longitudinal short range wakefield, =1 ; on, =0 ; off
IFTL : Flag for transverse long range wakefield, =1 ; on, =0 ; off

If 'incav' is not 'new' all parameters in this namelist are ignored.

(c) Elements of Linac

There are two ways to set elements of a linac. One is to read a file 'inl' which contain all elements and parameters of them. The file can be given as a output file 'outl' of one of previous runs. The other way is to read a file 'inlin' which contain main elements of a linac and some designed parameters of them. Some elements and parameters are added according to parameters given by 'inpara'. In this case, 'inl' should be 'new'.

(i) Format of file 'inl'

If you set the name of 'inl' (not 'new') in the filenames-file, elements of the linac and their parameters, including misalignment, are read from the file. This way is useful to simulate sequential corrections or to simulate the same linac with different conditions. For example, simulation of high current multibunch beam after WF correction with low current single bunch beam.

The first line has six integer numbers as

1 ; Total number of elements
2 ; Total number of quadrupole magnets
3 ; Total number of accelerating structures
4 ; Total number of BPMs
5 ; Number of kinds of structures with different error of wakefield for each designed type of accelerating structure.
6 ; Number of pieces per accelerating structure

From the second line, each line corresponds to one element. The order is from the beginning of the linac to the downstream. Each line has three integer numbers and seven real numbers, (i1, i2, i3, r1, r2, r3, r4, r5, r6, r7) meaning as follows.

Type of element : il

0 : drift space
1 : dipole corrector
2 : quadrupole magnet
5 : accelerating structures
6 : BPM at quadrupole magnet

For drift space

r1 ; Distance from the beginning of the linac to the head of the element
r2 ; Length of the element

For dipole corrector

r1 ; Distance from the beginning of the linac to the head of the element
r3 ; Integrated strength
r5 ; Designed energy at the element

For quadrupole magnet

r1 ; Distance from the beginning of the linac to the head of the element
r2 ; Length of the element
r3 ; Integrated strength
r5 ; Designed energy at the element
r7 ; Offset with respect to the center line

For accelerating structure

i2 ; Type of wakefield
i3 ; Piece number.

A piece of structure is treated as an element. This number tells the where the piece is in a structure.

r1 ; Distance from the beginning of the linac to the head of the element
r2 ; Length of the element
r3 ; Amplitude of RF
r4 ; Frequency of RF
r5 ; Phase of RF with respect to the center the first bunch
r7 ; Offset with respect to the center line

For BPM

r1 ; Distance from the beginning of the linac to the head of the element
r7 ; Offset with respect to the center line

BPM at accelerating structures in the case of the re-alignment of structures are not considered as elements of a linac. If the correction is on, the program assumes that there is a BPM at every accelerating structure.

To perform one-to-one correction, every focusing quadrupole magnet should have a BPM and a dipole corrector. One quadrupole magnet should be divided into two elements and a BPM and a dipole corrector should be between them : a quadrupole magnet at distance s (center of the magnet), designed beam energy E , with integrated strength Q , length L misalignment d with a BPM (misalignment d_B with respect to the magnet) and a dipole corrector (integrated strength B) will be set as follows.

i1	i2	i3	r1	r2	r3	r4	r5	r6	r7
2	0	0	$s-L/2$	$L/2$	$Q/2$	0.0	E	0.0	d
6	0	0	s	0.0	0.0	0.0	0.0	0.0	$d+d_B$
1	0	0	s	0.0	B	0.0	E	0.0	0.0
2	0	0	s	$L/2$	$Q/2$	0.0	E	0.0	d

There are total $NTYPE*NRNDC$ types of wakefield of accelerating structures, where $NTYPE$ is number of designed types and $NRNDC$ is number of different sets of random frequency error for each designed type (see later section for wakefield setting). The integer number for a structure with designed type ITY and frequency error set number $IRNDC$ is $NRNDC*ITY+IRNDC$ as a parameter of the element. If $IROL=1$ (in the namelist `RANDB`), the program assumes $i2 = NRNDC*ITY+IRNDC$ and use $i2$

as the parameter of the element. If IROLD=0, it is assumed that $i2 = ITY$ and IRNDC is newly decided randomly as uniform distribution from 1 to NRNDC. IROLD should be given properly according to the file 'inl'. If the file is created by the program (A) or (B), set IROLD=1. If the file is created by the program (C), set IROLD=0.

(ii) Create a new linac

Elements of a linac and their parameters can be also given from a file of lattice (tile 'inlin') and parameters in the file 'inpara'.

The lattice file gives the order, length and strength of quadrupole magnets, accelerating structures and drift space. It has six dummy lines for comments and lines from the seventh line give lattice design. Each line has one integer number and four real numbers

(11, R1, R2, R3, R4).

If $4.5 < R1 < 5.5$ and $R2 > 0.0$, the line gives a quadrupole magnet. R2 gives the length, R3 gives kick factor k . Except it is the first element of the linac, a quadrupole magnet should be attached another one with the same polarity. The pair is physically one magnet but treated as two magnet in the simulation. If $10.5 < R1 < 11.5$ and $R2 > 0.0$, the line gives an accelerating structure. R2 gives the length and R3 gives designed acceleration per length. If $4.5 < R1 < 5.5$ or $10.5 < R1 < 11.5$ and $R2 = 0.0$, this line gives a drift space. R2 is the length. If R1 is not in these region (4.5, 5.5) and (10.5, 11.5), the line is ignored. A BPM is added between every pair of quadrupole magnets and a dipole magnet is placed also, just after a BPM. Each element can be identified by sequential number from the beginning of the linac.

Parameters of each element is set as follows.

[Drift space] : length (l)

$$l = R2$$

[Dipole corrector] : integrated strength (B)

$$B = 0$$

[Quadrupole magnet] : length (l), integrated strength (Q) and misalignment.

$$l = R2,$$

$$Q = R3 \times E$$

where E is the designed energy at the magnet. E is initial energy plus designed acceleration ;

$$E = \left[R4(\text{first magnet}) + \sum_{\substack{\text{all preceding} \\ \text{accelerating structures}}} R2 \times R3 \right] \times 10^9$$

factor 10^9 is for changing unit from GeV to eV.

Misalignment is set randomly as gaussian like, according to parameters XQSIG and XQCUT of namelist 'ALIGN' in the file 'inpara'.

[Accelerating structure] : type of wakefield (iw), piece number (IPIECE)
length (l), amplitude (E_{acc}), frequency (f_{rf}),
off-crest angle (ϕ_{off}) and misalignment

Designed type of wakefield (ITY) is assigned orderly from the. upstream, for the NC-th structure from the beginning of the linac,

$$ITY = \text{mod}(NC, NTYPE).$$

Type of random error (IRNDC) is decided randomly as uniform distribution from 1 to NRNDC. NTYPE and NRNDC are given parameter in 'inpara'.

$$iw = ITY * NRNDC + IRNDC$$

A structure is divided into NPIECE, which is a given parameter in 'inpara'. Each piece is treated as an element and piece number is assigned from the head of the structure from 1 to NPIECE.

$$l = R2 / NPIECE$$

Parameters of RF is calculated from the designed acceleration as a lattice parameter and parameters of namelist RFLAT in 'inpara'.

$$E_{acc} = (R3 \times 10^9 + EWAKE) / \cos(\text{PHRF}(i))$$

$$f_{rf} = \text{FRF}$$

$$\phi_{off} = \text{PHRF}(i)$$

where i is minimum number ($i \geq 1$) satisfying

$$\text{EPH}(i) > E$$

E is the designed energy at the structure.

Misalignment is set randomly as gaussian like according to parameters of namelist 'ALIGN' in the file 'inpara'.

[BPM] : misalignment

(d) Misalignment

If 'inl' is 'new', misalignment is set randomly as gaussian like according to parameters of namelist 'ALIGN' in the file 'inpara'. The parameter NAL gives number of linacs to be simulated with different seeds of random numbers for misalignment with the

same lattice design. If 'inl' is not 'new', misalignment of each element is read from the file and only one linac is simulated.

Misalignment of several elements can be set arbitrarily from parameters in the namelist ALSET (NALSET, LALST(n) and DXALS(n)). NALSET is total number of elements of which misalignment are to be set. Misalignment of element of sequential number IALST(i) is set to be DXALS(i), where 'i' is 1 to NALSET.

(e) Wakefield

There are two ways to set wakefield of accelerating structures. One is to read a file 'incav' which contain wakefield of all types at positions at all slices of the beam. The file can be given as a output file 'outcav' of one of previous runs. The other way is to set wakefield from the file 'datwaki' and 'datwakt' and parameters of the namelist WAKE.

(i) Format of file 'incav'

If you set the name of 'incav' (not 'new') in the filenames-file, necessary data of wakefield (wakefunction) are read from the file. This way is useful to save CPU time when the same set of wakefields was used before, especially there are a lot of bunches and slices and a lot of types of accelerating structures. But note that a file can take a huge disk space.

The first line has five integer numbers (I1 ~ I5) as

I1 ; Number of designed types of structures
I2 ; Number of bunches
I3 ; Number of slices per bunch
I4 ; Number of error (of frequencies of transverse modes) types of
structure for each designed type
I5 ; Number of pieces per structure

I2, I3, I4 and I5 should be the same as parameters given by the file 'inpara' or 'inl'.

The second line is a dummy and next I1*I2*I3 lines are for longitudinal wakefield and each line has three integer numbers and one real number

(i1, i2, i3, rl).

Longitudinal wakefield dose not depend on type of error and piece number.

i1 ; Type (designed) number
i2 ; Bunch number
i3 ; Slice number
rl ; Sum of wakefield effect to the slice.

The next line is another dummy line and following I1*I2*I3*I4*I5 lines are for Transverse wakefield and each line has five integer numbers and one real number

(i1 ~ i5, rl).

i1 ; Type (designed) number
i2 ; Type (error) number
i3 ; Piece number
i4 ; Bunch number
i5 ; Slice number

rl ; Wakefunction of the type at distance $s_b * i4 + s_s * i5$

(ii) Set new wakefield

If you set the name of 'incav' as 'new', wakefield is set according to the file 'datwaki' and 'datwakt' and parameters of the namelist WAKE. And the result is stored in the file 'outcav' in the same format of 'incav' described above.

Setting IFLS=1, longitudinal short range wakefunction can be given by a file 'datwaki'. After three dummy lines, there are data lines of a set of numbers as

$$(z_i, W_{l,s}(z_i)), i = 1, 2, 3, \dots$$

$W_{l,s}(z_i)$ is the wakefunction at z_i .

If IFLS=0, longitudinal short range wakefield is set to be zero.

Longitudinal long range wakefield is calculated from parameters WLLO, FRLG and QL of namelist WAKE in 'inpara'.

Transverse short range wakefield is calculated from a parameter WTS1 of namelist WAKE in 'inpara'.

If IFTL=1, transverse long range wakefield is given by a file 'datwakt'. The third line of the file gives number of designed types of wakefield and the fifth line gives number of cells per structure (line 1, 2, 4, 6, 7 and 8 are ignored). Data of the type 1 are from the ninth line and data of the type 2 are next and so on. The first line of each type is type number and the second line of each type gives number of modes. Remaining lines give parameters of the modes as follows.

$$(i, f_{wt,i}, W_{t0,i}, n_{cell,i}, Q_i), i = 1, 2, \dots, N_m,$$

$f_{wt,i}$ and $W_{t0,i}$ are frequency and kick factor of i-th mode respectively. $n_{cell,i}$ is the cell number to which i-th mode is assumed to belong. Q_i gives Q value of the mode. If $Q_i=0$, all modes have the same Q value given as QT of namelist WAKE. To simulate error of frequencies due to random error of machining and/or fabrication, NRNDC (namelist RANDM) of different wakefield are calculated instead of calculating different wakefield for all accelerating structures in order to save CPU time. It is chosen randomly which structure has which type of wakefield. Parameter DFR of namelist WAKE gives the relative error of mode frequencies.

If IFTL=0, transverse long range wakefield is set to be zero.

(f) Correction

Parameters of namelist CORRECT decide the conditions of corrections. If MCOR=1, one-to-one correction is on and the resolution of BPMs at quads is set to be RESMON. If MCOR=0, one-to-one correction is off. If MCALIG=1, re-alignment of accelerating structures with respect to the beams is on and the accuracy of BPMs at structures is set to be RESCBP. If MCALIG=0, this correction is off.

Some parameters of elements of the linac will change after corrections because one-to-one correction changes strength of dipole magnets and re-alignment accelerating structures changes misalignment of them.

2. Output of Result

(a) Final emittance

Results of simulation are recorded in the file 'result'.

Final normalized emittance $\gamma_f \epsilon_f$ and $\sqrt{\frac{\gamma_0 \epsilon_0}{\gamma_f \epsilon_f - \gamma_0 \epsilon_0}}$, averages of them and r.m.s. of $\gamma_f \epsilon_f$ over different seeds of random numbers are recorded. $\gamma_0 \epsilon_0$ is initial normalized emittance and $\sqrt{\frac{\gamma_0 \epsilon_0}{\gamma_f \epsilon_f - \gamma_0 \epsilon_0}}$ can be used for estimation of alignment tolerances.

Final averaged beam energy and energy spread are also recorded.

(b) Emittance etc. along linac

Emittance, transverse position, momentum and beam energy at every quadrupole magnet can be recorded in the file 'outdr' for the first linac. Each line corresponds to one position of the linac and has five real numbers as

- 1; Distance from the beginning of the linac
- 2; Transverse position in m
- 3; Transverse momentum in eV/c
- 4; Normalized emittance in rad*m.
- 5; Beam energy in eV

Parameters IBDRAW, ISDRAW, IPDRAW and NSKIP of the namelist PLOT control the output.

If IBDRAW=0, projection emittance, averaged position, averaged momentum and averaged energy of all macro particles are recorded.

If IBDRAW>0, projection emittance of the bunch number IBDRAW is recorded.

If IBDRAW>0 and ISDRAW=0, averaged position, momentum and energy of macro particles in the bunch number IBDRAW are recorded.

If IBDRAW>0, ISDRAW>0 and IPDRAW=0, averaged position, momentum and energy of macro particles in the slice of bunch number IBDRAW and slice number ISDRAW are recorded.

If IBDRAW>0, ISDRAW>0 and IPDRAW>0, position, momentum and energy of the macro particle of bunch number IBDRAW, slice number ISDRAW and particle number IPDRAW are recorded.

If NSKIP=0, beam parameters at every quadrupole magnet are recorded. If NSKIP>0, beam parameters at every (NSKIP+1) quadrupole magnets are recorded. Parameter NSKIP is for saving disk space.

(c) Parameters of all macro particles

Parameters of all macro particles at the end of linac and several position of the linac can be recorded in the file 'outpl'. Each line corresponds to one macro particle and has three integer numbers and four real numbers (i1, i2, i3, r1, r2, r3, r4) as

- i1; Bunch number
- i2; Slice number

i3; Particle number
r1; Transverse position in m
r2; Transverse momentum in eV/c
r3; Energy
r4; Relative longitudinal position from the bunch center

And a set of data consists $i1*i2*i3$ lines. A line before each set of data, distance from the beginning of the linac is also recorded.

Maximum number of sets of data to be recorded is given as the parameter NPLOT of the namelist PLOT. For the first linac, SPLOT(n) gives the distance from the beginning of the linac where n-th set of data is to be recorded. At the first quadrupole magnet where distance is larger than SPLOT(n), a set of data is recorded if n is not larger than NPLOT. The data at the end of linacs are recorded, regardless of SPLOT(n), for all linacs if the number of sets of data dose not exceed NPLOT.

3. Output for following simulation

Parameters of elements of the first linac are stored in the file 'outl'. The format of the file is the same as the input file 'inl' described before. This file can be used in following simulations as an input data and IROLD should be set 1.

If 'incav' is 'new', data of wakefield are stored in the file 'outcav'. The format is the same as 'incav' and this file can be used in following simulations as an input data.

4. Other output

The file 'outpara' is temporarily used for output, mainly for debugging.

Program (B) Fast Kicker

This program is used almost as same as program (A).
Only differences are described here.

1. Input Data

(a) Names of files

All input data are given from files. A file which consists of a set of names of files in three namelists 'CNTRL' 'CNTLAT' and "DTWAK" should be prepared.

Namelist CNTRL

File 'kick' and 'plkick' are added for output of data of each kick.

(b) General input parameters

Most input parameters are given from a file whose name is given to 'inpara'.
Namelist PLOT and CORREC are different from the program (A).

Namelist PLOT

IMPL : Mode of output of beam parameters along linac
Other parameters are as same as in program (A)

Namelist CORREC

NKICK : Number of pairs of fast kickers
IQKICK(n) : ID# of quadrupole magnet at which the kickers are placed.
IKMOD : Mode of the correction
NQK : Number of quads between two kickers of a pair
NMQ : Number of BPMs used for each pair of kickers.
FLOW : Lower frequency or step of frequency for expansion
FUP : Upper limit of the frequency of the kickers
RESMK : Resolution of BPMs for individual bunches.
NITA : Number of iterations for each pair of kickers.
EWAKO : Estimated EWAKE (of namelist RFLAT)
MCOR : Flag for one-to-one correction. =1 correction on. =0 off.
DPXLIM : Limit of kicker strength
(maximum transverse momentum change in eV/c)
RESMON : Resolution (r.m.s.) of BPMs at quads in m.

(c) Elements of Linac

Data of elements of a linac are given in the same way as that for the program (A).
Fast kickers are not treated as elements.

(d) Misalignment

The way to give misalignment is also as same as for the program (A).

(e) Wakefield

The way to give wakefield is also as same as for the program (A).

(f) Correction

Parameters of namelist CORRECT decide the conditions of the correction.

If IKMOD=0, no correction, all other parameters are ignored.

If IKMOD=1, FUP gives the speed of the kicker system and FLOW gives the step of their frequency.

If IKOD=2, the speed of the kickers is assumed to be fast enough. All macro particles in a bunch are kicked by the same amount which is given by the fitting from BPM measurement. FLOW and FUP are ignored.

Kickers are assumed to have zero length and placed at some quadrupole magnets. NKICK is number of pairs of kickers and IQKICK(n) and NQK give positions of kickers. The first kicker of the i-th pair is at IQKICK(i)-th quadrupole magnet from the beginning of the linac. The second kicker of each pair is at NQK-th quadrupole magnet from the first kicker of the pair. Note that a pair of quadrupole magnets in the simulation corresponds to one real magnet. Kickers should be at the last quadrupole magnets of these pairs.

BPMs at focusing magnets after the second kicker of each pair are used for fitting to determine the amount of kicks. Number of BPMs used for the fitting is given as NMK. RESMK gives resolution of BPMs for individual bunch positions.

If NITA>0, kick, measurement and fitting are iterated NITA times.

EWAKEO is used to estimate transfer matrixes.

MCOR and RESMON are for one-to-one correction as same as 'linaca'.

2. Output of Result

(a) Final emittance

Results of simulation are recorded in the file 'result'.

Final normalized emittance $\gamma_f \epsilon_f$ and average and r.m.s. over different seeds of random numbers are recorded.

Maximum kick amount (change of transverse momentum) over all slices and all kickers is recorded for each linac.

Final averaged beam energy and energy spread are also recorded.

(b) Emittance etc. along linac

Emittance, transverse position, momentum and beam energy at every quadrupole magnet can be recorded in the file 'outr' as same as in program (A). The parameter IMPL of the namelist PLOT gives mode of output as follows.

IMPL=0 : No output

IMPL=1 : Data after correction are recorded

IMPL=2 : Data both during correction and after correction are recorded

(c) Parameters of all macro particles

Same as program (A).

(d) Kick

Averaged transverse position and **momentum** of every bunch are recorded in the file 'kick' before and after every fast kicker for the first linac. Each line is for each bunch and has one integer and two real numbers (i1, r1, r2) as

i1 ; Bunch number
i2 ; Average transverse position
i3 ; Average transverse momentum

Before these lines, element numbers of the quadrupole magnets where the kickers are placed are also recorded.

Momentum change (kicker strength) of each slice is also recorded in the file 'plkick' for the first linac. Each line has three integers and two real numbers (i1,i2,i3,r1,r2).

i1 ; Kicker number
i2 ; Bunch number
i3 ; Slice number
r1 ; Longitudinal position w.r.t. the center of the first bunch
r2 ; Change of momentum

3. Output for following simulations

Of 'ini' is 'new', parameters of elements of the first linac are stored in the file 'outl'. If 'inl' is not new, because fast kicker correction does not change any parameters of elements (fast kickers are not treated as elements of a linac), parameters are not stored.

If 'incav' is 'new', data of wakefield are stored in the file 'outcav'.

4. Other output

The file 'outpara' is temporarily used for output, mainly for debugging.

Program (C) WF/DF type correction

This program is used almost as same as program (A).
Only differences are described here.

1. How to give Input Data

(a) Names of files

All input data are given from files. A file which consists of a set of names of files in three namelists 'CNTRL' 'CNTLAT' and "DTWAK" should be prepared.

Namelist CNTRL

The file 'incav' is not used.

(b) General input parameters

Most input parameters are given from a file whose name is given to 'inpara'.
Namelist CORREC and RANDM are different from the program (A).

Namelist CORREC

RESMON	: Resolution of BPM
IMCOR1	: Mode of the first step
IMCOR2	: Mode of the second step
IMC1	: Choice of χ^2 of the first step
IMC2	: Choice of χ^2 of the second step
MCOR1	: Number of BPMs in a section of linac of the first step
MCOR2	: Number of BPMs in a section of linac of the second step
NTRJ1	: Number of trajectories to be measured in the first step
NTRJ2	: Number of trajectories to be measured in the second step
FQF(n)	: Relative strength of focusing quadrupole magnets and dipole correctors at at them.
FQD(n)	: Relative strength of defocusing quadrupole magnets and dipole correctors at at them.
ZCOR(n)	: Relative bunch length.
QCOR(n)	: Relative bunch charge
REO	: Estimated misalignment of BPMs.
RE1	: Estimated resolution of BPMs
NITA1	: Number of iterations in the first step
NITA2	: Number of iterations in the second step
AA	: Estimated factor used in the fitting
NCMOVE	: Number of quads per moving accelerating structures
DEVCUT	: Not used now. Ignored.
LSATU	: Should be 2.
M2COR1	: Number of BPMs in a overlapping of sections in the first step
M2COR2	: Number of BPMs in a overlapping of sections in the second step
PHRFO	: Estimated phase of RF.
EWAKEO	: Estimated EWAKE (of namelist RFLAT)

Namelist RANDM

NRNDC and NROLD are not used.

(c) Elements of Linac

Data of elements of a linac are given in the similar way as that for the program(A).

If 'inl' is not 'new' or MCMOVE of the namelist CORREC is zero, the way is exactly the same.

If 'inl' is 'new' and MCMOVE>0, a BPM is added at just before each moving accelerating structure and it is treated as an element of the linac.

(d) Misalignment

The way to give misalignment is also as same as for the program (A).

(e) Wakefield

The way to give wakefield is similar to the program (A) but errors of frequencies of transverse long range modes can not be introduced and data of wakefield at slice positions can not be read from old files. Detail simulation of long range wakefield will not be useful because it is recommended to use this correction with single bunch beams. Because calculation of wakefield for single bunch beams does not take much time it is not effective to read and store wakefield data.

(f) Correction

Parameters of namelist CORRECT decide the conditions of the correction.

It is possible to perform two sequential corrections, called the first step and the second step. The first step changes parameters of elements, strength of dipole magnets and/or alignment of some accelerating structures, and these parameters are used as initial parameters for the second step. NTRJ1 and NTRJ2 give number of trajectories to be measured.

If NTRJ1=1 and NTRJ2=0, no correction is performed, MCOR1 and IMCOR1 should be 0. If NTRJ2=0, the second step correction is not performed.

IMCOR1 and IMCOR2 give mode of correction of the first and second steps:

- =1 : Using dipole correctors
- =5 : Moving accelerating structures

IMC1 and IMC2 give choices of Choice of χ^2 for first and second steps :

- =0 : χ_d^2
- =1 : χ_m^2

If IMCOR1 = 1, IMC1 should be 0 and if IMCOR2 = 1, IMC2 should be 0.

FQF(i), FQD(i), ZCOR(i) and QCOR(i) give relative strength of magnets, relative bunch length and relative bunch charge of i-th trajectory. j-th trajectory of the second step is treated as NTRJ1+i-th trajectory here. At least one trajectory should have nominal parameters, FQF(i) = FQD(i) = ZCOR(i) = QCOR(i) = 1.0 for at least one i from 1 to NTRJ1+NTRJ2.

MCOR1 and MCOR2 give length of each section for fitting and M2COR1 and M2COR2 give length of overlapping of sections next each other. Each length is given as number of BPMs included in the section. The last section can be shorter than others because BPMs are counted from the beginning of the linac. It is required that MCOR1>M2COR1 and MCOR2>M2COR2.

MCMOVE is number of quadrupole magnets per one moving cavities. For only this parameter, a 'quadrupole magnet' means a real magnet which is divided into two elements in the program. If NCMOVE>0, the first moving structure is chosen between

the first and the second quadrupole magnets, the second moving structure is chosen between NCMOVE+1-th and NCMOVE+2-th quadrupole magnets, the third moving structure is chosen between NCMOVE*2+1-th and NCMOVE*2+2-th quadrupole magnets and so on. If there are m accelerating structures between magnets, (m+1)/2-th structure is chosen as a moving structure. If MCMOVE=0, there is no moving structure. A BPM is placed at the head of each moving cavity and treated as an element of the linac.

NITA1 and NITA2 are number of iterations of the first and the second steps. Iterations are performed for each section of a linac.

AA, PFRFO and EWAKEO are used to estimate transfer matrixes. Usually, AA is set to be about 0.56 for gaussian bunches. REO and RE1 are used for the fitting.

DEVCUT and LSATU are not useful now. But ILSATU should be always 2.

2. Output of Result

(a) Final emittance

Results of simulation are recorded in the file 'result'.

Normalized emittance $\gamma_f \epsilon_f$ after the first step correction and after the second step are recorded for each linac. Average of final (after the second step) emittance and r.m.s. over different seeds of random numbers are recorded.

Final averaged beam energy and energy spread are also recorded.

(b) Emittance etc. along linac

Same as program (A).

(c) Parameters of all macro particles

Same as program (A).

3. Output for following simulations

Parameters of elements of the first linac are stored in the file 'out1'.

Data of wakefield are stored in the file 'outcav'.

4. Other output

The file 'outpara' is temporarily used for output, mainly for debugging.

Examples of files

Examples of input files

'in_filea'

```
&CNTRL
  inpara='in_parama',
  outpar='/nfs/laslett/u1/kubo3/exempl/out_para05',
  outpl='/nfs/laslett/u1/kubo3/exempl/out_pl05.top',
  outdr='/nfs/laslett/u1/kubo3/exempl/out_dr05.top',
  result='/nfs/laslett/u1/kubo3/exempl/result05',
  incav='new',
  outcav='/nfs/laslett/u1/kubo3/exempl/out_wake05',
  inl='new',
  outl='/nfs/laslett/u1/kubo3/exempl/outl_05'
&END
&CNTRLAT
  inlin='lattice2.dat'
&END
&DTWAK
  dtwakl='wakel_new.dat',
  dtwakt='wakddt_n.dat'
&END
```

'in-fileb'

```
&CNTRL
  inpara='in_paramb',
  outpar='/nfs/laslett/u1/kubo3/exempl/out_paramb02',
  outpl='/nfs/laslett/u1/kubo3/exempl/out_plb02.top',
  outdr='/nfs/laslett/u1/kubo3/exempl/out_drb02.top',
  result='/nfs/laslett/u1/kubo3/exempl/resultb02',
  incav='new',
  outcav='dummy02',
  plkick='/nfs/laslett/u1/kubo3/exempl/out_plk02.top',
  kick='/nfs/laslett/u1/kubo3/exempl/out_kic02.top',
  inl='new',
  outl='/nfs/laslett/u1/kubo3/exempl/outl_02'
&END
&CNTRLAT
  inlin='lattice2.dat'
&END
&DTWAK
  dtwakl='wakel_new.dat',
  dtwakt='wakddt_n.dat'
&END
```

'in_filec'

&CNTRL

```
  inpara='in_paramc',  
  outpar='/nfs/laslett/u1/kubo3/exempl/out_parawcc11',  
  outpl='/nfs/laslett/u1/kubo3/exempl/out_plwcc11.top',  
  outdr='/nfs/laslett/u1/kubo3/exempl/out_wcc11.top',  
  result='/nfs/laslett/u1/kubo3/exempl/resultwcc11',  
  outcav='/nfs/laslett/u1/kubo3/exempl/outcav11',  
  inl='new',  
  outl='/nfs/laslett/u1/kubo3/exempl/out_wcc11'
```

&END

&CNLAT

```
  inlin='lattice2.dat',
```

&END

&DTWAK

```
  dtwakl='wake1_new.dat',  
  dtwakt='wakddt_n.dat'
```

&END

in-parama'

```
&NDIV
  NB=5, NS=5, NP=5
&END
&BUNCH
  NBUCKT=16,
  ZC=0., ZSIG=100.D-6, ZCUT=2.,
  E00=10.1D9, ESIG=101.D6, ECUT=2.,
  CTOTL=6.5000D9,
  X00=0.0D-6, PX00=0.d3,
  EMIO=1.485d-12, BET0=2.56, ALPO=O.,
  IORD=2, FRF0=11.424d9
&END
&PLOT
  NPLOT=1,
  SPLOT=1.D2, 1.D3, 2.D3, 3.d3,4.d3,5.d3,7.d3,0.,0.,0.,
  o., o., o., o.,o.,o.,o.,o.,o.,
  IBDRAW=O, ISDRAW=O, IPDRAW=O,
  NAPLOT=1,
  IAPLOT=1,2,3,4,5,
  NSKIP=O
&END
&CORREC
  MCOR=1, RESMON=1.d-6,
  MCALIG=1, RESCBP=3.d-6
&END
&RANDM
  NRAN=O, NNRNDC=1, NROLD=O
&END
&RFLAT
  FRF=11.424d9, EWAKE=0.49407d6,
  PHRF=-0.1047d0,O.d0,0.d0,O.d0,0.d0,
  EPH= 1000.d9, 1000.d9, 1000.d9, 1000.d9, 1000.d9
&END
&CTYPE
  NTYPE=4, NPIECE=1
&END
&ALIGN
  NAL=2,
  XQSIG=O.D-6, XQCUT=3.,
  XCSIG=500.D-6, XCCUT=3.,
  XMSIG=O.D-6, XMCUT=3.,
  XPSIG=O.d-6, XPCUT=3.,
  XCTSIG=O.d-6, XCTCUT=3.,NCTABL=4,
  IAMOD=1
&END
&ALSETX
  NALSET=O,
  IALST= 77, 113,
  DXALS=50.d-6, 50.d-6
&END
&WAKE
  WLL0=0.0D6, FRLG=11.424D9, QL=1000.,
  QT=6500.d0,DFR=1.d-4,
  WTS1=6.7d19,
  IFLS=1, IFTL=1
&END
```

in-paramb'

```
&NDIV
  NB=90, NS=5, NP=1
&END
&BUNCH
  NBUCKET=16,
  ZC=O.ZSIG=100.D-6, ZCUT=2.,
  E00=10.1D9, ESIG=10.1D6, ECUT=2.,
  CTOTL=7.0D9,
  XOO=O.D-6PX00=0.d3,
  EMI0=1.4851485d-12, BET0=2.56 , ALPO=O.,
  IORD=2,
  FRFO=11.424D9
&END
&PLOT
  NPLOT=1,
  SPLOT=1.D2, 1.D3, 2.D3, 3.d3,4.d3,5.d3,7.d3,0.,0.,0.,
    o., o., o., o.,o.,o.,o.,o.,o.,o.,
  IBDRAW=O, ISDRAW=O, IPDRAW=O,
  NAPLOT=3,
  IAPLOT=1,2,3,4,5,
  NSKIP=1, IMPL=1
&END
&CORREC
  NKICK=5,
  IQKICK=231, 451, 671, 887, 1219,
  IKMOD= 1, NQK=4, NMK=2,
  FLOW=3.96666666d6, FUP=252.d6,
  RESMK=0.2d-6,NITA=O,
  EWAK0=0.494d6,
  DPXLM=56.d3,
  MCOR=1, RESMON=O.dO
&END
&RANDM
  NRAN=O, NNRNDC=1, NROLD=O
&END
&ALIGN
  NAL=2,
  XQSIG=O.D-6, XQCUT=3.,
  XCSIG=O.Od-6,XCCUT=3.,
  XMSIG=O.D-6, XMCUT=3.,
  XPSIG=25.d-6, XPCUT=3.,
  XCTSIG=O.d-6,XCTCUT=3.,NCTABL=4,
  IAMOD= 1
&END
&ALSETX
  NALSET=O,
  IALST= 77, 113,
  DXALS=50.d-6, 50.d-6
&END
&WAKE
  WLL0=0.0D6, FRLG=11.424D9, QL=1000.,
  QT=6500.d0,
  DFR=O.d-4,
  WTS1=8.4d19,
  IFLS=1, IFTL=1
```

```
&END
&RFLAT
FRF=11.424d9, EWAKE=0.494d6,
PHRF=-0.10472d0, 0.d0,0.d0,0.d0,0.d0,
EPH= 1000.d9, 1000.d9, 1000.d9, 1000.d9, 1000.d9
&EN-D
&CTYPE
NTYPE=1, NPIECE=7
&END
```

in-paramc'

```
&NDIV
  NB=1, NS=10, NP=5
&END
&BUNCH
  NBUCKT=16,
  ZC=O.,ZSIG=100.D-6, ZCUT=2.,
  E00=10.1D9, ESIG=101.D6, ECUT=2.,
  CTOTL=6.5D9,
  XOO=O.D-6PX00=0.d3,
  EMIO=1.485d-12, BET0=2.56, ALPO=O.,
  IORD=2,
  FRF0=11.424D9
&END
&PLOT
  NPLOT=5,
  SPLOT=1.D2, 1.D3, 2.D3, 3.d3,4.d3,5.d3,7.d3,0.,0.0.,
    o., o., o., o.,o.,o.,o.,o.,o.,
  IBDRAW=O, ISDRAW=O, IPDRAW=O,
  NAPLOT=3,
  IAPLOT=1,2,3,4,5,
  NSKIP=100
&END
&CORREC
  RESMON=1.0d-6,
  IMCOR1=1, IMCOR2=5, IMC1=0, IMC2=1, MCOR1=90, MCOR2=101, NTRJ1=3, NTRJ2=0,
  FQF= 1.00d0, 0.85d0, 1.15d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0,
  FQD= 1.00d0, 0.85d0, 1.15d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0, 1.00d0,
  ZCOR=1.00d0, 1.00d0, 1.00d0, 2.00d0, 1.00d0, 1.00d0, 2.00d0, 1.00d0,
  QCOR=1.00d0, 1.00d0, 1.00d0, 1.00d0, 0.20d0, 1.00d0, 1.00d0, 0.20d0,
  RE0=70.d-6, RE1=1.0d-6,
  NITA1=4, NITA2=2, AA=0.56d0, NCMOVE=0, DEVCUT=0.0, LSATU=2,
  M2COR1=10, M2COR2=10,
  PIHRF0=-0.1047d0,
  EWAKE0=0.49407d6
&END
&RANDM
  NRAN=O
&END
&RFLAT
  FRF=1 1.424d9, EWAKE=0.49407d6,
  PHRF=-0.1047d0, 0.d0, 0.d0,0.d0,O.d0,
  EPH= 1000.d9, 1000.d9, 1000.d9, 1000.d9, 1000.d9
&END
&CTYPE
  NTYPE=4, NPIECE=2
&END
&ALIGN
  NAL=1,
  XQSIG=50.D-6, XQCUT=3.,
  XCSIG=O.O-6, XCCUT=3.,
  XMSIG=50.O-6, XMCUT=3.,
  XPSIG=.d-6, XPCUT=3.,
  XCTSIG=O.d-6, XCTCUT=3., NCTABL=4,
  IAMOD= 1
&END
```

```
&ALSETX
  NALSET=0,
  IALST= 77, 113,
  DXALS=50.d-6, 50.d-6
&END
&WAKE
  WLL0=0.0D6, FRLG=11.424D9, QL=1000.,
  QT=6500.d0,
  WTS1=6.7d19,
  IFLS=1, IFTL=0
&END
```

'lattice2.dat'

```
! 250 GeV NLC linac lattice
!   Generated with LINAC_04 03/09/93
!   Uses an integral number of structures between quads i
!   Scaled as energy**0.5 with initial betas 8.0 and 2.0
!
```

! #	Type	Length	Strength	Energy
1	1.0	.0000E+00	.0000E+00	10.10
2	5.0	.7390E-01	.2200E+01	10.10
3	11.0	.2000E+00	.0000E+00	10.10
4	11.0	.1800E+01	.3700E-01	10.20
5	11.0	.2000E+00	.0000E+00	10.20
6	11.0	.1800E+01	.3700E-01	10.20
7	11.0	.2000E+00	.0000E+00	10.20
8	5.0	.7390E-01	-.2190E+01	10.20
9	6.0	.0000E+00	.0000E+00	10.20
10	7.0	.0000E+00	.0000E+00	10.20
11	5.0	.7390E-01	-.2190E+01	10.20
12	11.0	.2000E+00	.0000E+00	10.20
13	11.0	.1800E+01	.3700E-01	10.30
14	11.0	.2000E+00	.0000E+00	10.30
15	11.0	.1800E+01	.3700E-01	10.40
16	11.0	.2000E+00	.0000E+00	10.40
17	5.0	.7390E-01	.2200E+01	10.40
18	8.0	.0000E+00	.0000E+00	10.40
19	9.0	.0000E+00	.0000E+00	10.40
20	5.0	.7390E-01	.2180E+01	10.40
21	11.0	.2000E+00	.0000E+00	10.40
22	11.0	.1800E+01	.3700E-01	10.40
23	11.0	.2000E+00	.0000E+00	10.40
24	11.0	.1800E+01	.3700E-01	10.50
25	11.0	.2000E+00	.0000E+00	10.50
26	5.0	.7390E-01	-.2190E+01	10.50
27	6.0	.0000E+00	.0000E+00	10.50
28	7.0	.0000E+00	.0000E+00	10.50
29	5.0	.7390E-01	-.2190E+01	10.50
30	11.0	.2000E+00	.0000E+00	10.50
31	11.0	.1800E+01	.3700E-01	10.60
32	11.0	.2000E+00	.0000E+00	10.60
33	11.0	.1800E+01	.3700E-01	10.60
34	11.0	.2000E+00	.0000E+00	10.60
35	5.0	.7390E-01	.2180E+01	10.60
36	8.0	.0000E+00	.0000E+00	10.60
37	9.0	.0000E+00	.0000E+00	10.60
38	5.0	.7390E-01	.2200E+01	10.60
39	11.0	.2000E+00	.0000E+00	10.60
40	11.0	.1800E+01	.3700E-01	10.70

(The rest is omitted)

Examples of output files

'result05'

```
IAL EMT      1 0.303569485768722471E-07 9.12890486377406241
IAL EMT      2 0.302512020760100985E-07 10.8629896322556601
NAL EMA SIGEM      2 0.303040753264411761E-07 0.528732504285157427E-10
9.99594724801486123
Energy spread 250869300201.540527 0.490100332989802222E-02
```

'resultb02' : fast kicker

```
final IAL EMT max.kick      1 0.373256077332265103E-07 56000.0000000000073
final IAL EMT max.kick      2 0.379043503102440336E-07 50909.5420689222155
NAL EMA SIGEM      2 0.376149790217352753E-07 0.289371288508550872E-09
Energy spread 250590204216.857819 0.543407515731627461E-02
```

'out_dr05.top'

```
set font duplex
(particle      0      0      0
set order x dummy dummy y
set scale y log
set limit x 0 7721.10439999991286
set limit y 2.9E-8 6.E-8
.0000000E+00 .0000000E+00 .0000000E+00 .2999700E-07 .1010000E+11
.4273900E+01 -.3468555E-08 -.1140004E+02 .2999725E-07 .1023295E+11
.4347800E+01 -.3529902E-08 -.5587404E+01 .3000382E-07 .1023295E+11
.8621700E+01 -.3429536E-08 .2920637E+00 .3002319E-07 .1036590E+11
.8695600E+01 -.3448048E-08 -.5486211E+01 .3002256E-07 .1036590E+11
.1296950E+02 -.1084827E-07 -.2071772E+02 .3002242E-07 .1049884E+11
.4347800E+01 -.3529902E-08 .9255261E+02 .3000382E-07 .1023295E+11
.8621700E+01 .3706214E-07 .9784514E+02 .3002319E-07 .1036590E+11
.8695600E+01 .3798453E-07 .1608964E+03 .3002256E-07 .1036590E+11
.1296950E+02 .1290003E-06 .2216694E+03 .3002238E-07 .1049884E+11
.1304340E+02 .1297845E-06 .1137850E+01 .3000360E-07 .1049884E+11
.1731730E+02 .4177421E-07 -.2194072E+03 .2999706E-07 .1063179E+11
.1739120E+02 .4049292E-07 -.1491559E+03 .2999733E-07 .1063179E+11
.2166510E+02 .8168949E-08 -.8030427E+02 .2999795E-07 .1076474E+11
.1304340E+02 .1297845E-06 .2293238E+03 .3000359E-07 .1049884E+11
.1731730E+02 .1335515E-06 .7414057E+01 .2999704E-07 .1063179E+11
.1739120E+02 .1343981E-06 .2362272E+03 .2999732E-07 .1063179E+11
.2166510E+02 .3214034E-06 .4701228E+03 .2999794E-07 .1076474E+11
.2173900E+02 .3226987E-06 -.9269568E+02 .3000442E-07 .1076474E+11
.2601290E+02 .6634471E-07 -.6544050E+03 .3002245E-07 .1089769E+11
(The rest is omitted)
```

'out_plb02.top'

```
set font duplex
new flame
titl ' S= 7521.1043999972Q9 IAL= 1 '
(energy of the first particle= 252915114509.422180
set symbol 10
set order dummy dummy dummy x y
1 1 1 -.36720E-06 -.49412E+05 .25292E+12 -.16000E-03
1 2 1 -.18291E-05 -.32159E+05 .25208E+12 -.80000E-04
1 3 1 .65518E-07 .20089E+05 .25042E+12 .00000E+00
1 4 1 .69163E-06-.14827E+04 .24909E+12 .80000E-04
1 5 1 .94868E-06 .44541E+05 .24890E+12 .16000E-03
2 1 1 -.99525E-07 -.11231E+05 .25292E+12 -.16000E-03
2 2 1 -.92150E-06 -.11118E+05 .25208E+12 -.80000E-04
2 3 1 -.31434E-07 .23408E+05 .25042E+12 .00000E+00
2 4 1 .77341E-06 .90762E+04 .24909E+12 .80000E-04
2 5 1 .12957E-05 .40424E+05 .24890E+12 .16000E-03
3 1 1 .34658E-06-.13786E+05 .25292E+12 -.16000E-03
3 2 1 -.64213E-06 -.11014E+05 .25208E+12 -.80000E-04
3 3 1 -.43188E-07 .21313E+05 .25042E+12 .00000E+00
3 4 1 .86972E-06 .83919E+04 .24909E+12 .80000E-04
3 5 1 .14018E-05 .16697E+05 .24890E+12 .16000E-03
4 1 1 .43060E-06-.27704E+04 .25292E+12 -.16000E-03
4 2 1 -.29107E-06 -.28120E+03 .25208E+12 -.80000E-04
4 3 1 .25847E-06 .27570E+05 .25042E+12 .00000E+00
4 4 1 .10711E-05 .15326E+05 .24909E+12 .80000E-04
4 5 1 .10289E-05 .24445E+05 .24890E+12 .16000E-03
5 1 1 .46138E-06-.88856E+03 .25292E+12 -.16000E-03
5 2 1 -.23242E-06 -.26933E+04 .25208E+12 -.80000E-04
5 3 1 .24406E-06 .25602E+05 .25042E+12 .00000E+00
5 4 1 .10490E-05 .13705E+05 .24909E+12 .80000E-04
5 5 1 .93855E-06 .27887E+05 .24890E+12 .16000E-03
6 1 1 .40429E-06 .30536E+04 .25292E+12 -.16000E-03
6 2 1 -.27125E-06 .25203E+04 .25208E+12 -.80000E-04
6 3 1 .93617E-07 .28144E+05 .25042E+12 .00000E+00
6 4 1 .92627E-06 .17646E+05 .24909E+12 .80000E-04
6 5 1 .94681E-06 .20817E+05 .24890E+12 .16000E-03
7 1 1 .52638E-06 .95650E+04 .25292E+12 -.16000E-03
7 2 1 .26145E-07 .75757E+04 .25208E+12 -.80000E-04
7 3 1 .23642E-06 .27745E+05 .25042E+12 .00000E+00
7 4 1 .10561E-05 .19079E+05 .24909E+12 .80000E-04
7 5 1 .13334E-05 .20532E+05 .24890E+12 .16000E-03
8 1 1 .60178E-06 .48233E+04 .25292E+12 -.16000E-03
8 2 1 .37222E-07 .31396E+04 .25208E+12 -.80000E-04
8 3 1 .24747E-06 .25058E+05 .25042E+12 .00000E+00
8 4 1 .10539E-05 .15630E+05 .24909E+12 .80000E-04
8 5 1 .12601E-05 .17387E+05 .24890E+12 .16000E-03
9 1 1 .46399E-06 .90614E+04 .25292E+12 -.16000E-03
9 2 1 .94761E-08 .79900E+04 .25208E+12 -.80000E-04
9 3 1 .18976E-06 .28083E+05 .25042E+12 .00000E+00
(The rest is omitted)
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