

Xfields physics manual

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1 FFT method

We illustrate the method in a single dimension then extend to multiple dimensions.

2 Space charge

We assume that the bunch travels rigidly along s with velocity $\beta_0 c$:

$$\rho(x, y, s, t) = \rho_0(x, y, s - \beta_0 c t) \quad (1)$$

$$\mathbf{J}(x, y, s, t) = \beta_0 c \rho_0(x, y, s - \beta_0 c t) \hat{\mathbf{i}}_s \quad (2)$$

We define an auxiliary variable ζ as the position along the bunch:

$$\zeta = s - \beta_0 c t. \quad (3)$$

We call K the lab reference frame in which we have defined all equations above, and we introduce a boosted frame K' moving rigidly with the reference particle. The coordinates in the two systems are related by a Lorentz transformation [3]:

$$ct' = \gamma_0 (ct - \beta_0 s) \quad (4)$$

$$x' = x \quad (5)$$

$$y' = y \quad (6)$$

$$s' = \gamma_0 (s - \beta_0 ct) = \gamma_0 \zeta \quad (7)$$

The corresponding inverse transformation is:

$$ct = \gamma_0 (ct' + \beta_0 s') \quad (8)$$

$$x = x' \quad (9)$$

$$y = y' \quad (10)$$

$$s = \gamma_0 (s' + \beta_0 ct') \quad (11)$$

The quantities $(c\rho, J_x, J_y, J_s)$ form a Lorentz 4-vector and therefore they are transformed between K and K' by relationships similar to the Eqs. 4-6 [3]:

$$c\rho'(\mathbf{r}', t') = \gamma_0 [c\rho(\mathbf{r}(\mathbf{r}', t'), t(\mathbf{r}', t')) - \beta_0 J_s(\mathbf{r}(\mathbf{r}', t'), t(\mathbf{r}', t'))] \quad (12)$$

$$J'_s(\mathbf{r}', t') = \gamma_0 [J_s(\mathbf{r}(\mathbf{r}', t'), t(\mathbf{r}', t')) - \beta_0 c\rho(\mathbf{r}(\mathbf{r}', t'), t(\mathbf{r}', t'))] \quad (13)$$

where the transformations $\mathbf{r}(\mathbf{r}', t')$ and $t(\mathbf{r}', t')$ are defined by Eqs. 8 and 11 respectively. The transverse components J_x and J_y of the current vector are invariant for our transformation, and are anyhow zero in our case.

Using Eq. 2 these become:

$$\rho'(\mathbf{r}', t') = \frac{1}{\gamma_0} \rho(\mathbf{r}(\mathbf{r}', t'), t(\mathbf{r}', t')) \quad (14)$$

$$J'_s(\mathbf{r}', t') = 0 \quad (15)$$

Using Eqs. 1 and 8-10, we obtain:

$$\rho(x', y', s(s', t'), t(s', t')) = \rho_0(x', y', s(s', t') - \beta_0 c t(s', t')) \quad (16)$$

From Eq. 7 we get:

$$s(s', t') - \beta_0 c t(s', t') = \frac{s'}{\gamma_0} \quad (17)$$

where the coordinate t' has disappeared.

We can therefore write:

$$\rho'(x', y', s', t') = \frac{1}{\gamma_0} \rho_0\left(x', y', \frac{s'}{\gamma_0}\right) \quad (18)$$

The electric potential in the bunch frame is solution of Poisson's equation:

$$\frac{\partial^2 \phi'}{\partial x'^2} + \frac{\partial^2 \phi'}{\partial y'^2} + \frac{\partial^2 \phi'}{\partial s'^2} = -\frac{\rho'(x', y', s')}{\epsilon_0} \quad (19)$$

From Eq. 18 we can write:

$$\frac{\partial^2 \phi'}{\partial x'^2} + \frac{\partial^2 \phi'}{\partial y'^2} + \frac{\partial^2 \phi'}{\partial s'^2} = -\frac{1}{\gamma_0 \epsilon_0} \rho_0\left(x', y', \frac{s'}{\gamma_0}\right) \quad (20)$$

We now make the substitution:

$$\zeta = \frac{s'}{\gamma_0} \quad (21)$$

obtained from Eq. 7, which allows to rewrite Eq. 20 as:

$$\frac{\partial^2 \phi'}{\partial x^2} + \frac{\partial^2 \phi'}{\partial y^2} + \frac{1}{\gamma_0^2} \frac{\partial^2 \phi'}{\partial \zeta^2} = -\frac{1}{\gamma_0 \epsilon_0} \rho_0(x, y, \zeta) \quad (22)$$

Here we have dropped the "'" sign from x and y as these coordinates are unaffected by the Lorentz boost.

The quantities $\left(\frac{\phi}{c}, A_x, A_y, A_s\right)$ form a Lorentz 4-vector, we can show that the s component of the vector potential in the lab frame vanishes:

$$\phi = \gamma_0 (\phi' + \beta_0 c A'_s) \quad (23)$$

$$A_s = A'_s + \beta_0 \frac{\phi'}{c} \quad (24)$$

In the bunch frame the charges are at rest therefore $A'_x = A'_y = A'_z = 0$ therefore:

$$\phi = \gamma_0 \phi' \quad (25)$$

$$A_s = \beta_0 \frac{\phi'}{c} = \frac{\beta_0}{\gamma_0 c} \phi \quad (26)$$

Combining Eq. 25 with Eq. 22 we obtain the equation in ϕ :

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{1}{\gamma_0^2} \frac{\partial^2 \phi}{\partial \zeta^2} = -\frac{1}{\epsilon_0} \rho_0(x, y, \zeta) \quad (27)$$

3 Lorentz force

We stay in the thin lens approximation so we approximate the velocity vector of the particle as:

$$\mathbf{v} = \beta c \hat{\mathbf{i}}_s \quad (28)$$

We want to compute the Lorentz force acting on the particle:

$$\begin{aligned} \mathbf{F} &= q \left(-\nabla\phi - \frac{\partial \mathbf{A}}{\partial t} + \beta c \hat{\mathbf{i}}_s \times (\nabla \times \mathbf{A}) \right) \\ &= q \left(-\nabla\phi - \frac{\beta_0}{\gamma_0 c} \frac{\partial \phi}{\partial t} \hat{\mathbf{i}}_s + \beta c \hat{\mathbf{i}}_s \times (\nabla \times \mathbf{A}) \right) \end{aligned} \quad (29)$$

We compute the vector product:

$$\begin{aligned} \hat{\mathbf{i}}_s \times (\nabla \times \mathbf{A}) &= \left(\frac{\partial A_s}{\partial x} - \frac{\partial A_x}{\partial s} \right) \hat{\mathbf{i}}_x + \left(\frac{\partial A_s}{\partial y} - \frac{\partial A_y}{\partial s} \right) \hat{\mathbf{i}}_y \\ &= \left(\frac{\partial A_s}{\partial x} - \frac{\partial A_x}{\partial s} \right) \hat{\mathbf{i}}_x + \left(\frac{\partial A_s}{\partial y} - \frac{\partial A_y}{\partial s} \right) \hat{\mathbf{i}}_y + \underbrace{\left(\frac{\partial A_s}{\partial s} - \frac{\partial A_s}{\partial s} \right)}_{=0} \hat{\mathbf{i}}_s \\ &= \nabla A_s - \frac{\partial \mathbf{A}}{\partial s} \end{aligned} \quad (30)$$

We replace:

$$\mathbf{F} = q \left(-\nabla\phi - \frac{\beta_0}{\gamma_0 c} \frac{\partial \phi}{\partial t} \hat{\mathbf{i}}_s + \beta \beta_0 \nabla\phi - \frac{\beta \beta_0}{\gamma_0} \frac{\partial \phi}{\partial s} \hat{\mathbf{i}}_s \right) \quad (31)$$

The potentials will have the same form as the sources (this can be shown explicitly using the Lorentz transformations):

$$\phi(x, y, s, t) = \phi \left(x, y, t - \frac{s}{\beta_0 c} \right) \quad (32)$$

For a function in this form we can write:

$$\frac{\partial \phi}{\partial s} = \frac{\partial}{\partial \zeta} = -\frac{1}{\beta_0 c} \frac{\partial \phi}{\partial t} \quad (33)$$

obtaining:

$$\mathbf{F} = q \left(-\nabla\phi + \frac{\beta_0^2}{\gamma_0} \frac{\partial \phi}{\partial \zeta} \hat{\mathbf{i}}_s + \beta \beta_0 \nabla\phi - \frac{\beta \beta_0}{\gamma_0} \frac{\partial \phi}{\partial \zeta} \hat{\mathbf{i}}_s \right) \quad (34)$$

Reorganizing:

$$\mathbf{F} = -q(1 - \beta \beta_0) \nabla\phi - \frac{\beta_0(\beta - \beta_0)}{\gamma_0} \frac{\partial \phi}{\partial \zeta} \hat{\mathbf{i}}_s \quad (35)$$

Explicit dependencies:

$$F_x(x, y, \zeta(t)) = -q(1 - \beta \beta_0) \frac{\partial \phi}{\partial x}(x, y, \zeta(t)) \quad (36)$$

$$F_y(x, y, \zeta(t)) = -q(1 - \beta \beta_0) \frac{\partial \phi}{\partial y}(x, y, \zeta(t)) \quad (37)$$

$$F_z(x, y, \zeta(t)) = -q \left(1 - \beta \beta_0 - \frac{\beta_0(\beta - \beta_0)}{\gamma_0} \right) \frac{\partial \phi}{\partial \zeta}(x, y, \zeta(t)) \quad (38)$$

Over the single interaction we neglect the particle slippage:

$$\beta = \beta_0 \quad (39)$$

$$\zeta(t) = \zeta \quad (40)$$

(in any case one would need to take into account also the dispersion in order to have the right slippage).

gives the following simplification:

$$F_x(x, y, \zeta) = -q(1 - \beta_0^2) \frac{\partial \phi}{\partial x}(x, y, \zeta) \quad (41)$$

$$F_y(x, y, \zeta) = -q(1 - \beta_0^2) \frac{\partial \phi}{\partial y}(x, y, \zeta) \quad (42)$$

$$F_z(x, y, \zeta) = -q(1 - \beta_0^2) \frac{\partial \phi}{\partial \zeta}(x, y, \zeta) \quad (43)$$

In this way the force over the single interaction becomes independent on time and therefore we can compute the kicks simply as:

$$\Delta \mathbf{P} = \frac{L}{\beta_0 c} \mathbf{F} \quad (44)$$

from which we can compute the kicks on the normalized momenta ($P_0 = m_0 \beta_0 \gamma_0 c$):

$$\Delta p_x = \frac{m_0}{m} \frac{\Delta P_x}{P_0} = -\frac{qL(1 - \beta_0^2)}{m\gamma_0\beta_0^2c^2} \frac{\partial \phi}{\partial x}(x, y, \zeta) \quad (45)$$

$$\Delta p_y = \frac{m_0}{m} \frac{\Delta P_y}{P_0} = -\frac{qL(1 - \beta_0^2)}{m\gamma_0\beta_0^2c^2} \frac{\partial \phi}{\partial y}(x, y, \zeta) \quad (46)$$

$$\Delta \delta \simeq \Delta p_z = \frac{m_0}{m} \frac{\Delta P_z}{P_0} = -\frac{qL(1 - \beta_0^2)}{m\gamma_0\beta_0^2c^2} \frac{\partial \phi}{\partial \zeta}(x, y, \zeta) \quad (47)$$

Of your beam includes particles of different species (tracking of fragments), note that heree q is the charge of the kicked particle while m_0 is the mass of the reference particle.

3.1 2.5D approximation

For large enough values of γ_0 , Eq. 22 can be approximated by:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = -\frac{1}{\varepsilon_0} \rho_0(x, y, \zeta) \quad (48)$$

which means that we can solve a simple 2D problem for each beam slice (identified by its ζ).

3.2 Modulated 2D

Often the beam distribution can be factorized as:

$$\rho_0(x, y, \zeta) = Nq_0\lambda_0(\zeta)\rho_{\perp}(x, y) \quad (49)$$

where:

$$\int \lambda_0(z) dz = 1 \quad (50)$$

$$\int \rho_{\perp}(x, y) dx dy = 1 \quad (51)$$

In this case the potential can be factorized as:

$$\phi(x, y, \zeta) = q_0\lambda_0(\zeta)\phi_{\perp}(x, y) \quad (52)$$

where $\phi_{\perp}(x, y)$ is the solution of the following 2D Poisson equation:

$$\frac{\partial^2 \phi_{\perp}}{\partial x^2} + \frac{\partial^2 \phi_{\perp}}{\partial y^2} = -\frac{1}{\varepsilon_0} \rho_{\perp}(x, y) \quad (53)$$

The kick can be expressed as:

$$\Delta p_x = \frac{m_0}{m} \frac{\Delta P_x}{P_0} = -\frac{qq_0NL(1-\beta_0^2)}{m\gamma_0\beta_0^2c^2} \lambda_0(\zeta) \frac{\partial \phi}{\partial x}(x, y) \quad (54)$$

$$\Delta p_y = \frac{m_0}{m} \frac{\Delta P_y}{P_0} = -\frac{qq_0NL(1-\beta_0^2)}{m\gamma_0\beta_0^2c^2} \lambda_0(\zeta) \frac{\partial \phi}{\partial y}(x, y) \quad (55)$$

$$\Delta \delta \simeq \Delta p_z = \frac{m_0}{m} \frac{\Delta P_z}{P_0} = -\frac{qq_0NL(1-\beta_0^2)}{m\gamma_0\beta_0^2c^2} \frac{d\lambda_0}{d\zeta}(\zeta) \phi(x, y) \quad (56)$$

4 FFT solver

We start from a 1D case for illustration and then we generalize.

We assume free space. The potential can be written as the convolution of a Green function with the charge distribution:

$$\phi(x) = \int_{-\infty}^{+\infty} \rho(x') G(x-x') dx' \quad (57)$$

We assume that the source is limited to a region of measure L :

$$\rho(x) = \rho(x) \Pi\left(\frac{x}{L}\right) \quad (58)$$

where $\Pi(x)$ is a rectangular window defined as:

$$\Pi(x) = \begin{cases} 1 & \text{for } -\frac{1}{2} < x < \frac{1}{2} \\ 0 & \text{elsewhere} \end{cases} \quad (59)$$

We are interested in the electric potential only the region occupied by the sources, so we can compute:

$$\phi_L(x) = \phi(x) \Pi\left(\frac{x}{L}\right) \quad (60)$$

We replace Eq. (58) and Eq. (60) into Eq.(57), obtaining:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \int_{-\infty}^{+\infty} \Pi\left(\frac{x'}{L}\right) \rho(x') G(x - x') dx' \quad (61)$$

We change variable into $x'' = x - x'$:

$$\phi_L(x) = \int_{-\infty}^{+\infty} \Pi\left(\frac{x}{L}\right) \Pi\left(\frac{x - x''}{L}\right) \rho(x - x'') G(x'') dx'' \quad (62)$$

The integrand vanishes outside the set of the (x, x'') defined by:

$$\begin{cases} -\frac{L}{2} < x < \frac{L}{2} \\ -\frac{L}{2} < (x'' - x) < \frac{L}{2} \end{cases} \quad (63)$$

Combining the two equations we obtain:

$$-L < -\frac{L}{2} + x < x'' < \frac{L}{2} + x < L \quad (64)$$

i.e. the integrand is zero for $-L < x'' < L$. Therefore in equation (62) we can replace the $G(x'')$ with its truncated version:

$$G_{2L}(x'') = G(x'') \Pi\left(\frac{x''}{2L}\right) \quad (65)$$

obtaining:

$$\phi_L(x) = \int_{-\infty}^{+\infty} \Pi\left(\frac{x}{L}\right) \Pi\left(\frac{x - x''}{L}\right) \rho(x - x'') G_{2L}(x'') dx'' \quad (66)$$

Since the two window function force the integrand to zero outside the region $|x''| < L$ we can replace $G_{2L}(x'')$ with its replicated version:

$$G_{2LR}(x'') = \sum_{n=-\infty}^{+\infty} G_{2L}(x'' - 2nL) = \sum_{n=-\infty}^{+\infty} G(x'' - 2nL) \Pi\left(\frac{x'' - 2nL}{2L}\right) \quad (67)$$

obtaining:

$$\phi_L(x) = \int_{-\infty}^{+\infty} \Pi\left(\frac{x}{L}\right) \Pi\left(\frac{x - x''}{L}\right) \rho(x - x'') G_{2LR}(x'') dx'' \quad (68)$$

We can go back to the initial coordinate by substituting $x'' = x - x'$:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \int_{-\infty}^{+\infty} \rho(x') G_{2LR}(x - x') dx' \quad (69)$$

This is a cyclic convolution, so we can proceed as followd. We split the integral:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \sum_{n=-\infty}^{+\infty} \int_{-\frac{L}{2}+2nL}^{+\frac{L}{2}+2nL} \rho(x') G_{2LR}(x-x') dx' \quad (70)$$

In each term I replace $x''' = x' + 2nL$:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \sum_{n=-\infty}^{+\infty} \int_{-\frac{L}{2}}^{+\frac{L}{2}} \rho(x''' - 2nL) G_{2LR}(x - x''' - 2nL) dx' \quad (71)$$

But G_{2LR} is periodic:

$$\begin{aligned} \phi_L(x) &= \Pi\left(\frac{x}{L}\right) \sum_{n=-\infty}^{+\infty} \int_{-\frac{L}{2}}^{+\frac{L}{2}} \rho(x''' - 2nL) G_{2LR}(x - x''') dx''' \\ &= \Pi\left(\frac{x}{L}\right) \int_{-\frac{L}{2}}^{+\frac{L}{2}} \sum_{n=-\infty}^{+\infty} \rho(x''' - 2nL) G_{2LR}(x - x''') dx''' \end{aligned} \quad (72)$$

I can define a replicated version of $\rho(x)$:

$$\rho_{2LR}(x) = \sum_{n=-\infty}^{+\infty} \rho(x - 2nL) \quad (73)$$

obtaining:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \int_0^{2L} \rho_{2LR}(x') G_{2LR}(x - x') dx' \quad (74)$$

The function:

$$\phi_{2LR}(x) = \int_{-\frac{L}{2}}^{+\frac{L}{2}} \rho_{2LR}(x') G_{2LR}(x - x') dx' \quad (75)$$

is periodic of period $2L$. From it the potential of interest can be simply calculated by selecting the half period $[-L/2, L/2]$:

$$\phi_L(x) = \Pi\left(\frac{x}{L}\right) \phi_{2LR}(x) \quad (76)$$

We expand $\phi_{2LR}(x)$ in Fourier series:

$$\phi_{2LR}(x) = \sum_{k=-\infty}^{+\infty} \tilde{\phi}_k e^{j2\pi k \frac{x}{2L}} \quad (77)$$

where the Fourier coefficient are given by:

$$\tilde{\phi}_k = \frac{1}{2L} \int_0^{2L} \phi_{2LR}(x) e^{-j2\pi k \frac{x}{2L}} dx \quad (78)$$

We replace Eq. (75) into Eq. (78) obtaining:

$$\hat{\phi}_k = \frac{1}{2L} \int_0^{2L} \int_0^{2L} \rho_{2LR}(x') G_{2LR}(x - x') e^{-j2\pi k \frac{x}{2L}} dx' dx \quad (79)$$

With the change of variable $x'' = x - x'$ we obtain:

$$\tilde{\phi}_k = \frac{1}{2L} \int_{-\frac{L}{2}}^{+\frac{L}{2}} \rho_{2LR}(x') e^{-j2\pi k \frac{x'}{2L}} dx' \int_{-\frac{L}{2}}^{+\frac{L}{2}} G_{2LR}(x'') e^{-j2\pi k \frac{x''}{2L}} dx'' \quad (80)$$

where we recognize the Fourier coefficients of $\rho_{2LR}(x)$ and $G_{2LR}(x)$:

$$\tilde{\rho}_k = \frac{1}{2L} \int_{-\frac{L}{2}}^{+\frac{L}{2}} \rho_{2LR}(x) e^{-j2\pi k \frac{x}{2L}} dx \quad (81)$$

$$\tilde{G}_k = \frac{1}{2L} \int_{-\frac{L}{2}}^{+\frac{L}{2}} G_{2LR}(x) e^{-j2\pi k \frac{x}{2L}} dx \quad (82)$$

obtaining simply:

$$\hat{\phi}_k = 2L \hat{G}_k \hat{\rho}_k \quad (83)$$

I assume to have the functions $\rho_{2LR}(x)$ and $G_{2LR}(x)$ sampled (or averaged) with step:

$$h_x = \frac{2L}{M} = \frac{L}{N} \quad (84)$$

I can approximate the integrals in Eqs. (81) and (82) as:

$$\tilde{\rho}_k = \frac{1}{M} \sum_{n=0}^{M-1} \rho_{2LR}(x_n) e^{-j2\pi \frac{kn}{M}} = \frac{1}{M} \hat{\rho}_k \quad (85)$$

$$\tilde{G}_k = \frac{1}{M} \sum_{n=0}^{M-1} G_{2LR}(x_n) e^{-j2\pi \frac{kn}{M}} = \frac{1}{M} \hat{G}_k \quad (86)$$

where we recognize the Discrete Fourier Transforms:

$$\hat{\rho}_k = \text{DFT} \{ \rho_{2LR}(x_n) \} \quad (87)$$

$$\hat{G}_k = \text{DFT} \{ G_{2LR}(x_n) \} \quad (88)$$

Using Eq. (77) we can obtained a sampled version of $\phi(x)$:

$$\phi_{2LR}(x_n) = \sum_{n=0}^{M-1} \tilde{\phi}_k e^{j2\pi \frac{kn}{M}} \quad (89)$$

where we have assumed that $\phi(x)$ is sufficiently smooth to allow truncating the sum. Using Eqs. (85) and (86)

$$\phi_{2LR}(x_n) = 2L \sum_{n=0}^{M-1} \tilde{G}_k \tilde{\rho}_k e^{j2\pi \frac{kn}{M}} = \frac{2L}{M^2} \sum_{n=0}^{M-1} \hat{G}_k \hat{\rho}_k e^{j2\pi \frac{kn}{M}} \quad (90)$$

This can be rewritten as:

$$\phi_{2LR}(x_n) = \frac{1}{M} \sum_{n=0}^{M-1} (h_x \hat{G}_k) \hat{\rho}_k e^{j2\pi \frac{kn}{M}} = \text{DFT}^{-1} \{ (h_x \hat{G}_k) \hat{\rho}_k \} \quad (91)$$

In summary the potential at the grid nodes can be computed as follows:

1. We sample or average the Green function with step h_x over the interval $[0, L]$, obtaining the sequence $G(x_n)$ for $n = 0, \dots, N - 1$
2. We build its replicate version in the interval $[L, 2L]$ using the fact that:

$$G_{2LR}(2L - x) = G(-x) = G(x) \quad (92)$$

4.1 Extension to 3D

In summary in 1D what one needs to do is:

Transform the sources and the Green function:

$$\hat{\rho}_k = \frac{1}{M} \sum_{n=0}^{M-1} \rho_{2LR}(x_n) e^{j2\pi \frac{kn}{M}} \quad (93)$$

$$\hat{G}_k = \frac{1}{M} \sum_{n=0}^{M-1} G_{2LR}(x_n) e^{j2\pi \frac{kn}{M}} \quad (94)$$

Do the product and antitransform:

$$\phi_{2LR}(x_n) = 2L \sum_{n=0}^{M-1} \hat{G}_k \hat{\rho}_k e^{-j2\pi \frac{kn}{M}} \quad (95)$$

Repeating the same reasoning along all directions one obtains:

$$\hat{\rho}_{k_x k_y k_z} = \frac{1}{M_x M_y M_z} \sum_{n_x=0}^{M_x-1} e^{j2\pi \frac{k_x n_x}{M_x}} \sum_{n_y=0}^{M_y-1} e^{j2\pi \frac{k_y n_y}{M_y}} \sum_{n_z=0}^{M_z-1} e^{j2\pi \frac{k_z n_z}{M_z}} \rho_{2LR}(x_{n_x}, y_{n_y}, z_{n_z}) \quad (96)$$

$$\hat{G}_{k_x k_y k_z} = \frac{1}{M_x M_y M_z} \sum_{n_x=0}^{M_x-1} e^{j2\pi \frac{k_x n_x}{M_x}} \sum_{n_y=0}^{M_y-1} e^{j2\pi \frac{k_y n_y}{M_y}} \sum_{n_z=0}^{M_z-1} e^{j2\pi \frac{k_z n_z}{M_z}} G_{2LR}(x_{n_x}, y_{n_y}, z_{n_z}) \quad (97)$$

$$\begin{aligned} \phi_{2LR}(x_{n_x}, y_{n_y}, z_{n_z}) = \\ (2L_x)(2L_y)(2L_z) \sum_{k_x=0}^{M_x-1} e^{-j2\pi \frac{k_x n_x}{M_x}} \sum_{k_y=0}^{M_y-1} e^{-j2\pi \frac{k_y n_y}{M_y}} \sum_{k_z=0}^{M_z-1} e^{-j2\pi \frac{k_z n_z}{M_z}} \hat{G}_{k_x k_y k_z} \hat{\rho}_{k_x k_y k_z} \end{aligned} \quad (98)$$

The continuous convolution in 3D is written as

$$\phi(x, y, z) = \iiint_{-\infty}^{+\infty} \rho(x', y', z') G(x - x', y - y', z - z') dx' dy' dz' \quad (99)$$

where:

$$G(x, y, z) = \frac{1}{4\pi\epsilon_0} \frac{1}{\sqrt{x^2 + y^2 + z^2}} \quad (100)$$

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