

PyPIC physics manual

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1 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]:

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

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

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

$$s' = \gamma_0 (s - \beta_0 c t) = \gamma_0 \zeta \quad (7)$$

The corresponding inverse transformation is:

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

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

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

$$s = \gamma_0 (s' + \beta_0 c t') \quad (11)$$

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. 27 we obtain the equation in ϕ :

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

2 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:

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

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

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 ($P_0 = m_0 \beta_0 \gamma_0 c$):

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

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

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

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.

2.1 2.5D approximation

For large enough values of γ_0 , Eq. 27 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).

2.2 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:

$$\frac{\partial^2 \phi_{\perp}}{\partial x^2} + \frac{\partial^2 \phi_{\perp}}{\partial y^2} = -\frac{1}{\epsilon_0} \rho_{\perp}(x, y) \quad (53)$$

The kick can be expressed as:

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

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

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

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