# Redistribution of cooling rates for electron bunch with nonuniform density 

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# Redistribution of cooling rates for electron bunch with nonuniform density 

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#### Abstract

In this paper we derive explicit formulas for the friction force and the cooling rates in non-magnetized electron coolers in the presence of redistribution of cooling decrements. In the derived formulas we take into account that the density of the electron bunch can be nonuniform.


## 1 Friction force

### 1.1 General remarks

Electron Cooling (EC) [1, 2] is a technique that allows increasing a 6-D phase space density of stored hadron beams.

In EC a beam of "cold" electrons co-propagate with a hadron beam with the same average velocity in a straight section of the storage ring, called a cooling section (CS). A hadron interacts with electrons in a CS via Coulomb force, which introduces dynamical friction [3] acting on each hadron. Over many revolutions in the accelerator the average friction reduces both the transverse and the longitudinal momentum spread of the ion bunch.

The friction force (in the beam frame) acting on an ion co-traveling with an electron bunch is given by [4, 5]:

$$
\begin{equation*}
\vec{F}=-\frac{4 \pi e^{4} Z_{i}^{2}}{m_{e}} \int \Lambda_{C} \frac{\vec{v}_{i}-\vec{v}_{e}}{\left|\vec{v}_{i}-\vec{v}_{e}\right|^{3}} f\left(r_{e}, v_{e}\right) d^{3} v_{e} \tag{1}
\end{equation*}
$$

Here, $e$ is the electron charge, $Z_{i} \cdot e$ is the ion charge, $m_{e}$ is the mass of electron, $\vec{v}_{i}$ and $\vec{v}_{e}$ are ion and electron velocities in the beam frame, $\Lambda_{C}$

[^1]is the Coulomb logarithm, which has a weak dependence on $v_{e}$ and can be moved from under the integral, and $f\left(r_{e}, v_{e}\right)$ is a six-dimensional distribution function of the electrons.

The cooling rate ( $\lambda_{x, y, z}$ ) in the laboratory frame can be obtained from:

$$
\begin{equation*}
\lambda_{x, y, z}=\frac{F_{x, y, z} \eta}{\gamma m_{i} v_{x i, y i, z i}} \tag{2}
\end{equation*}
$$

where the duty factor $\eta=L_{C S} /(2 \pi R), R$ is the storage ring radius, $L_{C S}$ is the length of the cooling section, $m_{i}=A_{i} m_{p}, m_{p}$ is the proton mass, $A_{i}$ is the ion mass number, and indexes $x, y, z$ correspond to the horizontal, vertical and longitudinal components of $F, v$ and $\lambda$.

Similarly to Eq. (2), the change in the ion's velocity on a single pass through the CS is given by:

$$
\begin{equation*}
\Delta v_{i(x, y, z)}=\frac{F_{x, y, z}}{m_{i}} \frac{L_{C S}}{\gamma \beta c} \tag{3}
\end{equation*}
$$

It is well known [5] that the cooling rates can be "redistributed" between the longitudinal and transverse directions.

The redistribution requires two conditions. The first one is a coupling between the longitudinal and the transverse (we will consider the horizontal one) motion of an ion. This is created by the ions' dispersion in the CS. The second condition is a nonzero longitudinal drag force dependent on the horizontal position of an ion in the cooling section (a so called transverse gradient of the longitudinal friction force). A robust way to create the required gradient is to introduce the electron beam dispersion in the CS.

The cooling force can be well approximated by a linear function of the ion velocity $\left(v_{i}\right)$ if $v_{i}$ is less than the rms velocity spread of the electrons.

For the following considerations we will assume:

$$
\begin{align*}
& F_{x}=-C_{x} n_{e} v_{x i}  \tag{4}\\
& F_{z}=-C_{z} n_{e}\left(v_{z i}-K \cdot x_{i}\right)
\end{align*}
$$

where $n_{e}$ is the density distribution of the e-bunch and $K$ is the horizontal gradient of the longitudinal cooling force.

Substituting Eq. (4) into Eq. (3) and noticing that an ion's relative momentum $\delta_{i}=v_{z i} /(\beta c)$ and an ion's angle $x_{i}^{\prime}=v_{x i} /(\gamma \beta c)$, we get the following changes in an ion's angle ( $\Delta x_{i}^{\prime}$ ) and its relative momentum $\left(\Delta \delta_{i}\right)$ for a single pass through the CS:

$$
\begin{align*}
& \Delta x_{i}^{\prime}=-c_{x} n_{e} x_{i C S}^{\prime}  \tag{5}\\
& \Delta \delta_{i}=-c_{z} n_{e}\left(\delta_{i C S}-k \cdot x_{i C S}\right)
\end{align*}
$$

where $c_{x}=\frac{C_{x} L_{C S}}{\gamma \beta c m_{i}}, c_{z}=\frac{C_{z} L_{C S}}{\gamma \beta c m_{i}}, k=\frac{K}{\beta c}$, and $x_{i C S}, x_{i C S}^{\prime}$ and $\delta_{i C S}$ are respectively an ion's positions, angle and relative momentum in the cooling section.

### 1.2 Explicit expression for linear part of friction force

We consider an electron bunch with Gaussian 6-D distribution in the presence of e-beam dispersion $\left(D_{e}\right)$ in the cooling section. To simplify the resulting formulas we will assume electron Twiss $\alpha_{e}=0$ in the cooling section, which is a reasonable approximation for an electron cooler (a treatment of $\alpha_{e} \neq 0$ case can be found in [6]). Then the electron bunch distribution in the beam frame is:

$$
\begin{align*}
f\left(r_{e}, v_{e}\right) & =\frac{1}{\gamma(2 \pi)^{3} \Delta_{x} \Delta y \Delta_{z} \sigma_{x e} \sigma_{y e} \sigma_{z e}} f_{x} f_{y} f_{z} \\
f_{x} & =\exp \left[-\frac{\left(-D_{e} e^{2}\right)^{2}}{2 \sigma_{x e}^{2}}-\frac{v_{x e}^{2}}{2 \Delta_{x}^{2}}\right] \\
f_{y} & =\exp \left(-\frac{y^{2}}{2 \sigma_{z_{e}}^{2}}-\frac{v_{y e}^{2}}{2 \Delta_{y}^{2}}\right)  \tag{6}\\
f_{y} & =\exp \left(-\frac{z^{2}}{2 \sigma_{z e}^{2}}-\frac{v_{z e}^{2}}{2 \Delta_{z}^{2}}\right)=\exp \left(-\frac{z^{2}}{2 \sigma_{z e}^{2}}-\frac{\delta_{e}^{2}}{2 \sigma_{\delta_{e}}^{2}}\right)
\end{align*}
$$

Here $\Delta_{x, y, z}$ are the electrons' rms velocity spreads in the beam frame and $\sigma_{x e, y e, z e}$ are the e-bunch rms sizes along horizontal, vertical and longitudinal directions in the laboratory frame respectively.

With simple algebraic manipulations the distribution can be split in a density and a velocity distribution parts:

$$
\begin{align*}
f\left(r_{e}, v_{e}\right) & =n_{e} f_{v e} \\
n_{e} & =\frac{1}{\gamma(2 \pi)^{3 / 2} \sigma_{1 x e} \sigma_{y e} \sigma_{z e}} \exp \left[-\frac{x^{2}}{2 \sigma_{1 x e}^{2}}-\frac{y^{2}}{2 \sigma_{y e}^{2}}-\frac{z^{2}}{2 \sigma_{z e}^{2}}\right] \\
f_{v e} & =\frac{1}{(2 \pi)^{3 / 2} \Delta_{x} \Delta_{y} \Delta_{1 z}} \exp \left[-\frac{v_{x e}^{2}}{2 \Delta_{x}^{2}}-\frac{v_{y e}^{2}}{2 \Delta_{y}^{2}}-\frac{\left(v_{z e}-\mu_{z}\right)^{2}}{2 \Delta_{1 z}^{2}}\right]  \tag{7}\\
\sigma_{1 x e} & =\sqrt{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}} \\
\Delta_{1 z} & =\Delta_{z} \frac{\sigma_{x e}}{\sqrt{\sigma_{x e}^{x}+D_{e}^{2} \sigma_{\delta e}^{2}}} \\
\mu_{z} & =x \Delta_{z} \frac{D_{e} \delta_{\delta e}}{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}
\end{align*}
$$

Substituting Eq. (7) into Eq. (1) we get the expression for the friction force of the form:

$$
\begin{equation*}
\vec{F}=-C n_{e} \int \frac{\vec{v}_{i}-\vec{v}_{e}}{\left|\vec{v}_{i}-\vec{v}_{e}\right|^{3}} f_{v e} d^{3} v_{e} \tag{8}
\end{equation*}
$$

where $C=\frac{4 \pi N_{e} e^{4} Z_{i}^{2} \Lambda_{C}}{m_{e}}$ and $N_{e}$ is the number of electrons in the e-bunch.
Equation (8) with distribution $f_{v e}$ of the form (7) can be reduced to 1-D integrals for each component of the friction force (so called Binney's formulas
[7]) by noticing that the friction force in v-space looks like a point-charge Coulomb force in the physical space. Then we can introduce an effective potential in a velocity-space:

$$
\begin{equation*}
U=C \int \frac{f_{v e}}{\left|\vec{v}_{i}-\vec{v}_{e}\right|} d^{3} v_{e} \tag{9}
\end{equation*}
$$

such that

$$
\begin{equation*}
F_{x, y, z}=\partial U / \partial v_{x i, y i, z i} \tag{10}
\end{equation*}
$$

The detailed step-by-step derivation of the Binney's formulas for the considered case is given in [8]. Here we simply give the final result for $\Delta_{x}=\Delta_{y}$. Considerations of unequal v-distributions in all three directions can be found in 9.

For the case of $\Delta_{x}=\Delta_{y} \equiv \Delta_{\perp}$ the friction force is:

$$
\left\{\begin{align*}
F_{x, y} & =-\widetilde{C} n_{e} v_{x i, y i} \int_{0}^{\infty} g_{\perp}(q) d q  \tag{11}\\
F_{z} & =-\widetilde{C} n_{e}\left(v_{z i}-\mu_{z}\right) \int_{0}^{\infty} g_{z}(q) d q \\
g_{\perp}(q) & =\frac{1}{\Delta_{\perp}^{2}(1+q)^{2} \sqrt{\Delta_{\perp}^{2} q+\Delta_{1 z}^{2}}} \exp \left[-\frac{v_{x i}^{2}+v_{y i}^{2}}{2 \Delta_{\perp}^{2}(1+q)}-\frac{\left(v_{z i}-\mu_{z}\right)^{2}}{2\left(\Delta_{\perp}^{2} q+\Delta_{1}^{2}\right)}\right] \\
g_{z}(q) & =\frac{1}{(1+q)\left(\Delta_{\perp}^{2} q+\Delta_{1 z}^{2}\right)^{3 / 2}} \exp \left[-\frac{v_{x i}^{2}+v_{y i}^{2}}{2 \Delta_{\perp}^{2}(1+q)}-\frac{\left(v_{z i}-\mu_{z}\right)^{2}}{2\left(\Delta_{\perp}^{\perp} q+\Delta_{1 z}^{2}\right)}\right]
\end{align*}\right.
$$

where $\widetilde{C}=2 \sqrt{2 \pi} N_{e} r_{e}^{2} m_{e} c^{4} Z_{i}^{2} \Lambda_{C}$.
The integrals (11) can be taken analytically in the approximation of "small amplitudes":

$$
\begin{align*}
F_{x, y} & =-v_{x i, y i} \frac{\widetilde{C} n_{e}}{\Delta_{\perp}^{2} \Delta_{1 z}} \Phi\left(\Delta_{1 z} / \Delta_{\perp}\right) \\
F_{z} & =-\left(v_{z i}-\mu_{z}\right) \frac{2 \widetilde{C} n_{e}}{\Delta_{\perp} \Delta_{1 z}}\left(1-\Phi\left(\Delta_{1 z} / \Delta_{\perp}\right)\right) \\
\Phi(d) & =\left\{\begin{array}{l}
\left.\frac{d}{1-d^{2}} \frac{\arccos (d)}{\sqrt{1-d^{2}}}-d\right), d<1 \\
2 / 3, d=1 \\
\frac{d}{d^{2}-1}\left(\frac{\log \left(d-\sqrt{d^{2}-1}\right)}{\sqrt{d^{2}-1}}+d\right), d>1
\end{array}\right. \tag{12}
\end{align*}
$$

where $d=\Delta_{1 z} / \Delta_{\perp}$.
Equations (12) can be rewritten in the form of Eq. (4):

$$
\begin{align*}
F_{x} & =-C_{x} \cdot n_{e} \cdot v_{x i} \\
F_{z} & =-C_{z} \cdot n_{e} \cdot\left(v_{z i}-K \cdot x_{i}\right) \\
C_{x} & =C_{0} \cdot h \cdot \Phi \cdot \Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{e e}} \frac{1}{h}\right) \\
C_{z} & =2 C_{0} \cdot h \cdot\left[1-\Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{e}} \frac{1}{h}\right)\right]  \tag{13}\\
C_{0} & =\frac{2 \sqrt{2 \pi} N_{e} r_{e}^{2} m_{e} c Z_{i}^{2} \Lambda_{C}}{\gamma^{2} \beta^{3} \sigma_{\theta \theta}^{2} \sigma_{\delta e}} \\
h & =\frac{\sqrt{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}}{\sigma_{x e}} \\
K & =\beta c \frac{D_{e} \sigma_{\delta e}^{2}}{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}
\end{align*}
$$

Here, we used for the e-bunch angular spread we used $\sigma_{\theta e}=\Delta_{\perp} /(\gamma \beta c)$ and for the e-bunch relative momentum spread we used $\sigma_{\delta e}=\Delta_{z} /(\beta c)$.

Finally, from Eqs. (4) (5) and (13) we get:

$$
\begin{align*}
& \Delta x_{i}^{\prime}=-c_{x} \cdot n_{e 1} \cdot x_{i C S}^{\prime} \\
& \Delta \delta_{i}=-c_{z} \cdot n_{e 1} \cdot\left(\delta_{i C S}-k \cdot x_{i C S}\right) \\
& c_{x}=\tilde{c}_{0} \cdot h \cdot \Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{\theta e}} \frac{1}{h}\right) \\
& c_{z}=2 \tilde{c}_{0} \cdot h \cdot\left[1-\Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{\theta e}} \frac{1}{h}\right)\right] \\
& k=\frac{D_{e} \sigma_{\delta e}^{2}}{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}  \tag{14}\\
& n_{e 1}=\frac{1}{(2 \pi)^{3 / 2} \sigma_{1 x e} \sigma_{y e} \sigma_{z e}} \exp \left[-\frac{x^{2}}{2 \sigma_{1 x e}^{2}}-\frac{y^{2}}{2 \sigma_{y e}^{2}}-\frac{z^{2}}{2 \sigma_{z e}^{2}}\right] \\
& \tilde{c}_{0}=\frac{2 \sqrt{2 \pi} N_{e} r_{e}^{2} Z_{\Lambda}^{2} \Lambda_{C} L_{C S}}{\gamma^{4} \beta^{4}} \frac{m_{e}}{A_{i} m_{p}} \frac{1}{\sigma_{\theta e}^{2} \sigma_{\delta e}} \\
& h=\frac{\sqrt{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}}{\sigma_{x e}} \\
& \sigma_{1 x e}=\sqrt{\sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}
\end{align*}
$$

## 2 Cooling rate redistribution

### 2.1 General considerations

We assume that there is a non-zero horizontal ion dispersion in the cooling section $D_{i}$ and that in the CS $D_{i}^{\prime}=0$. We will further assume that $D_{i}$ is localized to the CS.

Let us denote all the coordinates of the ion upstream of the cooling section with an index " 0 ", at the entrance of the cooling section with an index " $C S$ ", and downstream of the cooling section with an index " 1 ".

We are interested in redistribution of cooling rate between the longitudinal and the horizontal directions. Derivation of the cooling rate for vertical direction (cooling without redistribution) can be found in [9].

We assume that the cooling is weak enough to produce the "velocity kick" only and not to change an ion's position through the CS. Then on a single pass through the CS the ion's coordinate $x$ changes as follows:

$$
\begin{align*}
& x_{i C S}=x_{i 0}+D_{i} \cdot \delta_{i 0} \\
& x_{i 1}=x_{i C S}-D_{i} \cdot\left(\delta_{i C S}+\Delta \delta_{i}\right)=x_{i C S}-D_{i} \cdot\left(\delta_{i 0}+\Delta \delta_{i}\right) \tag{15}
\end{align*}
$$

Combining Eqs. (15) and (14) we get:

$$
\begin{align*}
\Delta x_{i} & =c_{z} \cdot n_{e 1} \cdot D_{i} \cdot\left[\delta_{i 0}-k \cdot\left(x_{i 0}+D_{i} \cdot \delta_{i 0}\right)\right] \\
\Delta x_{i}^{\prime} & =-c_{x} \cdot n_{e 1} \cdot x_{i 0}^{\prime}  \tag{16}\\
\Delta \delta_{i} & =-c_{z} \cdot n_{e 1} \cdot\left[\delta_{i 0}-k \cdot\left(x_{i 0}+D_{i} \cdot \delta_{i 0}\right)\right]
\end{align*}
$$

Notice, that the density of the e-bunch "probed" by the considered ion in the CS is:

$$
\begin{equation*}
n_{e 1}=\frac{1}{(2 \pi)^{3 / 2} \sigma_{1 x e} \sigma_{y e} \sigma_{z e}} \exp \left[-\frac{\left(x_{i}+D_{i} \delta_{i}\right)^{2}}{2 \sigma_{1 x e}^{2}}-\frac{y_{i}^{2}}{2 \sigma_{y e}^{2}}-\frac{z_{i}^{2}}{2 \sigma_{z e}^{2}}\right] \tag{17}
\end{equation*}
$$

Next, an action $J_{x}$ characterizing horizontal motion of an ion is given by:

$$
\begin{equation*}
J_{x}=\frac{1}{2}\left(\gamma_{x} x_{i}^{2}+\beta_{x} x_{i}^{\prime 2}\right) \tag{18}
\end{equation*}
$$

where $\beta_{x}$ is a Twiss $\beta$-function, $\gamma_{x}=1 / \beta_{x}$ is the Twiss $\gamma$-function and we assumed that the ions' Twiss $\alpha$-function in the CS is equal to zero.

On a single pass through the cooling section, taking into account only the first order of small changes $\Delta x_{i}$ and $\Delta x_{i}^{\prime}$, we get:

$$
\begin{align*}
\Delta J_{x} & \approx \frac{x_{i 0} \Delta x_{i}}{\beta_{x}}+\beta_{x} x_{i 0}^{\prime} \Delta x_{i}^{\prime}= \\
& =\frac{c_{z} D_{i}}{\beta_{x}} n_{e 1}\left(x_{i 0} \delta_{i 0}\left(1-k D_{i}\right)-k x_{i 0}^{2}\right)-c_{x} n_{e 1} \beta_{x} x_{i 0}^{\prime 2} \tag{19}
\end{align*}
$$

We will further assume that the ions have a Gaussian distribution with the distribution function:

$$
\begin{equation*}
f_{i}=\frac{\exp \left(-\frac{x^{2}}{2 \sigma_{x i}^{2}}-\frac{y^{2}}{2 \sigma_{y i}^{2}}-\frac{z^{2}}{2 \sigma_{z i}^{2}}-\frac{x^{\prime 2}}{2 \sigma_{\theta x i}^{2}}-\frac{y^{\prime 2}}{2 \sigma_{\theta y i}^{2}}-\frac{\delta^{2}}{2 \sigma_{\delta i}^{2}}\right)}{(2 \pi)^{3} \sigma_{x i} \sigma_{y i} \sigma_{z i} \sigma_{\theta x i} \sigma_{\theta y i} \sigma_{\delta i}} \tag{20}
\end{equation*}
$$

where $\sigma_{x i} \sigma_{y i} \sigma_{z i}$ are the rms sizes of the ion bunch, $\sigma_{\theta x i}, \sigma_{\theta y i}$ are the ions' rms angular spreads, and $\sigma_{\delta i}$ is the ion bunch relative momentum spread in the CS.

Finally, the change in horizontal emittance on a single pass through the CS is given by:

$$
\begin{align*}
\Delta \varepsilon_{x} & =\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f_{i} \Delta J_{x} d x_{i} d y_{i} d z_{i} d x_{i}^{\prime} d y_{i}^{\prime} d \delta_{i}=  \tag{21}\\
& =\frac{1}{(2 \pi)^{7 / 2} \sigma_{x i} \sigma_{y i} \sigma_{z i} \sigma_{\delta i} \sigma_{1 x e} \sigma_{y e} \sigma_{z e}}\left(\frac{c_{z} D_{i}}{\beta_{x}} I_{1} I_{y} I_{z}-c_{x} \beta_{x} \sigma_{\theta x i}^{2} I_{2} I_{y} I_{z}\right)
\end{align*}
$$

Where integrals $I_{1}, I_{2}, I_{y}, I_{z}$ are given by the following expressions:

$$
\begin{align*}
I_{1} & =\int_{-\infty}^{\infty} \int_{-\infty}^{\infty}\left(x_{i} \delta_{i}\left(1-k D_{i}\right)-k x_{i}^{2}\right) \exp \left[-\frac{\left(x_{i}+D_{i} \delta_{i}\right)^{2}}{2 \sigma_{1 x e}^{2}}-\frac{x_{i}^{2}}{2 \sigma_{x i}^{2}}-\frac{\delta_{i}^{2}}{2 \sigma_{\delta i}^{2}}\right] d x_{i} d \delta_{i}= \\
& =-\frac{2 \pi \sigma_{1 x e} \sigma_{i j} \sigma_{x i}^{3}\left(D_{i} \sigma_{\delta i}^{2}+k \sigma_{1 x e}^{2}\right)}{\left(D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}\right)^{3 / 2}}  \tag{22}\\
I_{2}= & \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp \left[-\frac{\left(x_{i}+D_{i} \delta_{i}\right)^{2}}{2 \sigma_{1 x e}^{2}}-\frac{x_{i}^{2}}{2 \sigma_{x i}^{2}}-\frac{\delta_{i}^{2}}{2 \sigma_{\delta i}^{2}}\right] d x_{i} d \delta_{i}=\frac{2 \pi \sigma_{1 x e} \sigma_{\delta i} \sigma_{x i}}{\sqrt{D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}}} \tag{23}
\end{align*}
$$

$$
\begin{align*}
& I_{y}=\int_{-\infty}^{\infty} \exp \left(-\frac{y_{i}^{2}}{2 \sigma_{y e}^{2}}-\frac{y_{i}^{2}}{2 \sigma_{y i}^{2}}\right) d y_{i}=\frac{\sqrt{2 \pi} \sigma_{y e} \sigma_{y i}}{\sqrt{\sigma_{y i}^{2}+\sigma_{y e}^{2}}}  \tag{24}\\
& I_{z}=\int_{-\infty}^{\infty} \exp \left(-\frac{z_{i}^{2}}{2 \sigma_{z e}^{2}}-\frac{z_{i}^{2}}{2 \sigma_{z i}^{2}}\right) d z_{i}=\frac{\sqrt{2 \pi} \sigma_{z e} \sigma_{z i}}{\sqrt{\sigma_{z i}^{2}+\sigma_{z e}^{2}}} \tag{25}
\end{align*}
$$

Substituting Eqs. (22)-(25) into Eq. (21) we get:

$$
\begin{align*}
\frac{\Delta \varepsilon_{x}}{\varepsilon_{x}} & =-\frac{1}{(2 \pi)^{3 / 2} \sqrt{D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}} \sqrt{\sigma_{y i}^{2}+\sigma_{y e}^{2}} \sqrt{\sigma_{z i}^{2}+\sigma_{z e}^{2}}} .  \tag{26}\\
& \cdot\left(c_{x}+c_{z} \frac{D_{i}^{2} \sigma_{\delta i}^{2}+k D_{i} \sigma_{1 x e}^{2}}{D_{i i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}}\right)
\end{align*}
$$

Similar to above considerations, we introduce a longitudinal action $J_{z}$ :

$$
\begin{equation*}
J_{z}=\frac{1}{2}\left(\frac{z_{i}^{2}}{\beta_{z}}+\beta_{z} \delta_{i}^{2}\right) \tag{27}
\end{equation*}
$$

where $\beta_{z}=\sigma_{z i} / \sigma_{\delta i}$.
Then, for a single pass through the CS we get:

$$
\begin{equation*}
\Delta J_{z} \approx \beta_{z} \delta_{i 0} \Delta \delta_{i}=-c_{z} n_{e 1} \beta_{z}\left(\delta_{i 0}^{2}\left(1-k D_{i}\right)-k x_{i 0} \delta_{i 0}\right) \tag{28}
\end{equation*}
$$

The change in the longitudinal emittance $\left(\varepsilon_{z}=\sigma_{z i} \sigma_{\delta i}\right)$ on a single pass through the CS is given by:

$$
\begin{align*}
\Delta \varepsilon_{z} & =\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f_{i} \Delta J_{z} d x_{i} d y_{i} d z_{i} d x_{i}^{\prime} d y_{i}^{\prime} d \delta_{i}=  \tag{29}\\
& =\frac{-c_{z} \beta_{z}}{(2 \pi)^{7 / 2} \sigma_{x i} \sigma_{y i} \sigma_{z i} \sigma_{\delta i} \sigma_{1 x e} \sigma_{y e} \sigma_{z e}} I_{3} I_{y} I_{z}
\end{align*}
$$

where

$$
\begin{align*}
I_{3} & =\int_{-\infty}^{\infty} \int_{-\infty}^{\infty}\left(\delta_{i}^{2}\left(1-k D_{i}\right)-k x_{i} \delta_{i}\right) \exp \left[-\frac{\left(x_{i}+D_{i} \delta_{i}\right)^{2}}{2 \sigma_{1 x e}^{2}}-\frac{x_{i}^{2}}{2 \sigma_{x i}^{2}}-\frac{\delta_{i}^{2}}{2 \sigma_{\delta i}^{2}}\right] d x_{i} d \delta_{i}= \\
& =-\frac{\left.2 \pi \sigma_{1 x e} \sigma_{\delta i}^{3} \sigma_{x i}\left(\sigma_{x i}^{2}+\sigma_{1 x e}^{2}\right)(1-D i k)\right)}{\left(D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}\right)^{3 / 2}} \tag{30}
\end{align*}
$$

Substituting Eqs. (24), (25) and (30) into Eq. (29) we get:

$$
\begin{align*}
\frac{\Delta \varepsilon_{z}}{\varepsilon_{z}}= & -\frac{1}{(2 \pi)^{3 / 2} \sqrt{D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}} \sqrt{\sigma_{y i}^{2}+\sigma_{y e}^{2}} \sqrt{\sigma_{z i}^{2}+\sigma_{z e}^{2}}} \\
& \cdot\left(c_{z}-c_{z} \frac{D_{i}^{2} \sigma_{\delta i}^{2}+k D_{i} \sigma_{1 x e}^{2}}{D_{i}^{2} \sigma_{\delta i}^{2}+\sigma_{x i}^{2}+\sigma_{1 x e}^{2}}\right) \tag{31}
\end{align*}
$$

### 2.2 Explicit formulas for redistributed cooling rates

We can get the resulting horizontal and vertical cooling rates by dividing Eqs. (26) and (31) by a revolution period $T_{\text {rev }}=\frac{2 \pi R}{\beta c}$ :

Equations (32) give explicit expressions for the cooling rates for the case of $x-z$ redistribution. The plot of function $\Phi$ is shown in Fig. 11.

It is important to notice that function $\Phi$ is strongly nonlinear, as Fig. 1 demonstrates. Therefore, generally speaking, the rates $\lambda_{x}$ and $\lambda_{z}$ can not be


Figure 1: Function $\Phi(d)$.
represented as linear combinations of "undisturbed" cooling rates at $D_{e}=0$ and $D_{i}=0\left(\lambda_{x 0} \equiv \lambda_{x}\left(D_{e}=0, D_{i}=0\right), \lambda_{z 0} \equiv \lambda_{z}\left(D_{e}=0, D_{i}=0\right)\right)$.

Setting $D_{e}=0$ and $D_{i}=0$ we get a well expected result for $\lambda_{x 0}$ and $\lambda_{y 0}$ :

$$
\begin{align*}
& \lambda_{x 0}=-\frac{N_{e} r_{e}^{2} Z_{z}^{2} m_{e} c \Lambda_{C} \eta}{\pi \gamma^{4} \beta^{3} A_{i} m_{p} \sigma_{\theta e}^{2} \sigma_{\delta e} \sqrt{\left(\sigma_{x i}^{2}+\sigma_{e}^{2}\right)\left(\sigma_{i j}^{2}+\sigma_{y e}^{2}\right)\left(\sigma_{z i}^{2}+\sigma_{z e}^{2}\right)}} \Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{\theta e}}\right) \\
& \lambda_{z 0}=-\frac{2 N_{e} r_{e}^{2} Z_{i}^{2} m_{e} c \Lambda_{c i}}{\pi \gamma^{4} \beta^{3} A_{i} m_{p} \sigma_{\theta e}^{2} \sigma_{\delta e} \sqrt{\left(\sigma_{x i}^{2}+\sigma_{x e}^{2}\right)\left(\sigma_{y i}^{2}+\sigma_{y e}^{2}\right)\left(\sigma_{z i}^{2}+\sigma_{z e}^{2}\right)}}\left[1-\Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{\theta e}}\right)\right] \tag{33}
\end{align*}
$$

Finally, for the case of a small ion bunch placed at the center of an ebunch (i.e. when $\sigma_{x i}^{2}+D_{i}^{2} \sigma_{\delta i}^{2} \ll \sigma_{x e}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}$, $\sigma_{y i} \ll \sigma_{y e}, \sigma_{z i} \ll \sigma_{z e}$ ) Eqs. (32) are getting reduced to the form derived in [10]:

$$
\begin{align*}
& \lambda_{x}=\lambda_{1 x}+\frac{D_{i} D_{e} \sigma_{\delta e}^{2}}{\sigma_{x}^{2}+D_{e}^{2}} \lambda_{1 z}^{2} \sigma_{1 z}^{2} \\
& \lambda_{z}=\lambda_{1 z}-\frac{D_{i} D_{e} \sigma_{\delta e}^{2}}{\sigma_{x}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}} \lambda_{1 z} \\
& \lambda_{1 x}=\frac{N_{e} r_{e}^{2} m_{e} c Z^{2} L_{C \eta}}{\pi \gamma^{4} \beta^{3} A_{i} m_{p} \sigma_{x} \sigma_{y} \sigma_{z} \sigma_{\theta e}^{2} \sigma_{\delta e}} \Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{\theta e}} \frac{\sigma_{x}}{\sqrt{\sigma_{x}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}}\right)  \tag{34}\\
& \lambda_{1 z}=\frac{2 N_{e} r_{e}^{2} m_{e} C Z^{2} L_{C} \eta}{\pi \gamma^{4} \beta^{3} A_{i} m_{p} \sigma_{x} \sigma_{y} \sigma_{z} \sigma_{\theta e}^{2} \sigma_{\delta e}}\left[1-\Phi\left(\frac{\sigma_{\delta e}}{\gamma \sigma_{e e}} \frac{\sigma_{x}}{\sqrt{\sigma_{x}^{2}+D_{e}^{2} \sigma_{\delta e}^{2}}}\right)\right]
\end{align*}
$$

It is worth reminding our readers that formulas (33) and (34) give proper expressions (first derived in [11]) for the two classical asymptotic cases of the spherically symmetric ( $\Delta_{\perp}=\Delta_{z}$ ) and the flat ( $\Delta_{z} \ll \Delta_{\perp}$ ) e-velocity
distributions. For farther discussions of the asymptotic expressions please see [9] and [10].

## 3 Conclusion

We derived the explicit formulas (Eqs. 32) for the cooling rates redistribution in a non-magnetized electron cooler taking into account the non-uniformity of the density of the electron bunch.

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