Optimization of the Dechirper for Electron Bunches of Arbitrary Longitudinal Shapes

(How to use the dechirper as a deflector to measure arbitrary longitudinal structure of electron bunch)

Jimin Seok, Moses Chung
Ulsan National Institute of Science and Technology (UNIST)

Heung Sik Kang, Jang Hui Han, Ju Ho Hong
Pohang Accelerator Laboratory (PAL)
What is dechirper?

Dechirper is an interesting instrument consisting of a vacuum chamber of two corrugated, metallic plates with an adjustable gap.

One-meter long Dechirper at Pohang Accelerator Laboratory (PAL)

The corrugation is characterized by period $p$, height $h$, aspect ratio $h/t$, the gap of vacuum chamber $g=2a$ and width $w$. 

Side View

Front View
Recent dechirper studies

Corrugated pipe as a beam dechirper

K.L.F. Bane, G. Stupakov

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 690, 21 October 2012, Pages 106–110

Experimental Demonstration of Energy-Chirp Control in Relativistic Electron Bunches Using a Corrugated Pipe


Experimental Demonstration of Longitudinal Beam Phase-Space Linearizer in a Free-Electron Laser Facility by Corrugated Structures

Haixiao Deng, Meng Zhang, Chao Feng, Tong Zhang, Xingtao Wang, Taihe Lan, Lie Feng, Wenyuan Zhang, Xiaoqing Liu, Haifeng Yao, Lei Shen, Bin Li, Junqiang Zhang, Xuan Li, Wencheng Fang, Dan Wang, Marie-emmanuelle Couprie, Guoqiang Lin, Bo Liu, Qiang Gu, Dong Wang, and Zhentang Zhao

Phys. Rev. Lett. 113, 254802 – Published 19 December 2014

Electron beam energy chirp control with a rectangular corrugated structure at the Linac Coherent Light Source

Zhen Zhang, Karl Bane, Yuantao Ding, Zhirong Huang, Richard Iverson, Timothy Maxwell, Gennady Stupakov, and Lanfa Wang

Phys. Rev. ST Accel. Beams 18, 010702 – Published 30 January 2015

MOPOW044 Commissioning of the RadiaBeam / SLAC Dechirper

Marc Walter Guett, Karl Leopold Freitag Bane, Axel Brachmann, Alan Stephen Fisher, Zhirong Huang, Richard Iverson, Patrick Krejcik, Alberto Andrea Lutman, Timothy John Maxwell, Alexander Novokhatski, Gennady Stupakov (SLAC, Menlo Park, California), Mark Andrew Harrison, Marcos Ruelas (RadiaBeam Systems, Santa Monica, California), Johann Zemella (SLAC, Menlo Park, California; DESY, Hamburg), Zhen Zhang (SLAC, Menlo Park, California; TUB, Beijing)
Recent dechirper studies

Energy chirp control


Linearizer simulation outputs

Radiobeam/SLAC Dechirper

Installed in a running FEL facility (LCLS) Experimental results show:
- Electron energy chirp control
- Photon bandwidth control
- Transverse shaping of the electron beam
- Deflection by transverse wakefield

Energy-loss in Micro-bunches due to the longitudinal wakefield of the dechirper

More information see:
MOPOW044
MOPOW046
MOPOW049

courtesy of Marc Guetg
Dechirper test for deflector performance

Recently, Heung-Sik Kang of PAL proposed to use the dechirper as a deflector.

When the beam has an offset from the center of the dechirper, it acts like a deflector.

- w >> g
- Wakefield depends on geometry of dechirper.
- Voltage kick is convolution of wakefield and current.
- Quadropole wakefield is ignored at Eq (2). (Later, quadrupole effect will be included in terms of spread)

\[
W_y(s) = W_d(s)y_1 + W_q(s)y_t, \quad W_x = W_q(s)(x_1 - x_t), \quad (1)
\]

\[
V_y(t) \equiv y_l \int_{-\infty}^{t} W_d(t - t') * I(t')dt'. \quad (2)
\]

\[
W_y : y\text{-directional total wakefield} \quad W_x : x\text{-directional total wakefield}
\]

\[
W_d : \text{dipole wakefield} \quad W_q : \text{quadrupole wakefield}
\]

\[
V_y : Y\text{-directional voltage kick}
\]

\[
y_l, x_l : \text{offsets of leading one.} \quad y_t, x_t : \text{offsets of trailing one.}
\]

\[
I : \text{Normalized longitudinal beam current}
\]

\[
s : \text{distance between leading and trailing one.}
\]


(From Introduction to Wakefield and Wake Potentials P. B. Wilson)
Dechirper test for deflector performance

Dechirper deflects the beam non-linearly.
Head of the beam rarely have a voltage kick because there is no particle in front of the head.
The voltage kick is convolution of wakefield and current distribution.

(Heung-Sik Kang’s simulation data)
Dechirper test for deflector performance

**RF deflector** (Expensive RF system)

Deflecting Cavity

\[ x' = \arctan \left( \frac{qV_t}{E_0} \right) \sim \frac{qV_t}{E_0} \]

\[ x = R_{12} \frac{qV_t}{E_0} \]

\[ R_{12} : \text{transport matrix} \]

Dechirper test for deflector performance

**Dechirper** (Passive device)

Electron Bunches

From “RF Deflecting Mode Cavities Lecture 1 – Basic and Applications”, Dr. Graeme Burt
Dechirper test for deflector performance

Simulation outline

- **ELEGANT** used for dechirper simulation.
- **Longitudinal beam distribution** is assumed to be broad.
- Except the transverse beam distribution, **other conditions are fixed**.
ELEGANT simulation results

Fat beam ($\sigma_x$ and $\sigma_y$ are $2.8 \times 10^{-4}$ m, $\sigma_z = 0.45$ mm)

Pencil beam ($\sigma_x$ and $\sigma_y$ are $2.8 \times 10^{-7}$ m, $\sigma_z = 0.45$ mm)
How to reconstruct $I(t)$ from screen measurement

- The screen distribution is the only measurable information.
- Deflection is **non-linear** and longitudinal current distribution $I(t)$ is **unknown**.
- We reconstruct $I(t)$ by means of **iterative process**.

### Normalized Gaussian

$I_{\text{guess}}$

#### Step 1

**Calculate** $V_y$

#### Step 2

**Calculate** $y_2$

#### Step 3

**Get** $I_{\text{new}}$

#### Step 4

**Upadaing** $I_{\text{guess}}$

---

No transverse distribution, only for the pencil beam. Measured y-directional distribution on screen is $f(y)$.

- **Step 1**: Calculate the y-directional voltage kick using given current distribution.
  \[
  V_y(t) = y_l \int_{-\infty}^{t} W_d(t - t')I_{\text{guess}}(t')dt'
  \]

- **Step 2**: From the voltage kick, calculate the y position on the screen.
  \[
  y_2 = R_{34} \frac{qV(t)}{E}
  \]

- **Step 3**: Calculate new current distribution.
  \[
  I_{\text{new}}(t)dt = f(y)dy
  \]

- **Step 4**: Reconstruct with the value from Step 1 in terms of current distribution and current distribution from Step 3.
  \[
  I_{\text{re}} = I_{\text{new}} + \alpha(I_{\text{guess}} - I_{\text{new}}) \quad (\alpha: \text{Adjusting constant})
  \]

And Updating $I_{\text{guess}}$ as a reconstructed current $I_{\text{re}}$.

When loop is repeated enough, current converge to specific value.
Reconstruction: Case I

$$\sigma_z = 0.45\ \text{mm}$$ pencil beam $f(y)$ used at reconstruction.

Initial longitudinal current distribution: **Uniform-ellipse**
(r is iteration cycle of reconstruction and $I_o$ is original current)
Reconstruction: Case II

\[ \sigma_z = 0.45 \text{ mm pencil beam } f(y) \text{ used at reconstruction.} \]

Initial longitudinal current distribution: **Gaussian**
(r is iteration cycle of reconstruction and \( I_o \) is original current)
Effect of spread

- **Major components of spread distribution.**
  1. Transverse distribution of the beam.
  2. Quadrupole kick due to Dechirper.

- Reconstruction is only for **pencil beam** case.
- In order to adopt reconstruction at fat beam, spread distribution is required. Fat beam’s y directional distribution on screen $F(y)$ is convolution of pencil beam’s y directional distribution on screen $f(y)$ and spread distribution $\sigma_{spread}$.

\[
F(y) = \int_{-\infty}^{y} f(y - y')\sigma_{spread}(y')dy'
\]

**On screen: y-directional distribution**

- Calculated from MATLAB for Fat beam $F(y)$
- Spread distribution supposed as a normalized Gaussian

- **Pencil beam**

- **Fat beam**

*Graphs showing normalized frequency distribution for pencil and fat beams.*
Effect of spread

How to determine the spread distribution (in particular, experimentally).

1. Measure the beam distribution at screen **without the dechirper** → Transverse spread
2. Measure the beam distribution at screen with the dechirper and **no offset** → Quadrupole wake
3. Measure the beam distribution at screen with the dechirper and offset.

Estimation of spread distribution: \( a \sim \sqrt{\langle y^2 \rangle} \)

If spread is known, according to **convolution theorem**, we can get \( f(y) \).

\[
F(y) = \int_{-\infty}^{y} f(y - y') \sigma_{spread}(y') dy'
\]

\[
f_f(w) = \frac{F_f(w)}{\sigma_{f,spread}(w)}
\]

\[
F_f(w) = f_f(w) \sigma_{f,spread}(w)
\]

(Work in progress).
When beam length is long enough that the voltage kick’s gradient is negative, then it isn’t monotonic anymore.

In this situation, analysis of the beam becomes much more difficult.

We can handle 2-to-1 mapping by dividing $z$ into two regions. At each region, the function has 1-to-1 mapping (Work in progress).
Optimization of the dechirper as a deflector

- Wakefields are dependent on geometry of the dechirper.
- Maximizing the dipole wake and minimizing the quadrupole wake are desirable for the dechirper’s deflector performance.
- Total bunch length should be less than the first peak position of dipole wakefield. If not, we will have a long beam case in the previous slide.
- To avoid the long beam case, we should apply a shorter bunch.
- If a long bunch has to be measured, changing the dechirper geometry would be necessary.

Assumptions for dechirper calculation

1. \( w \gg g \),
2. \( p, h \ll a \),
3. \( h \geq p \), (steeply corrugated)
4. \( 0 < kz \leq 3\pi \), (\( k \): wave number of test charge as a pure cosine oscillation, \( z \): distance between leading and trailing particles).
Optimization of the dechirper as a deflector

\[ a=3 \text{ mm}, \ h=1.0 \text{ mm}, \ t=1.0 \text{ mm}, \ p=0.5 \text{ mm} \]

\[ a=3 \text{ mm}, \ h=1.2 \text{ mm}, \ t=0.4 \text{ mm}, \ p=0.5 \text{ mm} \]
Optimization of the dechirper as a deflector

- The wakefield calculation of dechirper by G. Stupakov’s model.
- Transverse wake functions, $W_d(s)$ and $W_q(s)$; both functions depend on the gap as $\propto a^{-4}$ (Experimental Demonstration of Energy-Chirp Control in Relativistic Electron Bunches Using a Corrugated Pipe, P. Emma, et al, phys. Rev. Lett. 112, 034801 – Published 23 January 2014)
- The half gap $a$ is adjustable using two different motors on each plate.
- Except $a$, other parameters are fixed once a dechirper is installed, but simulation facilitates various structures of the dechirper.
- The dechirper assumption is the condition for the corrugated vacuum chamber used as energy chirp control and linearizer, not as a deflector.
- One of the future works would be numerical calculation for transverse wakefield for maximizing the performance as a deflector of the dechirper.
• Dechirper has been actively studied by experts worldwide.
• Dechirper also performs as a transverse deflector.
• However, a non-linearity of the deflection is much stronger than the case with the RF deflector.
• Using ELEGANT simulation, the characteristics of the dechirper as a deflector has been investigated.
• A reconstruction method has been proposed to determine the longitudinal beam current distribution.
• Spread distribution includes three main components such as transverse beam distribution, quadrupole kick, and blurring effect.
• The screen measurement of the fat beam is indeed the convolution of pencil beam screen measurement and spread distribution.
• For long beam case, the non-linearity is much stronger than the other cases, and voltage kick is no longer monotonic.
• Further optimization of the dechirper as a deflector requires advanced studies with numerical calculation of the transverse wakefield in the dechirper.
Thank You