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)

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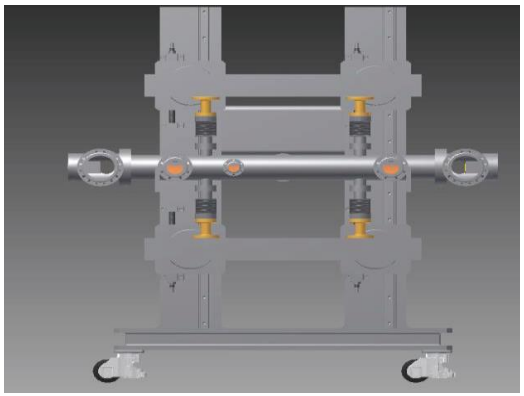
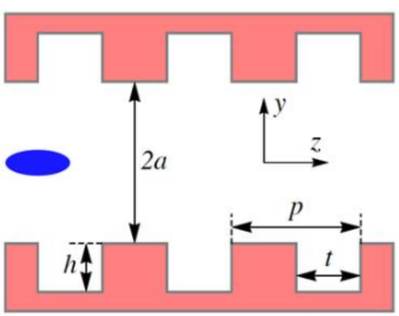
What is dechirper?

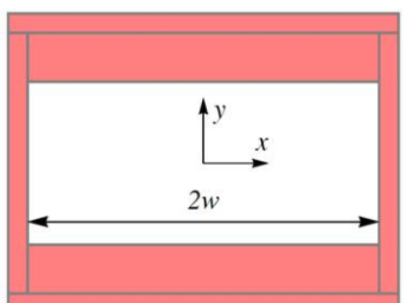
Dechirper is an interesting instrument consisting of a vacuum chamber of two corrugated, metallic plates with an adjustable gap.



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



Side View



Front View

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

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
P. Emma, M. Venturini, K. L. F. Bane, G. Stupakov, H.-S. Kang, M. S. Chae, J. Hong, C.-K. Min, H. Yang, T. Ha, W. W. Lee, C. D. Park, S. J. Park, and I. S. Ko
Phys. Rev. Lett. 112, 034801 – Published 23 January 2014

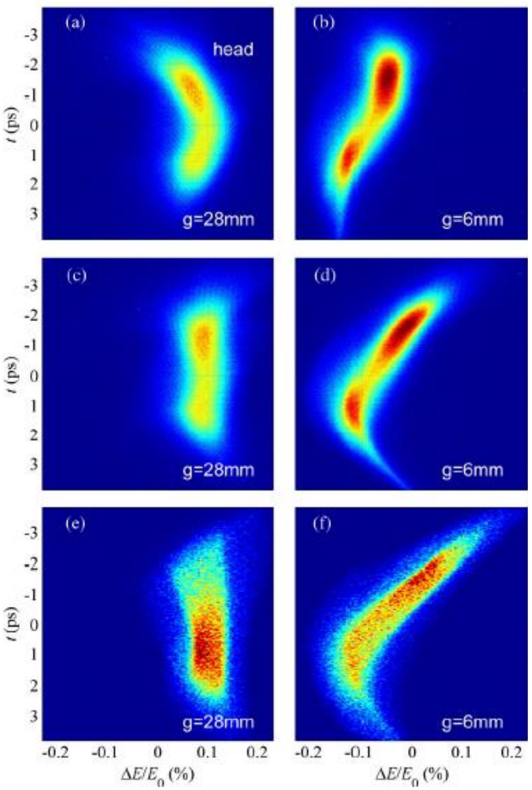
Experimental Demonstration of Longitudinal Beam Phase-Space Linearizer in a Free-Electron Laser Facility by Corrugated Structures
Haixiao Deng, Meng Zhang, Chao Feng, Tong Zhang, Xingtao Wang, Taihe Lan, Lie Feng, Wenyan Zhang, Xiaoqing Liu, Haifeng Yao, Lei Shen, Bin Li, Junqiang Zhang, Xuan Li, Wencheng 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

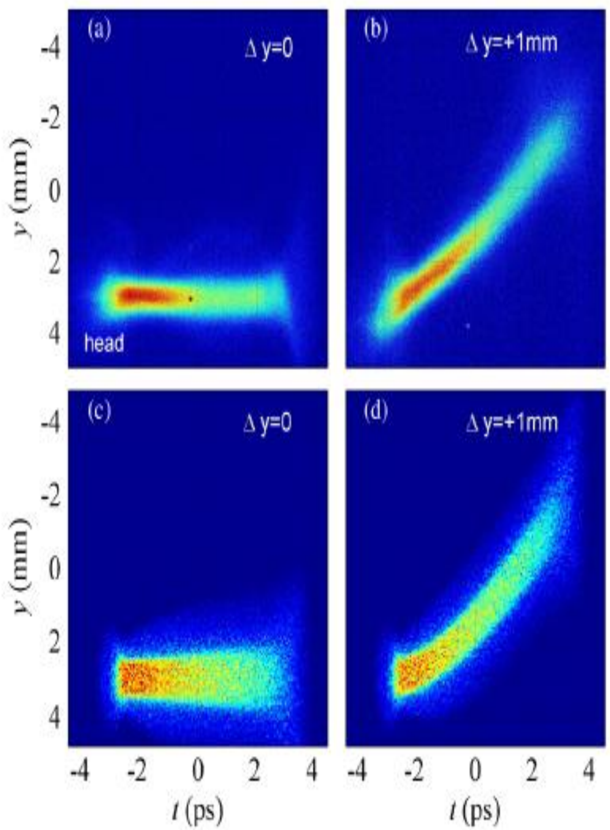
Electron beam energy chirp control with a rectangular corrugated structure at the Linac Coherent Light Source
Zhen Zhang, Karl Bane, Yuantao Ding, Zhirong Huang, Richard Iverson, Timothy Maxwell, Gennady Stupakov, and Lanfa Wang
Phys. Rev. ST Accel. Beams 18, 010702 – Published 30 January 2015

MOPOW044 Commissioning of the RadiaBeam / SLAC Dechirper
Marc Walter Guetg, 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

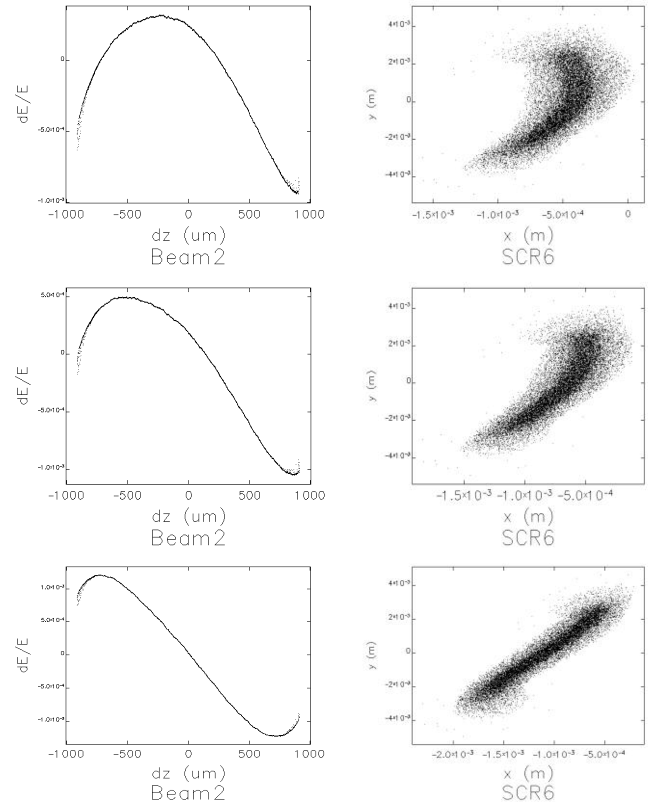
Energy chirp control





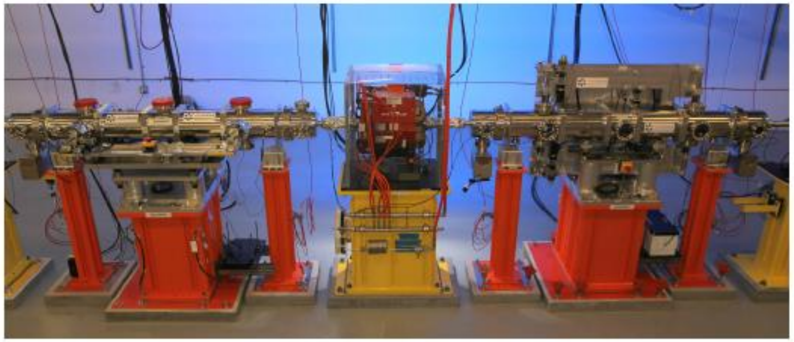
Experimental Demonstration of Energy-Chirp Control in Relativistic Electron Bunches Using a Corrugated Pipe, P. Emma, *et al*, Phys. Rev. Lett. 112, 034801 – Published 23 January 2014

Linearizer simulation outputs



Kang, H.S. *et al*, A BEAM TEST OF CORRUGATED STRUCTURE FOR PASSIVE LINEARIZER. *Proc. FEL Conf.* 2014 paper TUP093 (2014)

Radiabeam/SLAC Dechirper

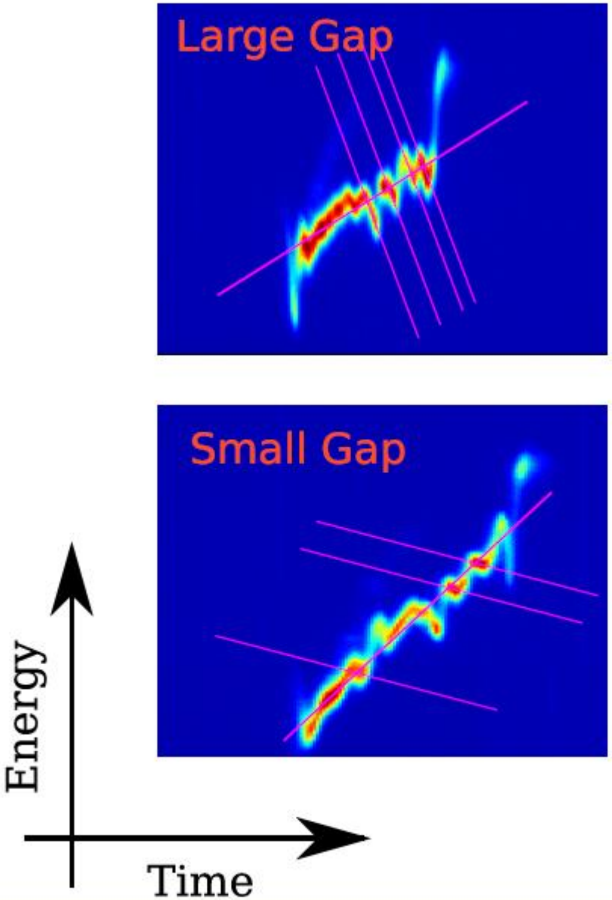


Installed in a running FEL facility (LCLS)
Experimental results show:
- Electron energy chirp control
- Photon bandwidth control
- Transverse shaping of the electron beam
- Deflection by transverse wakefield

More information see:

MOPOW044
MOPOW046
MOPOW049

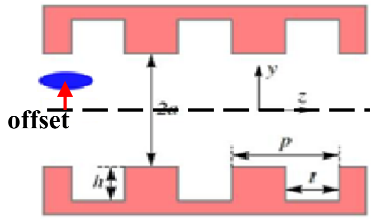
Energy-loss in Micro-bunches due to the longitudinal wakefield of the dechirper



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)

(From 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)

$$W_y(s) = W_d(s)y_l + W_q(s)y_t, \quad W_x = W_q(s)(x_l - x_t), \qquad (1)$$

$$V_y(t) \cong y_l \int_{-\infty}^{t} W_d(t-t') * I(t')dt'. \qquad (2)$$

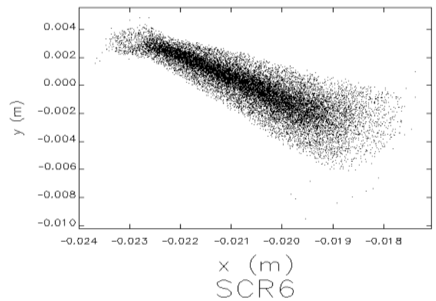
(From Introduction to Wakefield and Wake Potentials P. B. Wilson)

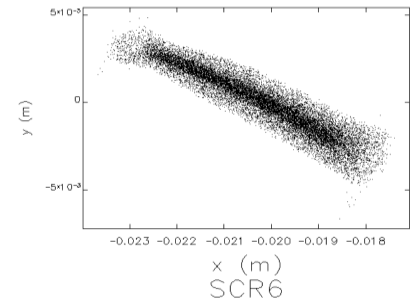
W_y : y-directional total wakefield **W_x : x-directional total wakefield**
W_d : dipole wakefield **W_q : quadrupole wakfield**
V_y : Y-directional voltage kick
y_l, x_l : offsets of leading one. **y_t, x_t : offsets of trailing one.**
I : Normalized longitudinal beam current
s : distance between leading and trailing one.

Dechirper test for deflector performance

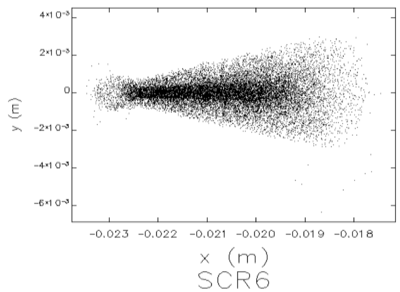
With RF deflector ON

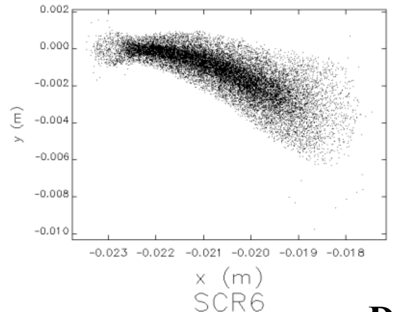
Dechirper a= 3 mm, offset= 0   a =4 mm, offset=0

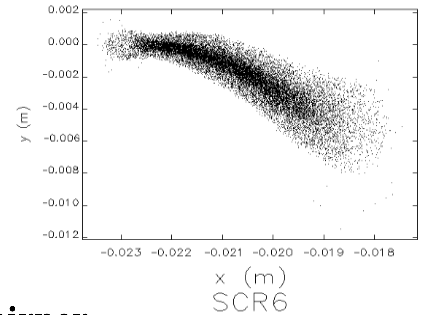


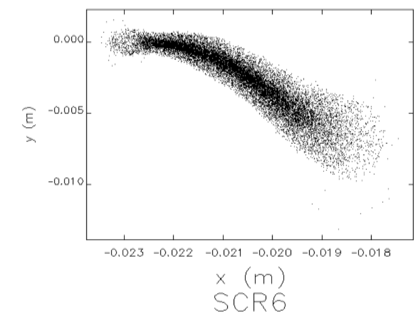


With RF deflector OFF









Dechirper

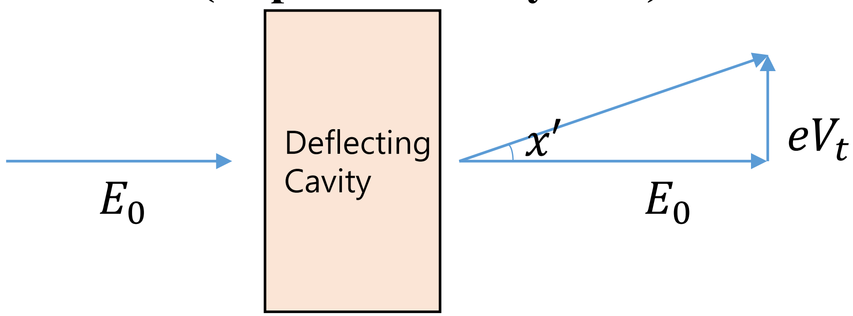
a =3 mm, offset=0   a =3 mm, offset=1 mm   a =3 mm, offset=1.5 mm   a = 3mm, offset=2 mm

(Heung-Sik Kang's simulation data)

- 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.

Dechirper test for deflector performance

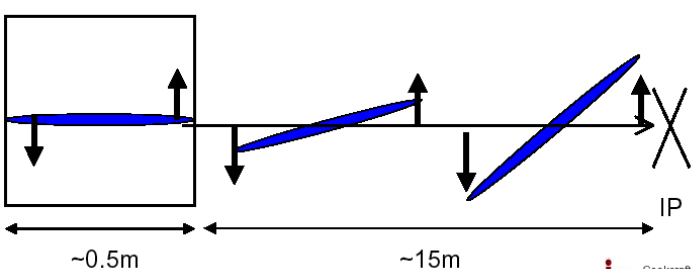
RF deflector
(Expensive RF system)



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

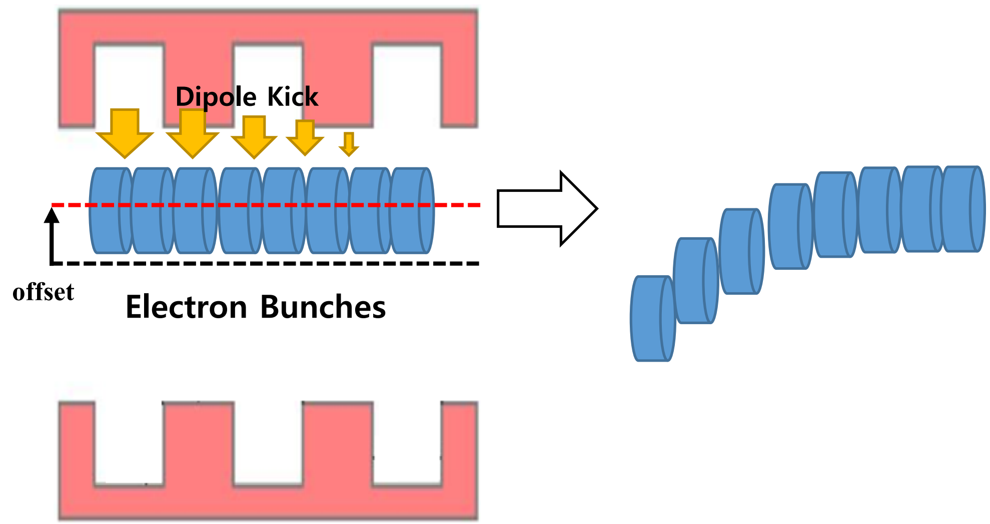
$$x = R_{12}\frac{qV_t}{E_0}$$

R_{12} :transport matrix

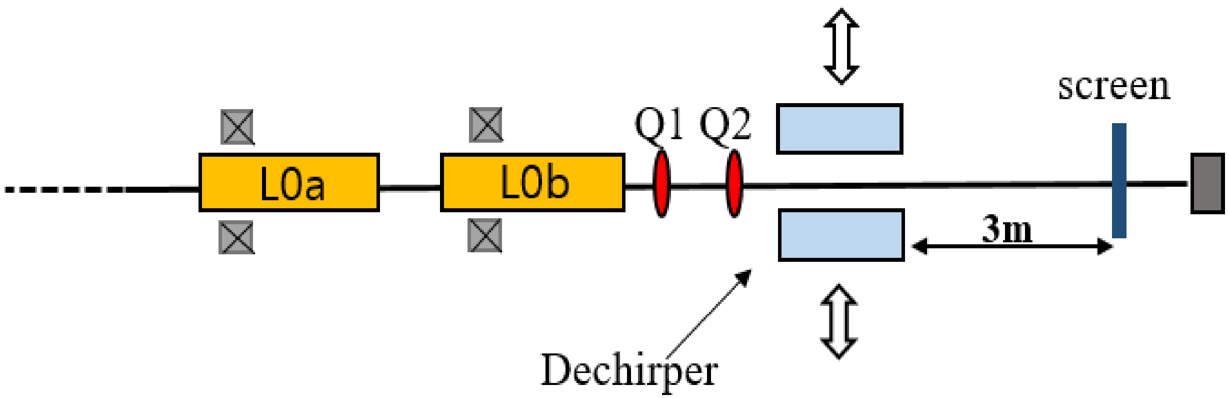


From "RF Deflecting Mode Cavities Lecture 1 –Basic and Applications", Dr. Graeme Burt

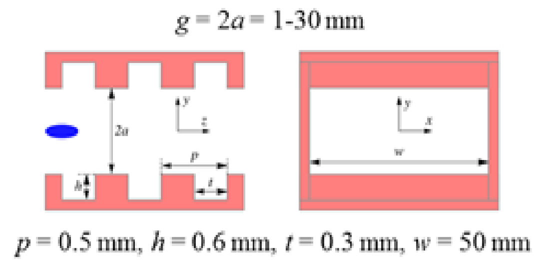
Dechirper
(Passive device)



Dechirper test for deflector performance



Simulation outline

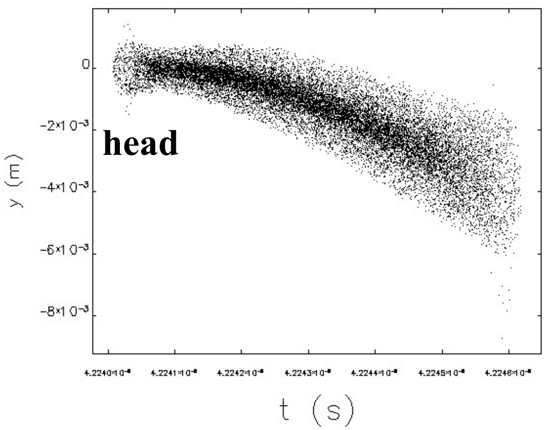


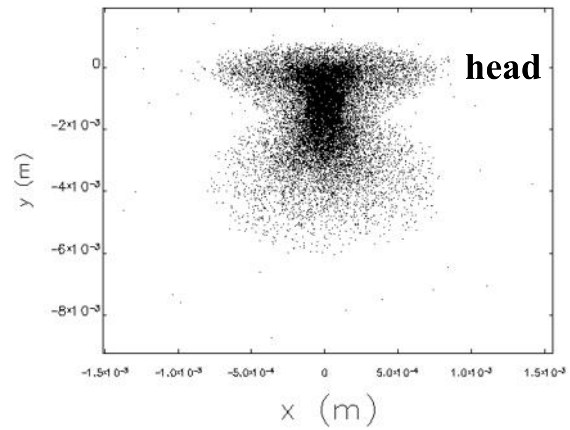
Characteristic of dechirper
a=3mm
h=0.6 mm
t=0.3 mm
p= 0.5 mm

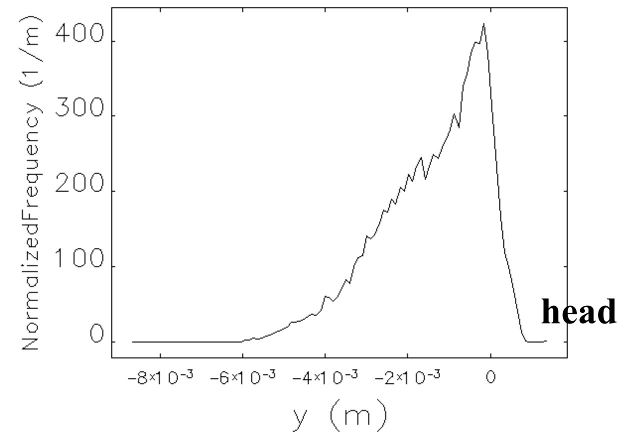
- **ELEGANT** used for **dechirper** simulation.
- **Longitudinal beam distribution** is assumed to be broad.
- Except the transverse beam distribution, **other conditions are fixed.**

ELEGANT simulation results

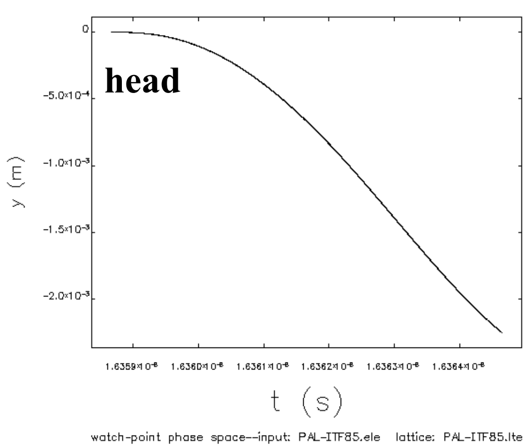
Fat beam (σ_x and σ_y are 2.8×10^{-4} m, $\sigma_z = 0.45$ mm)

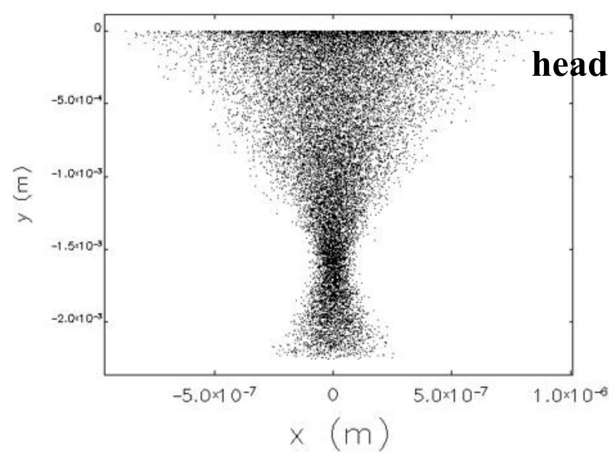


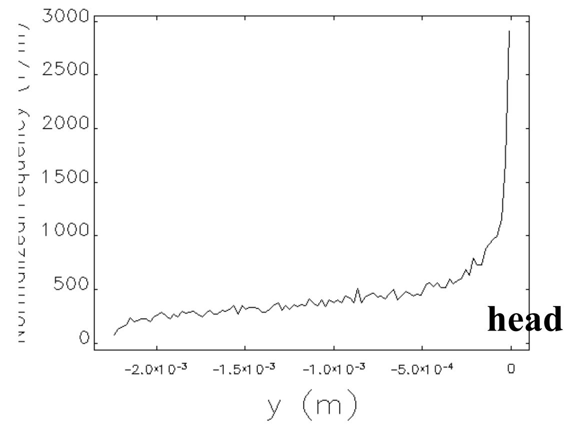




Pencil beam (σ_x and σ_y are 2.8×10^{-7} m, $\sigma_z = 0.45$ mm)

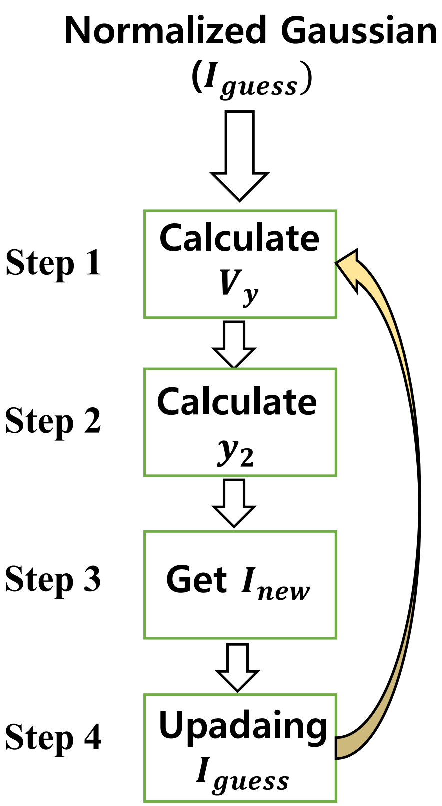






How to reconstruct I(t) from screen measurement

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



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.**

$$V_y(t) = y_l \int_{-\infty}^{t} W_d(t-t') I_{guess}(t') dt'$$

- **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.**

$$I_{new}(t)dt = f(y)dy$$

- **Step 4 : Reconstruct with the value from Step 1 in terms of current distribution and current distribution from Step 3 .**

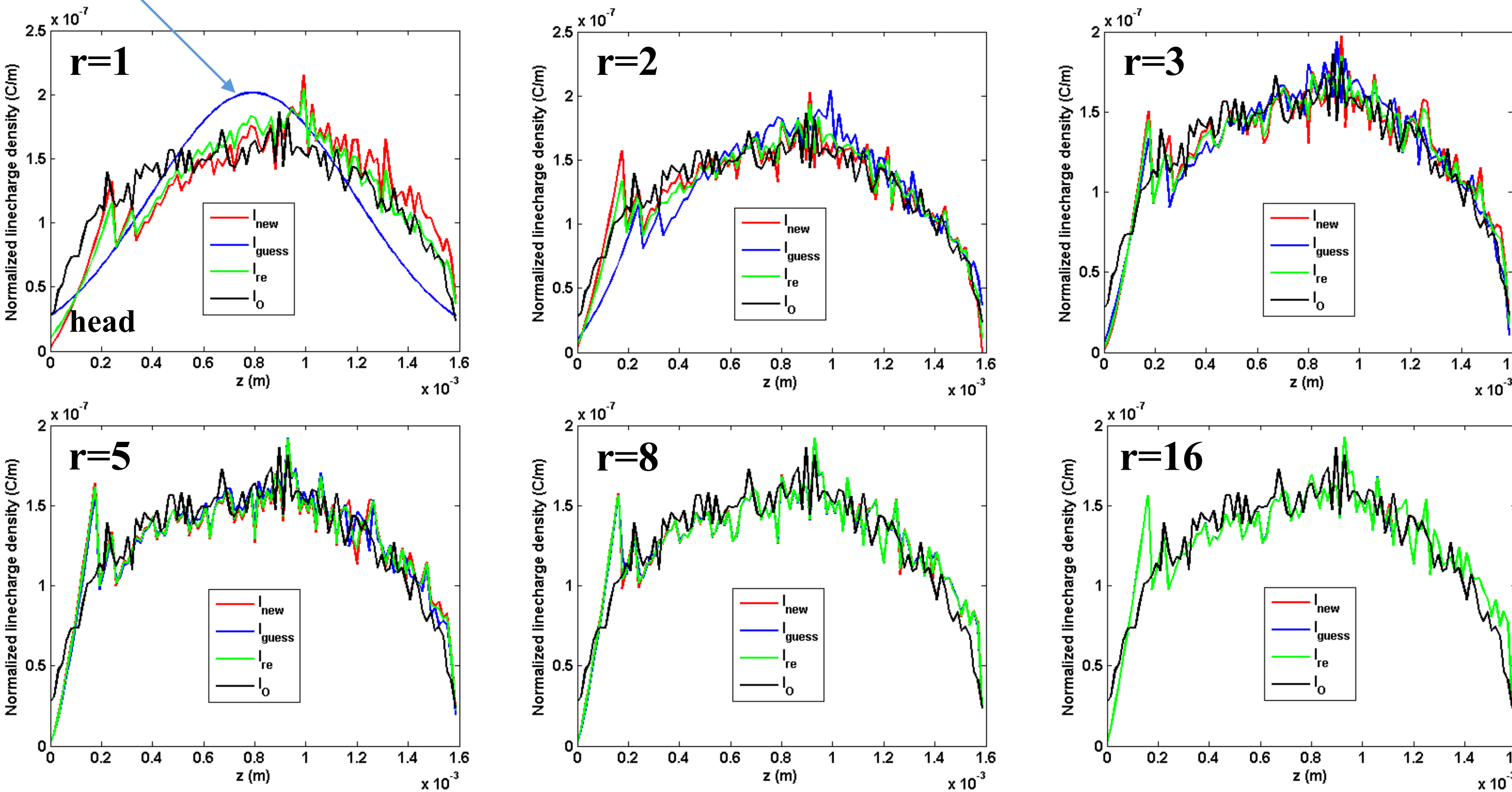
$$I_{re} = I_{new} + \alpha\left(I_{guess} - I_{new}\right) \quad (\alpha : Adjusting\ constant)$$

And Updating I_{guess} as a reconstructed current I_{re} .
When loop is repeated enough, current converge to specific value.

Reconstruction: Case I

First guessed normalized Gaussian current dist.

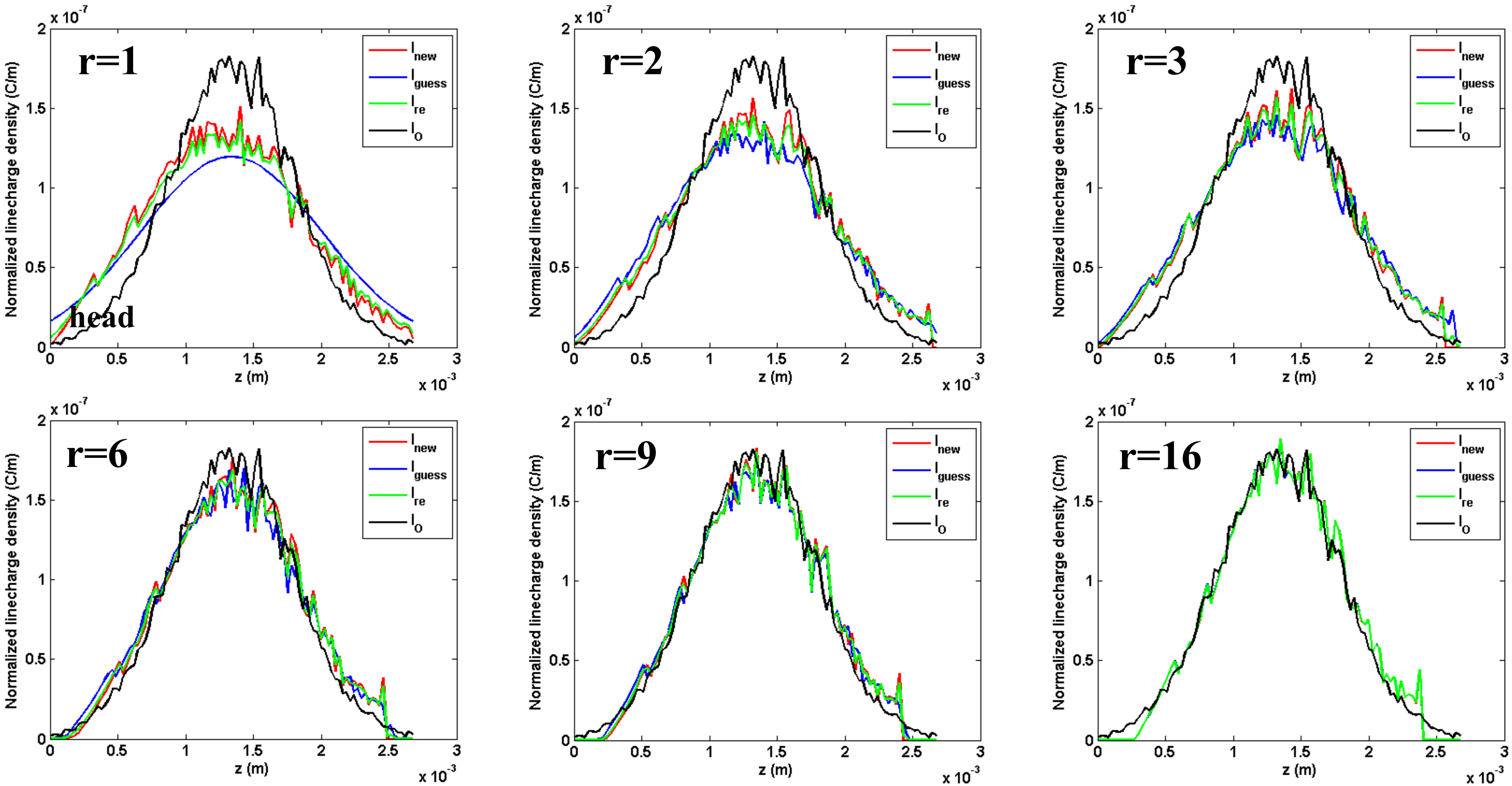
σ_z = 0.45 mm pencil beam f(y) used at reconstruction.



Initial longitudinal current distribution: Uniform-ellipse
(r is iteration cycle of reconstruction and I_o is original current)

Reconstruction: Case II

σ_z = 0.45 mm pencil beam f(y) used at reconstruction.



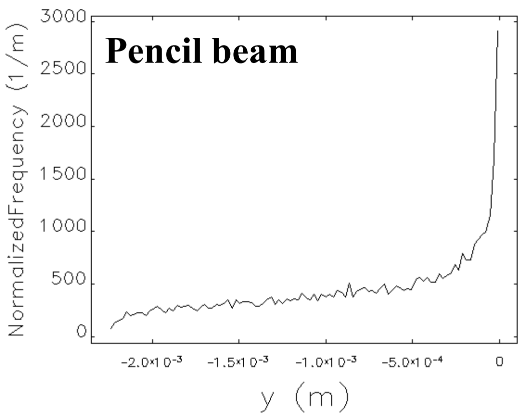
Initial longitudinal current distribution: Gaussian

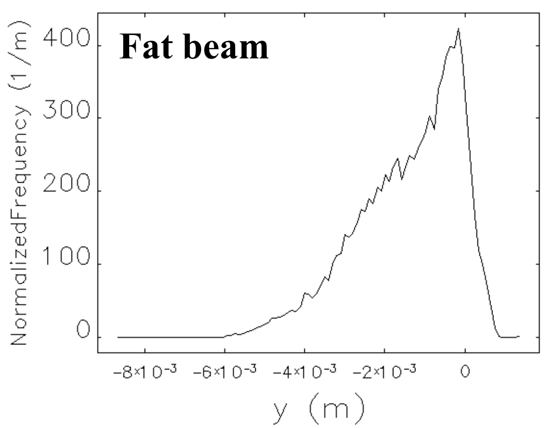
(r is iteration cycle of reconstruction and I_o is original current)

Effect of spread

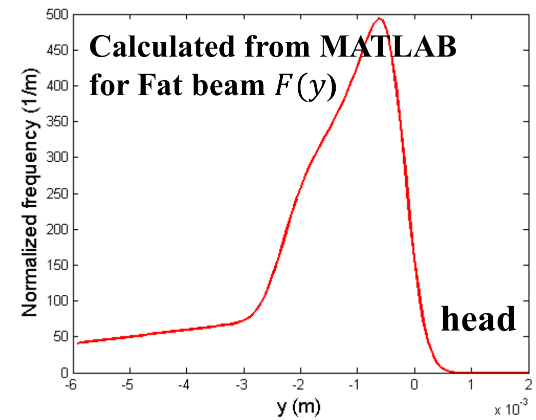
- **Major components of spread distribution.**
  1. Transverse distribution of the beam.
  2. Quadrupole kick due to Dechirper.
  3. Blurring effect.
- Reconstruction is only for **pencil beam** case.
- In order to adopt reconstruction at fat beam, spread distribution is required. Fat beam's y directional distribution on screen $F(y)$ is convolution of pencil beam's y directional distribution on screen $f(y)$ and spread distribution σ_{spread}.

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





On screen: y-directional distribution



Spread distribution supposed as a normalized Gaussian

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: $a \sim \sqrt{< y^2 >}$

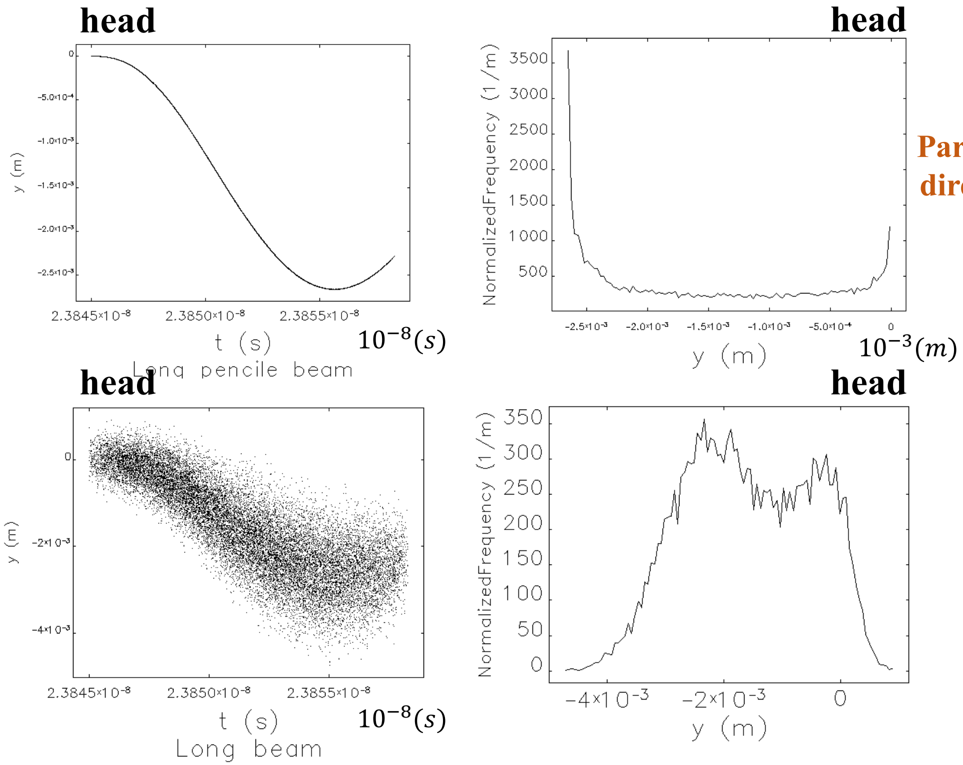
If spread is known, according to **convolution theorem**, we can get $f(y)$.

$$F(y) = \int_{-\infty}^{y} f(y - y')\sigma_{spread(y')} dy' \quad \xrightarrow{\text{Fourier transform}} \quad F_f(w) = f_f(w)\sigma_{f,spread}(w)$$

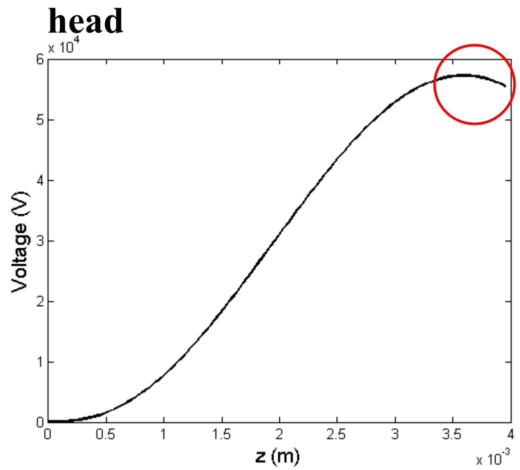
$$f_f(w) = \frac{F_f(w)}{\sigma_{f,spread}(w)} \quad \xrightarrow{\text{Inverse Fourier transform}} \quad f(y)$$

(Work in progress).

Long Beam Case



Particles experienced y-directional voltage kick

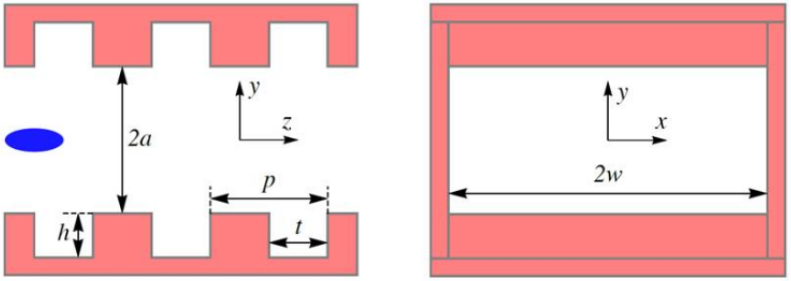


When dV/dz is negative, voltage kick is no longer a monotonic function (2 to 1 mapping).

- 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 become 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

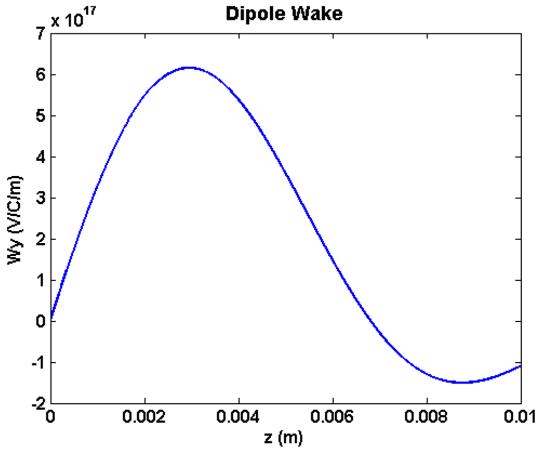
- Wakefields are dependent on geometry of the dechirper.
- Maximizing the dipole wake and minimizing the quadrupole wake are desirable for the dechirper's deflector performance.
- Total bunch length should be less than the first peak position of dipole wakefield. If not, we will have a long beam case 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.

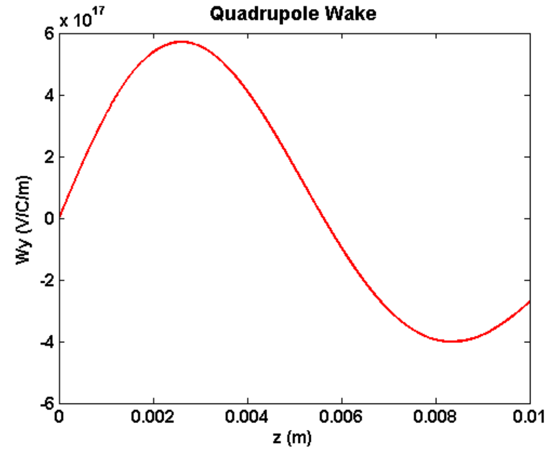


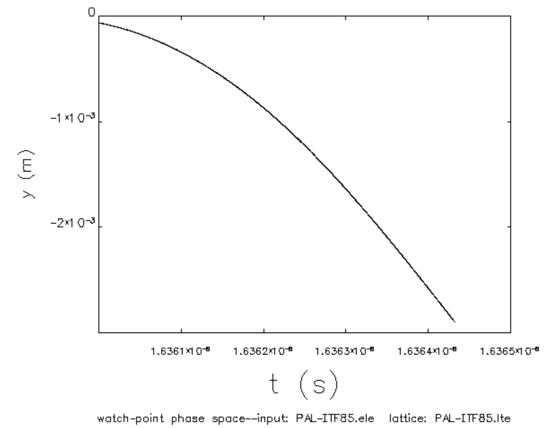
Assumptions for dechirper calculation

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*).

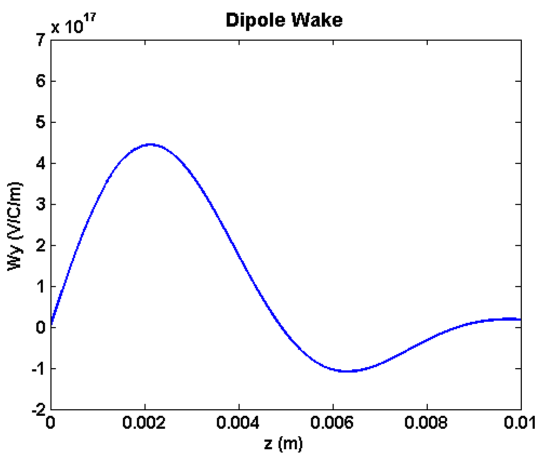
Optimization of the dechirper as a deflector

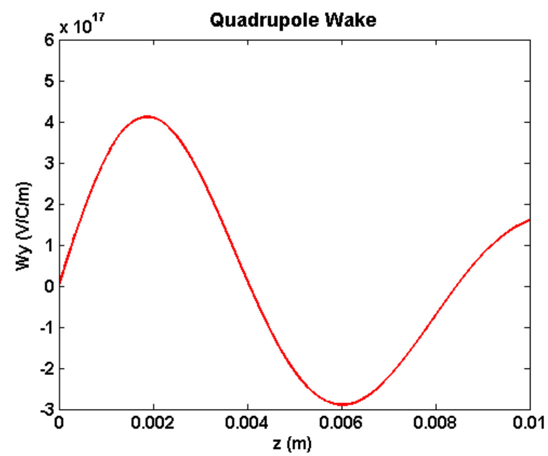


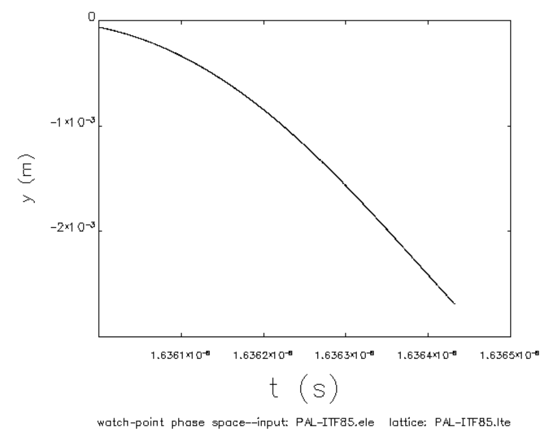




a=3 mm, h=1.0 mm, t=1.0 mm, p= 0.5 mm







a=3 mm, h=1.2 mm, t=0.4 mm, p= 0.5 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.

Summary

- 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