Transverse-to-longitudinal emittance-exchange with an energy chirped beam
Outline of the talk

Motivation

Emittance exchange beamline
  – Diagnostics
  – Measurements

Experimental results of emittance exchange
  – Energy-chirped beam
Motivation

• X-ray FELs demand ultra-low transverse emittance beam*

• State-of-the art photo-injectors can generate low 6-D emittance. Typically asymmetric emittances. Emittance exchange can swap transverse with the longitudinal emittance.

• Allows one to convert transverse modulations to longitudinal modulations : Beam shaping application

• Can also be used to suppress microbunching instability**

Emittance exchange: Concept

\[ R = \begin{pmatrix} 0 & \frac{Lc}{4} & -(4L + Lc) \frac{1}{4\eta} & -\frac{\alpha(4L + Lc)}{4} \\ 0 & 0 & -1 \frac{1}{\eta} & -\alpha \\ -\alpha & \frac{\alpha(4L + Lc)}{4} & \frac{\alpha Lc}{4\eta} & \frac{\alpha^2 Lc}{4} \\ \frac{1}{\eta} & -(4L + Lc) \frac{1}{4\eta} & \frac{\alpha Lc}{4\eta^2} & \frac{\alpha Lc}{4\eta} \end{pmatrix} \]

\[ \alpha : \text{Bending angle} \]
\[ \eta : \text{dispersion of dogleg} \]
\[ L : \text{Length of the dogleg} \]
\[ Lc : \text{Length of the 5-cell} \]
\[ \kappa = \frac{-1}{\eta} : \text{Condition for EEX} \]

\[ \frac{1}{4} \]
Fermilab A0 photoinjector: Emittance exchange

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>1.3 GHz NC</td>
</tr>
<tr>
<td>Accelerating Cavity</td>
<td>1.3 GHz SC</td>
</tr>
<tr>
<td>Deflecting cavity</td>
<td>3.9 GHz NC</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>100 pC – 1 nC</td>
</tr>
<tr>
<td>Energy</td>
<td>14.3 MeV</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>~ 3 ps</td>
</tr>
<tr>
<td>Energy spread (rms)</td>
<td>~ 10 KeV</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Typical number of bunches in a train</td>
<td>~ 100</td>
</tr>
</tbody>
</table>
Emittance measurement diagnostics and techniques

- **Beam size:** OTR and YAG screens
- **Bunch length:** Streak or Interferometer
- **Energy spread:** Spectrometer magnet and a screen
- **Transverse emittance:** Multi-slit method
- **Longitudinal emittance:** Product of minimum energy spread and bunch length (upper limit)
GUI to extract Courant-Snyder parameters

Select File: /scratch/Amber

Emittance Cross: X03
Number To Average: 5

Get Images, Take New Background, View Images

Transverse Beam Profile

Rotation: 0.0, Raden Peak: 8951

Vertical, New Fit, Fit Again
Size Image Sigmas: 20.0
Background, Flat

Averaging Individual...


g1: Amp +/- 7.95, Mean +/- 0.0436, Sigma +/- 384, 1.72, 56.6, 1.05
Con: 0.207, 0.0115, 0, 0, 0, 0, 0, 0
Bck: 0.124, 0.048, 0, 0, 0, 0, 0, 0

dof: ch/n +/dof 0, 0, 0, 0, 0, 0, 0, 0

Slit Image Cross: X06
Number To Average: 5

Get Images, Take New Background, View Images

Slit Image

Rotation: 0.0, Raden Peak: 1.12e+04

Vertical, New Fit, Fit Again
Size Image Sigmas: 5.0
Background, Quadratic

Averaging Individual...


g1: Amp +/- 4.76, Mean +/- 0.0119, Sigma +/- 234, 0.484, 4.73, 0.183
Con: 16.5, 0.722, 330, 0.322, 4.56, 0.0692
Bck: 9.92, 0.721, 356, 0.14, 3.89, 0.163

G4: 12.4, 0.524, 404, 0.25, 4.85, 0.12
C5: 6.56, 0.152, 437, 0.22, 4.4, 0.16

X Emittance Analysis

Camera Calib Date: 07-Oct-2011
Slit Gaussians

Slit Numbers: 123456

Transverse Phase Space

Angle (mrad)

Position (mm)

Angle (mrad)

Position (mm)

α = 0.698 ± 0.11, β = 17.1 ± 0.96

0.0869 ± 0.01

Bunch Size (mm): 1.572 ± 0.034
Bunch Divergence (mrad): 0.09187 ± 0.0021

Beam Energy (MeV): 13.2
Emittance (mm-mrad): 3.88 ± 0.12
1 RF – scan to locate minimum energy spread i.e. no chirp
2 Streak camera to measure bunch length (Longitudinal emittance)
3 X-Slits and Y-slits to measure the transverse emittances (X3)
4 Tune quadrupoles to maximize CTR radiation thus minimizing the bunchlength. Tune quadrupoles to minimize energy spread at XS4. Finer scan along the minimum values.
5 X-slits and Y-slits to measure outgoing transverse emittance (X23)
First Observation of the Exchange of Transverse and Longitudinal Emittances


Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 16 February 2011; published 17 June 2011)

An experimental program to demonstrate a novel phase-space manipulation in which the horizontal and
Message: Chirped beam has improved performance

- Emittance-exchanger
  - Improved performance
  - Minimizes thick lens effect
How to minimize thick lens effect?

Minimize this term: 

\[ \langle z^2 \rangle + \alpha^2 D^2 \langle \delta^2 \rangle + 2\alpha D \langle z\delta \rangle \]

Introduce correlation: \( \delta =_hz \)

then:

\[ \langle z^2 \rangle + \alpha^2 D^2 h^2 \langle z^2 \rangle + 2\alpha h D < z^2 > \]

\[ \Rightarrow h = \frac{-1}{\alpha D} \] will make this term zero.

In other words, set Chirp to \(-1/R_{56}\)

Effect of chirp on the R-matrix

\[ R = \begin{pmatrix}
0 & \frac{Lc}{4} & \frac{-(4L + Lc)}{4\eta} & \eta - \frac{\alpha(4L + Lc)}{4} \\
0 & 0 & -\frac{1}{\eta} & -\alpha \\
-\alpha & \eta - \frac{\alpha(4L + Lc)}{4} & \frac{\alpha Lc}{4\eta} & \frac{\alpha^2 Lc}{4} \\
-\frac{1}{\eta} & \frac{-(4L + Lc)}{4\eta} & \frac{\alpha Lc}{4\eta^2} & \frac{\alpha Lc}{4\eta}
\end{pmatrix} \]
Minimize thick lens effect: Add energy chirp

<table>
<thead>
<tr>
<th>Chirp</th>
<th>RF-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-30</td>
</tr>
<tr>
<td>2.0</td>
<td>-35</td>
</tr>
<tr>
<td>4.5</td>
<td>-40</td>
</tr>
<tr>
<td>7.7</td>
<td>-45</td>
</tr>
</tbody>
</table>

Pick 9-cell phase to introduce chirp

Look for bunch length, transverse beam size, emittances (x and z)

Chirp RF-phase

$$\text{chirp} = \frac{d \delta}{dz} = \frac{(2\pi/\lambda)eV_0 \sin \phi}{E_0 + eV_0 \cos \phi}$$
Chirped beam study: Streak camera

- Bunch length after EEX (ps) [r.m.s.]
- Quadrupole current before EEX (A)

- Simulation
- Streak Camera Measurement

Approximate streak camera resolution
Finer quadrupole scan using interferometer pyros

- Pyro signal increases ~ by a factor of 2
Interferometer measurement

Bunch length reduction ~ 2
CSR Power (pyrometer) Vs RF Phase (bunchlength)
Emittance exchange with chirped beam

- Energy: 13.2 MeV
- Charge: 400 pC
- Emit x: 4 um
- Emit z: 20 um

250 pC; PRL 106, 244801 (2011)
Emittance exchange simulation with GPT

Energy: 13.2 MeV
Charge: 400 pC
Emit x: 4 um
Emit z: 20 um
Alternative schemes to EEX

- Use two deflecting cavity to compensate thick lens effect
- Can also use single accelerating cavity to compensate the thick lens effect (A. Zholents APS Note LS 327)
- Chicane style possible with some modifications to the doglegs (D. Xiang Phys. Rev. ST Accel. Beams 14, 114001)
- Being pursued for Advanced Superconducting Test Accelerator (ASTA) facility at 40 MeV.
Summary

• Emittance exchange with an energy-chirped beam shows improved performance. Emittance dilution still exists.

• Next generation EEX has to take into account the thick lens cavity with modification to exchange lattice.

• Simulations are being done for studying a chicane-style emittance exchange at the Advanced Superconducting Test Accelerator (ASTA) facility @ 40 MeV.