Experimental studies on an emittance exchange beamline at the A0 photoinjector

J. C. T. Thangaraj  
Fermi National Accelerator Laboratory, Batavia, Illinois
Outline of the talk

Motivation

I. Emittance exchange beamline
   – Diagnostics
   – Measurements

II. Coherent synchrotron radiation studies
   – Detection and characterization of radiation
   – Studies on the electron beam

III. Experimental results of emittance exchange with chirped beam

Next-generation emittance exchangers
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 beamline

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

- \( \alpha \): Bending angle
- \( \eta \): Dispersion of dogleg
- \( L \): Length of the dogleg
- \( Lc \): Length of the 5-cell

\[ \kappa = \frac{-1}{\eta} : \text{Condition for EEX} \]
Fermilab A0 photoinjector: Emittance exchange

<table>
<thead>
<tr>
<th></th>
<th>Charge per bunch</th>
<th>Energy</th>
<th>Bunch length (rms)</th>
<th>Energy spread (rms)</th>
<th>Rep. rate</th>
<th>Typical number of bunches in a train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun</td>
<td>100 pC – 1 nC</td>
<td>14.3 MeV</td>
<td>~ 3 ps</td>
<td>~ 10 KeV</td>
<td>1 Hz</td>
<td>~ 100</td>
</tr>
<tr>
<td>Accelerating Cavity</td>
<td>1.3 GHz SC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflecting cavity</td>
<td>3.9 GHz NC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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
The A0 photoinjector: Machine tuning

Varying quadrupoles here changes bunchlength here

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 emittance exchange

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

An Observation of a Transverse to Longitudinal Emittance Exchange at the Fermilab A0 Photoinjector

by Timothy W. Koeth

Ph. D. Dissertation
The A0 beamline: Part II

1.3 GHz booster cavity

3.9 GHz cavity (on/off)

D1 D2 D3 D4

Collecting Optics

Pyrodetector

Coherent Synchrotron light

= quadrupole

= dipoles

= diagnostics
Coherent Synchrotron Radiation

• Synchrotron radiation is the result of individual electrons that randomly emit photons when passing through a bending magnet.

• Coherent synchrotron radiation (CSR) is produced when a group of electrons collectively emit photons in phase. This occurs when bunch length is shorter than radiation wavelength.
Condition for coherent radiation

Form factor
\[ P(\lambda) = p(\lambda)N_e[1 + (N_e - 1)f(\lambda)] \]

- \( P(\lambda) \): Total power radiated at wavelength \( \lambda \)
- \( p(\lambda) \): Synchrotron radiation from one electron
- \( N_e \): Number of electrons in the bunch
- \( f(\lambda) = 1 \) for \( \lambda \gg \sigma_t \)

Long wavelength cutoff due to vacuum chamber

\[ \lambda_{\text{cutoff}} = 2h \sqrt{\frac{h}{\rho}} \]

- \( h \): Height of the chamber 1.8 inches
- \( \rho \): Bending radius 900 mm
- \( \lambda_{\text{cutoff}} \): 20 mm

CSR effect on the bunch is….

\[ \Delta E = 0.35mc^2 \frac{N_e r_e L_B}{(\rho \sigma_z^2)^{2/3}} \]

- \( r_e \): Classical electron radius
- \( L_B \): Length of the bend
- \( N_e \): Number of electrons in the bunch
The A0 beamline

1.3 GHz booster cavity

3.9 GHz cavity (on/off)

Coherent Synchrotron light

Collecting Optics

Pyrodetector

= quadrupole

= dipoles

= diagnostics
CSR : Measurements

- Power
- Polarization
- Angular Distribution
- Using CSR as a bunchlength monitor
CSR Power Vs RF Phase (bunchlength)
Polarizer angle vs CSR

Intensity (V)

Polarizer angle (θ) in radians

Data
Fit: $A^2 \cos(X) + B^2 \sin^2(X)$
CSR Angular distribution

Ratio (Horizontal to vertical) = 4.6
Bunch length measurement: Experimental Setup

- 1.3 GHz booster cavity
- 3.9 GHz cavity (off)
- D1, D2, D3, D4
- Collecting Optics
- Martin 6 Puplett Interferometer
- Synchrotron light
- =quadrupole
- =dipoles
- =diagnostics

XS4
Martin – Puplett interferometer
Bunch length measurement: Simulation Vs Experiment
Studying the effects of CSR on the beam*

* Using a Skew Quad in a Chicane to Temporally Resolve the Transverse Effects of CSR – P. Emma (uBI 2010)
Twin pulse at the cathode
Twin pulse Profile @X24 vs SkewQuad

![Graph showing separation between pulses vs 9-cell phase in degrees for different amplitudes.](image)
Twin pulse Profile @X24 vs SkewQuad

-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
Skew quad diagnostic to resolve CSR effects

Skew QUAD OFF

(a)

CSR OFF

(b)

Skew QUAD ON

(c)

CSR ON

(d)
Skew quad measurements at X24

Skew QUAD OFF

Charge 300pC

Skew QUAD ON

Charge 600pC

Charge 900pC
Part III: Chirped beam has improved performance

- Improved performance
- Minimizes thick lens effect
How to minimize thick lens effect?*

\[
\varepsilon_{x,\text{out}}^2 = \varepsilon_z^2 + \left(\frac{17 \lambda^2}{40D}\right)^2 \langle x'^2 \rangle \left[ \langle z^2 \rangle + \alpha^2 D^2 \langle \delta^2 \rangle + 2\alpha D \langle z \delta \rangle \right]
\]

\[
\varepsilon_{z,\text{out}}^2 = \varepsilon_x^2 + \left(\frac{17 \lambda^2}{40D}\right)^2 \langle x'^2 \rangle \left[ \langle z^2 \rangle + \alpha^2 D^2 \langle \delta^2 \rangle + 2\alpha D \langle z \delta \rangle \right]
\]

Minimize this term:

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

Introduce correlation:

\[
\delta = h z
\]

then:

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

\[
=> h = \frac{-1}{\alpha D}
\]

will make this term zero.

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

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>

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

Pick 9-cell phase to introduce chirp

1.3 GHz booster cavity

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

- Streak camera resolution
- Quadrupole current before EEX (A)
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)

![Graph showing the relationship between CSR power, pyrometer readings, and RF phase (bunchlength). The graph includes lines for different charge levels: 1000 pC, 800 pC, 500 pC, and 300 pC. The x-axis represents degrees off crest, and the y-axis represents power (V). An inset graph shows power (V) versus charge (nC).]
Emittance exchange with chirped beam*

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

Emittance exchange simulation with GPT

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

Graph: Emittance ratio vs. degrees off crest (minimum energy spread at 30 DOC)
Next generation EEX: upgraded Classic EEX*

- Use two (or one) more deflecting cavity to compensate thick lens effect
Next generation EEX : A Negative drift EEX

FIG. 13. Transverse-to-longitudinal emittance exchange optic with optics for negative drift lengths between the doglegs.
Next generation EEX : A Chicane style EEX

FIG. 2. A chicane-type exact EEX beam line. Two quadrupoles (green diamonds) are put upstream of the transverse cavity to reverse the dispersion.
Next generation EEX : A Double EEX*

A schematic of a proposed bunch compressor

Emittance exchange

Telescope

Emittance exchange

z → x emit. exch.

x → z emit. exch.

Manipulate the longitudinal phase space with ease of manipulation of the transverse phase space

A. Zholents & Zolotorev
A brief history of EEX (just a sample)

• Chicane style EEX: Cornacchia and Emma (2002)
• Double dogleg EEX: Kim and Sessler (2005)
• A0 emittance exchange beamline commissioned
• Beam shaping results: Yin-e et al (2010)
• Emittance exchange result: Jinhao et al (2010)
• EEX for tailoring current distributions: Piot (2011)
• EEX for HHG: B. Jiang (2011)
• Double EEX proposal: Zholents & Zolotorev (2011)
• Use of EEX as a bunch compressor: Carlsten (2011)
• Chicane style EEX: Xiang and Chao (2012)
• Terra incognita
Summary

• Coherent synchrotron radiation has been studied at the emittance exchange beamline.

• 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.

• A chicane-style emittance exchange looks promising and is planned to be tested at the Advanced Superconducting Test Accelerator (ASTA) facility @ 40 MeV