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**TOPICS**

**Part I. Introduction**
- HEP Accelerators
  - S. Holmes (FNAL)
  - Attend the LC Workshop
- Physics
  - KJK
- Beam Dynamics
  - KJK
- Beam Dynamics
  - T. Raubenheimer (SLAC)
- LC Overview
  - J. Rosenzweig (UCLA)

**Part II. Subsystems**
- Particle Sources
  - L. Emery (ANL)
- Damping Rings
  - J. Wang (SLAC)
- RF (RT)
  - L. Lilje (DESY)
- SCRF
  - F. Zimmermann (CERN)
- Beam Delivery
  - V. Shiltsev (FNAL)
- Ground Vibration
  - W. Gai (ANL)
- > 1 TeV

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**ACCELERATOR PHYSICS AND TECHNOLOGIES FOR LINEAR COLLIDERS**

The high-energy physics community is in general agreement that a linear collider (LC) will be the most important high-energy physics accelerator project after the Large Hadron Collider (LHC) for comprehensive exploration of fundamental interactions on the TeV scale. The requirements of a linear collider are very challenging: high-current electron beams must be accelerated to several hundred GeV, focused to a few-nanometer spot, and collided with similarly prepared opposing positron beams. Thanks to the intense international effort on accelerator physics studies and hardware development during the past decade, it now appears that linear colliders meeting these requirements can be built.

This course will provide an introduction to the accelerator physics and technology topics required to construct a linear collider. It is intended for graduate students as well as advanced undergraduate students with a good background in classical mechanics and E&M. Prior knowledge of accelerator physics is not necessary. The course will begin with a basic introduction to accelerator physics and then progress into more detailed discussions of important subtopics by guest lecturers who are leaders in the respective areas. Attendance by scientists from Chicago-area institutions interested in the future development of high-energy accelerators is also encouraged.

**Lecture Room:** KPTC 103, Physics Department, The University of Chicago

**Time:** Tuesdays and Thursdays 1:30-3:00 p.m.

**Review and Exercise Sessions:** Thursdays 3:00-3:50 p.m.

**Course Website:** [http://hep.uic.edu/~kwang/phy575.html](http://hep.uic.edu/~kwang/phy575.html)
Revised and corrected 4-10-97

Published in Physical Review E 55, 7595-7599 (1997)

Envelope analysis of intense relativistic quasi-laminar beams in RF photoinjectors: A theory of emittance compensation

Evidence for the validity of this picture is obtained from both multiparticle simulations, and experiments at Brookhaven [3].

In this set of conditions, which defines the notion of a quasi-laminar beam paper, is generally attained in RF photoinjectors, in particular when they are operated in the space-charge emittance compensation regime[4]. This regime is achieved when the beam propagates for one transverse plasma oscillation, so that the space which develop in the first half of the regime in a typical transverse plasma oscillation is not destroyed. However, plasma which properly focusing the beam of the beam is still effective in significantly perturbing the evolution of the phase space distribution, introducing distortions and longitudinal-
Flat Beam Generation

\[
V = \begin{pmatrix} X \\ Y \end{pmatrix}; \quad X = \begin{pmatrix} x \\ x' \end{pmatrix}; \quad Y = \begin{pmatrix} y \\ y' \end{pmatrix}; \quad (') \equiv \frac{d}{dz}
\]

and rotation matrix

\[
R = \begin{pmatrix} I_c & I_s \\ -I_s & I_c \end{pmatrix},
\]

where \( c \equiv \cos \alpha, \ s \equiv \sin \alpha, \) and \( I \) is the \( 2 \times 2 \) unit matrix. Then, the \( 4 \times 4 \) matrix of skew block, \( S \), in the transition

\[
V_2 = SV_1
\]

(1)

can be found as

\[
S = R^{-1} \begin{pmatrix} M & O \\ O & N \end{pmatrix} R = \frac{Mc^2 + Ns^2}{(M - N)cs} \begin{pmatrix} (M - N)cs \\ Ms^2 + Nc^2 \end{pmatrix}.
\]

(2)

Flat Beam Generation and Emittance Exchange

Yine Sun
Accelerator System Division
Argonne National Lab.

Coherence in Particle and Photon Beams: Past, Present, and Future Symposium
March 15, 2019
Outline

- Round-to-Flat Beam Transformation
  - Theory;
  - Experimental demonstration.

- Transverse-to-longitudinal Emittance EXchange (EEX)
  - Theory;
  - Experimental demonstration;
  - Longitudinal phase-space shaping via EEX.

- Acknowledgements
Flat Beam Generation: Beam Matrix Formulation

\[ \Sigma_{\text{round}} = \begin{bmatrix} \varepsilon_{\text{eff}} \beta & 0 & 0 & L \\ 0 & \varepsilon_{\text{eff}} / \beta & -L & 0 \\ 0 & -L & \varepsilon_{\text{eff}} \beta & 0 \\ L & 0 & 0 & \varepsilon_{\text{eff}} / \beta \end{bmatrix} \]

General form of the beam matrix of a round beam at waist location.

\[ \Sigma_{\text{flat}} = M \Sigma_{\text{round}} M^T \]

Going through a round-to-flat beam transformation matrix \( M \) which is symplectic.

\[ \Sigma_{\text{flat}} = \begin{bmatrix} \varepsilon_- \beta & 0 & 0 & 0 \\ 0 & \varepsilon_- / \beta & 0 & 0 \\ 0 & 0 & \varepsilon_+ \beta & 0 \\ 0 & 0 & 0 & \varepsilon_+ / \beta \end{bmatrix} \]

Beam is decoupled in \( x \) and \( y \) and a flat beam with emittance \( \varepsilon_- \) and \( \varepsilon_+ \) is generated.
Invariants of the Symplectic Transformation $\rightarrow$ Flat Beam Emittances

\[ I_1 = \varepsilon_{4D} = \sqrt{\Sigma} \Rightarrow \varepsilon_+ \varepsilon_- = \varepsilon_{\text{eff}}^2 - L^2 \]

\[ I_2 = -\frac{1}{2} \text{Trace}(J_4 \Sigma J_4 \Sigma) \Rightarrow \varepsilon_+^2 + \varepsilon_-^2 = 2(\varepsilon_{\text{eff}}^2 + L^2) \]

Round beam emittance:

\[ \varepsilon_{\text{eff}} = \sqrt{\varepsilon_u^2 + L^2} \]

Flat beam emittances are given by:

\[ \varepsilon_{\pm} = \sqrt{\varepsilon_u^2 + L^2} \pm L \]

e.g. \( L=20 \, \mu m, \varepsilon_u=1 \, \mu m \)

\( \varepsilon_+=47 \, \mu m; \varepsilon_-=0.02 \, \mu m \)

Uncorrelated emittance

Const. related to canonical angular momentum \( L=\frac{\langle L \rangle}{2Pz} \)

For \( L \gg \varepsilon_u \),

\[ \varepsilon_- = \frac{\varepsilon_u^2}{2L} \ll \varepsilon_u \]

Flat beam emittance can be much smaller than the thermal emittance!
Measurements of the canonical angular momentum as a function of magnetic field on cathode

\[ \langle L \rangle = 2p_z \sigma_z \sin \theta / D \, \text{(neV s)} \]

\[ \langle L \rangle = eB_0 \sigma_c^2 \, \text{(neV s)} \]

\[ \sigma_c = 0.97 \pm 0.04 \, \text{mm} \]

weighted least-squares linear fit: \[ y = (0.98 \pm 0.03)x \]
Removal of angular momentum $\rightarrow$ flat beam generation

$\varepsilon_x (\mu m) \ 0.39 \pm 0.02$
$\varepsilon_y (\mu m) \ 35.2 \pm 0.5$
$\varepsilon_y/\varepsilon_x \ 90 \pm 5$

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Round-to-Flat
transverse phase-space manipulation

Emittance Exchange
transverse $\leftrightarrow$ longitudinal phase-space manipulation
### Transverse-to-Longitudinal Phase-Space Exchange

**EEX Theory:**
- 2002: Cornacchia and Emma, PRSTAB 5, 084001.
  - Partial exchange: chicane
  - Complete Exchange: double-dogleg

**2010:** Double-dogleg EEX experiment demonstration:
- J. Ruan et al., PRL 106, 244801 (2011).

**2010:** Applications of EEX in beam current profile modulation:
- Y. Sun et al., PRL 105, 234801 (2010).
Transverse-to-Longitudinal Emittance EXchange

- Under thin-lens approximation, with proper matching of the deflecting cavity strength \( k \) and the dogleg dispersion \( D \), i.e., \( 1+kD=0 \), the diagonal sub-block elements of the exchanger’s transfer matrix are zero \( \leftrightarrow \) the initial horizontal phase space is mapped into the longitudinal phase space, vice versa.

- Transfer matrix of a deflecting cavity with strength \( k \) under thin lens approximation:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & k & 0 \\
0 & 0 & 1 & 0 \\
k & 0 & 0 & 1
\end{pmatrix}
\]

\[
\begin{pmatrix}
x \\
x' \\
z \\
\delta
\end{pmatrix}_{\text{out}} =
\begin{pmatrix}
0 & 0 & L + S & \alpha S \\
0 & 0 & \frac{1}{\alpha L} & \alpha \\
\alpha & \alpha S & 0 & 0 \\
\frac{1}{\alpha L} & \frac{L + S}{\alpha L} & 0 & 0
\end{pmatrix}
\begin{pmatrix}
x \\
x' \\
z \\
\delta
\end{pmatrix}_{\text{in}}
\]
EEX Beamline at A0 Photo-Injector, Fermilab

- Cs$_2$Te cathode, Nd:YLF drive-laser
- Beam energy 14 - 15 MeV
- Charge 100pC - 1nC

1.3 GHz 9-cell SC cavity

X3: multislits insertion

Matching quadrupoles

1.3 GHz rf gun with CsTe cathode

Vertical spectrometer

X23

X24: temporal diagnostics

Autocorrelator

Bolometer

Energy diagnostics

X54

3.9 GHz, 5-cell deflecting cavity
Sub-ps Bunch Train Generation using EEX at Fermilab A0

(1) cavity off: horizontal modulation on X23 and XS4; but no energy modulation on XS4;
(2) cavity on: NO horizontal modulation on X23 and XS4; but clear energy modulation appears on XS4

Transverse-longitudinal Phase-space Exchange
EEX Beamline at Argonne Wakefield Accelerator (AWA)

Transverse Deflecting cavity

Transverse Mask

5 nC / 48 MeV

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Precision Control of the Electron Longitudinal Bunch Shape via EEX at AWA/ANL

EXPERIMENT: Transverse mask to tailor longitudinal density profile


Take initial x-horizontal profile

Take final z-longitudinal bunch shape with transverse deflecting cavity on

5 nC / 48 MeV

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Acknowledgements

To the brilliant

Kim Kwang-Je
金 光齐
Golden Light-Coherent

Thank you for introducing me to the accelerator field, offering me the first scholarship at UofC, serving as my Ph.D. advisor, and offering your support in every step of my career…

Happy Retirement!