Generation and Dynamics of Magnetized Beams for High-Energy Electron Cooling

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Outline

• Introduction
• Features and parameterization of magnetized beams
• Formation of magnetized bunches:
  – methods and limitations,
  – experiments in rf gun.
• Transport and Manipulation:
  – transverse matching,
  – longitudinal manipulations,
  – decoupling into flat beams.
• Outlook
Required Electron-Beam Parameters

- Cooling interaction time

\[ \tau \approx \frac{\rho}{v_e} \quad \text{(not magnetized)} \]

\[ \tau \approx \frac{\rho}{v - v_e} \quad \text{(magnetized)} \]

- Magnetized cooling less dependent on e-beam transverse emittance (to what extent?)

- Electron-cooling accelerator provides beam eventually matched to cooling-solenoid section
Cooler configurations

- **low-energy coolers:**
  - lattice (bends) embedded in magnetic fields,
  - based on DC electron sources,
  - no further acceleration or bunching, needed.

- **high-energy coolers:**
  - medium energies required (50-100 MeV),
  - acceleration in SCRF linac → bunching
  - lumped solenoidal fields → matching

![Diagram of cooler configurations](image)
High-energy coolers

- **injector**: produces bunched beam for RF acceleration
- **debuncher**: matched electron bunch length to ion-beam’s,
- **matching + mode/converter sections**: repartition “physical” emittances, match in cooling-solenoid section.
Beam dynamics regimes (round beams)

• Radial envelope ($\sigma$) equation in a drift (Lawson):

$$\sigma'' - \frac{K}{4\sigma} - \frac{\epsilon_u^2}{\sigma^3} - \frac{L^2}{\sigma^3} = 0,$$

- space charge
- emittance “pressure”
- angular momentum contribution

$K$: generalized perveance
$\epsilon_u$: uncorrelated geometric emittance
$L$: magnetization

adapted from Y.-E Sun, Dissertation U. Chicago (2005)
Features & Parameterization

• possible parameterization of coupled motion between 2 degrees of freedom has been extensively discussed; see:

• Simpler description that provides the necessary insights..
A simple description of coupled motion

- Consider the 4x4 beam matrix

\[
\Sigma \equiv \begin{bmatrix}
\langle XX \rangle & \langle XY \rangle \\
\langle YX \rangle & \langle YY \rangle
\end{bmatrix}
\]

where \( \bar{X} \equiv (x, x') \) and \( \bar{Y} \equiv (y, y') \)

- Introduce the “correlation” matrix: \( C \equiv \langle Y\bar{X} \rangle \langle X\bar{X} \rangle^{-1} \)

- Beam matrix takes the form:

\[
\Sigma = \left( \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} + \begin{bmatrix} 0 & C^{-1} \\ C & 0 \end{bmatrix} \right) \begin{bmatrix}
\langle X\bar{X} \rangle & 0 \\
0 & \langle Y\bar{Y} \rangle
\end{bmatrix}
\]

- The correlation subjects to \( R = \begin{bmatrix} H & G \\ U & V \end{bmatrix} \) transforms as \( C_0 \rightarrow C \)

\[
C = (U + VC_0)(H + GC_0)^{-1}.
\]

- \( C \) provides information on the coupling only.

P. Piot, EIC’14, JLab, Mar. 17-21, 2014
Beam matrix for a round magnetized beam

• At a waist, the matrix of a magnetized (round) beam is
  \[ \Sigma_0 = \begin{bmatrix} \varepsilon T_0 & \mathcal{L} J \\ -\mathcal{L} J & \varepsilon T_0 \end{bmatrix} \]
  where \[ T_0 = \begin{bmatrix} \beta & -\alpha \\ -\alpha & \frac{1+\alpha^2}{\beta} \end{bmatrix} \]
  and the magnetization is
  \[ \mathcal{L} = \langle xy' \rangle = -\langle x'y \rangle = \frac{L}{2p_z} \]

• The eigen-emittances of this beam matrix are:
  \[ \varepsilon_{\pm} = \varepsilon \pm \mathcal{L} \]
  where \[ \varepsilon^2 = \mathcal{L}^2 + \varepsilon_u^2 = |\Sigma| \]

• The eigen-emittances can be mapped into “physical” emittances using a skewed beamline
  \[ \begin{bmatrix} M_+ & M_- \\ M_- & M_+ \end{bmatrix} \]
  decoupling when
  \[ M_- + M_+ C_0 = 0. \]

K.-J. Kim, PRSTAB 6, 104002 (2003)
D. A. Edwards, unpublished (2001)
Formation of magnetized bunches

- Cathode immersed in an axial $\mathbf{B}$ field
- Sheet beams at birth (with subsequent flat-to-round beam converter)
  - shaped cathode,
  - line-laser focus
  - Nonlinear optics (speculative)


Cathode in a magnetic field

- electrons born in an axial B field $B_z \rightarrow$ CAM

$$L(r) = er A_\theta \simeq \frac{er^2}{2} B_{z,0} + O(r^4)$$

- upon exit of solenoid field ($A_\theta = 0$): CAM becomes purely kinetic.

$$P_\theta(r, z = 0) = eA_\theta(r, z = 0)$$

$$p_\theta(r, z > z_{sol}) = P_\theta(r, z = 0)$$
Emittance vs magnetization

- “effective emittance” \( \varepsilon^2 = \mathcal{L}^2 + \varepsilon_u^2 \)

- magnetization
  \[ \mathcal{L} = \frac{eB_0}{2mc} \sigma_c^2 \]

- The emittance has a lower-bound value:
  \[ \varepsilon_u^n \equiv \beta \gamma \varepsilon_u \geq \varepsilon_{th} = \sigma_c \left( \frac{2\delta E}{3mc^2} \right)^{1/2} \]
  where \( \delta E \) is the excess in kinetic energy during emission

- Practically, \( \varepsilon_u \) includes other contributions.
Example of 3.2-nC magnetized bunch

- high-charge bunch subject to emittance degradation
- proper optimization (emittance compensation) → 4-D emittance comparable to round beams.

![Image of high-charge bunch]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flat-beam Configuration</th>
<th>Round-beam Configuration</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>3.2</td>
<td>3.2</td>
<td>nC</td>
</tr>
<tr>
<td>$E$</td>
<td>47.18</td>
<td>48.77</td>
<td>MeV</td>
</tr>
<tr>
<td>$\varepsilon_x$</td>
<td>105.04</td>
<td>5.43</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>0.31</td>
<td>5.44</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>$\varepsilon_{4D}$</td>
<td>5.53</td>
<td>5.44</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\approx 334$</td>
<td>$\approx 1$</td>
<td>—</td>
</tr>
</tbody>
</table>

P. Piot et al. IPAC13; C.-X. Wang, FEL06, 721 (2006)
Measuring (kinetic) angular momentum

• Kinetic angular momentum can be measured using a slit technique (similar to emittance)

\[ \langle L \rangle = 2P_z \frac{\sigma_1 \sigma_2 \sin \theta}{D} \]

\( \sigma_1, 2 \): rms beam size at slit (1) and observation screen (2),
\( P_z \): axial momentum
\( D \): drift length between locations (1) and (2).
Experimental generation in a photoinjector

- Fermilab A0 normal-conducting photoinjector (decommissioned),
- 15 MeV, charge up to 2 nC, ~3-10 ps bunch

Experimental generation in a photoinjector

- linear scaling with B field on photocathode
Experimental generation in a photoinjector

- weak $Q$ dependence,
- quadratic scaling with laser spot size $\sigma_c$ on photocathode.
Decoupling into flat ($\varepsilon_x/\varepsilon_y \neq 1$) beam

- Transport of magnetized bunches while preserving $L$ is challenging,
- Use of round-to-flat beam transformer to convert into uncoupled (flat) beam
  $\rightarrow$ eigen-emittances maps into “physical” transverse emittances:

$$
\varepsilon_n^\pm = \sqrt{(\varepsilon_n^u)^2 + (\beta \gamma L)^2}
$$

$$
\pm (\beta \gamma L) \beta \gamma L \gg \varepsilon_n^u \Rightarrow \\
\begin{cases}
\varepsilon_n^+ \approx 2\beta \gamma L, \\
\varepsilon_n^- \approx \frac{(\varepsilon_n^u)^2}{2\beta \gamma L},
\end{cases}
$$

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Decoupling into flat beam: experiments (1)

- Same experimental setup as used for generation of CAM-dominated beams

![Graph and images showing experimental and simulation results for X3, X7, and X8 positions.](image)
Decoupling into flat beam: experiments (2)

- normal emittances map into the flat-beam emittance
- large experimental uncertainties for smallest emittance meas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experiment</th>
<th>Simulation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{x}^{X7}$</td>
<td>$0.088 \pm 0.01$ (±0.01)</td>
<td>0.058</td>
<td>mm</td>
</tr>
<tr>
<td>$\sigma_{y}^{X7}$</td>
<td>$0.63 \pm 0.01$ (±0.01)</td>
<td>0.77</td>
<td>mm</td>
</tr>
<tr>
<td>$\sigma_{x}^{X8,v}$</td>
<td>$0.12 \pm 0.01$ (±0.01)</td>
<td>0.11</td>
<td>mm</td>
</tr>
<tr>
<td>$\sigma_{y}^{X8,h}$</td>
<td>$1.68 \pm 0.09$ (±0.01)</td>
<td>1.50</td>
<td>mm</td>
</tr>
<tr>
<td>$\varepsilon_{n}^{x}$</td>
<td>$0.41 \pm 0.06$ (±0.02)</td>
<td>0.27</td>
<td>μm</td>
</tr>
<tr>
<td>$\varepsilon_{n}^{y}$</td>
<td>$41.1 \pm 2.5$ (±0.54)</td>
<td>53</td>
<td>μm</td>
</tr>
<tr>
<td>$\varepsilon_{n}^{y}/\varepsilon_{n}^{x}$</td>
<td>$100.2 \pm 20.2$ (±5.2)</td>
<td>196</td>
<td></td>
</tr>
</tbody>
</table>

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Outlook + open questions

- magnetized beam from a SCRF gun:
  - flux concentrator around cathode?
  - flat beam at cathode
    [J. Rosenzweig, PAC93 showed \((\varepsilon_+, \varepsilon_-) = (95, 4.5) \mu m\)]

- needed \(\epsilon_u\) and \(\mathcal{L}\) ? and limit on 4-D emittance?

- planned future experiment at ASTA