Physics Requirements for
Straight Ahead Spectrometer Beamline

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Brief Summary:
In this PRD, we define specifications for the 135 MeV spectrometer beamline, also called the Straight-Ahead Beamline or SAB. One of the main functions of this beamline is to measure the slice (intrinsic) energy spread of the electron beam in order to confirm the proper function of the laser heater system.

Change History Log

<table>
<thead>
<tr>
<th>Rev Number</th>
<th>Revision Date</th>
<th>Sections Affected</th>
<th>Description of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>12-Dec-2005</td>
<td>All</td>
<td>Initial Version</td>
</tr>
<tr>
<td>001</td>
<td>11-Apr-2006</td>
<td></td>
<td>Update on Beamline elements location</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clarification on BXS parameters</td>
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</table>
This document describes the functionality and requirement of the Straight Ahead Spectrometer Beamline (SAB). The SAB is a diagnostics beamline located the end of the Injector. It will also be used for dumping the beam during commissioning. Its purpose is to characterize the beam at 135MeV before it enters the dogleg (DL1). The typical measurements will be:

- beam energy and energy jitter
- energy spread (correlated and uncorrelated)
- vertical slice emittance
- longitudinal phase space

The beam is sent to a 35 degree bending magnet which then directs the beam to a beamline parallel to the linac. The components are described in the schematic below. Their location is given in the MAD deck in http://www-ssrl.slac.stanford.edu/lcls/linac/optics/

![Schematic of SAB beamline elements](image)

3- **Electron Beam Optics**

The characteristics of the spectrometer bending magnet have been described in [1]. They are repeated here in table 1. A schematic of the beamline is given in figure 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leff (Effective Length)</td>
<td>0.5</td>
<td>m</td>
</tr>
<tr>
<td>Angle</td>
<td>35</td>
<td>degrees</td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>0.8185</td>
<td>m</td>
</tr>
<tr>
<td>Pole Face rotation</td>
<td>7.5</td>
<td>degrees</td>
</tr>
<tr>
<td>Nominal Energy e beam</td>
<td>135</td>
<td>MeV</td>
</tr>
<tr>
<td>Maximum Beam Energy</td>
<td>180</td>
<td>MeV</td>
</tr>
<tr>
<td>Nominal B field</td>
<td>5.498</td>
<td>kG</td>
</tr>
<tr>
<td>Nominal integrated field - $\int B\cdot dl$</td>
<td>2.7490</td>
<td>kG-m</td>
</tr>
<tr>
<td>Maximum integrated field - $\int B\cdot dl_{\max}$</td>
<td>4.0</td>
<td>kG-m</td>
</tr>
</tbody>
</table>
Table 1 - Characteristics parameters of the BXS spectrometer bending magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Gap Height</td>
<td>34 mm</td>
</tr>
<tr>
<td>Minimum Horizontal Beam Stay Clear due to Sagitta (38mm)</td>
<td>76 mm</td>
</tr>
<tr>
<td>No trim Coil required</td>
<td></td>
</tr>
<tr>
<td>SR Power (incoherent)</td>
<td>0.46 µW</td>
</tr>
<tr>
<td>SR Power (coherent)</td>
<td>2.2 mW</td>
</tr>
<tr>
<td>SR Power (total)</td>
<td>2.2 mW</td>
</tr>
</tbody>
</table>

Power Load
The coherent synchrotron radiation dominates the power load in the bend. Using (1), we obtain a power per unit length of 4.4 mW per m.

\[
\frac{P}{L} [W/m] = \frac{f_{rep} N^2 q^2 \Gamma(5/6)}{4\sigma^{7/2} \epsilon^{1/3} \rho^{2/3} \sigma^{4/3}} \tag{1}
\]

Field Quality
The Quadrupoles QS01, QS02 will be of the ETA (Everson-Tesla Type) with field characteristics described in 

BXS Field Quality requirements
This version of the PRD makes all the information of both revision 0 and http://www-ssrl.slac.stanford.edu/lcls/prd/1.2-128-r0.pdf obsolete.
One should only refer to data of table 1 above and table 2 below.

The tolerances for multipole components are given in the table 1 below.

| Quadrupole field tolerance wrt max. (@ r = 20 mm): | 0.24 % of \( \int B \cdot dl_{max} \) |
| Sextupole field tolerance wrt max. (@ r = 20 mm)  | 0.88 % of \( \int B \cdot dl_{max} \) |
| Decapole field tolerance wrt max. (@ r = 20 mm)   | 3.5 % of \( \int B \cdot dl_{max} \) |

Table 1 – Field Quality specification

The field uniformity should be as good as \( 10^{-4} \) in the good field region which is defined by the beam stay clear of 76 mm.

The pole face rotation of the magnet is 7.5 degrees. As the magnet is viewed from above (as shown below), the iron should be more square in shape with respect to a standard sector magnet (i.e., closer to a rectangular magnet).
Figure 2 – Schematic showing convention on pole face rotation

The field stability of the spectrometer bending magnet (BXS) should be better than $10^{-4}$ for the short term. This requires the power supply stability to be better than $10^{-4}$.

II- Measurements

We discuss the longitudinal phase space measurements in particular the uncorrelated energy spread. The screen requirements and resolution of the imaging system encompass those required for energy and energy stability.

The SAB is used to measure with a high accuracy the uncorrelated energy spread. By using the combination of the transverse deflecting cavity with the spectrometer bending magnet, we can project the longitudinal phase space onto the physical space of a screen.

By applying a vertical kick using the transverse deflecting cavity (TCAV), a correlation between temporal position and vertical position is introduced on the beam. Then as the beam is deflected in the spectrometer bending magnet (BXS), a correlation between the temporal position and vertical position is introduced on the beam. Then as the beam is deflected in the spectrometer bending magnet (BXS), a correlation between the horizontal position and the energy is generated (via the dispersion function).

The horizontal $\Delta x$ and vertical beam $\Delta y$ extension at the screen are then given by

$$\Delta x = \frac{\Delta E}{E_{beam}} \cdot D_x \quad (2)$$

$$\Delta y = \frac{eV_{car}}{pc} \sqrt{\beta_{cav} \beta_y} \sin(\Delta \psi)\sin(kz + \varphi) \quad (3)$$

where

- $\Delta E/E_{beam}$ is the beam total energy spread
- $D_x$ is the dispersion at the screen
- $\beta_{cav}$ is the vertical betatron function at the transverse deflecting cavity 5.558 m
- $\beta_y$ is the transverse betatron function at the screen
- $\Delta \psi$ is the vertical phase advance
- $k$ is the wave vector $k = \frac{2\pi}{c} f_{of}$
z is the position along the bunch (at zero-crossing, we use $z = \text{half bunch length} = 1.5 \, \text{mm}$)

$V_{\text{cav}}$ is the transverse deflecting cavity voltage, typically 1 MV

$pc$ is the electron beam energy

The rms horizontal beam size of a temporal slice is given by

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + D_x^2 \sigma_{\delta}^2} \quad (4)$$

- $\beta_x$ is the betatron function
- $\varepsilon_x$ the beam emittance
- $D_x$ the dispersion function
- $\sigma_{\delta}$ the rms of the relative energy spread (uncorrelated)

To achieve a good resolution of the uncorrelated energy spread $\sigma_{\delta}$, the emittance term, $\beta_x \varepsilon_x$, needs to be smaller than the dispersion term. For our nominal 1nC tuning, at 135 MeV, the emittance $\varepsilon$ is expected to be 1 mm-mrad. To resolve a $\sigma_{\delta} = 3$ keV, the following condition $\beta_x \varepsilon_x < D_x^2 \sigma_{\delta}^2 \quad (5)$ needs to be fulfilled which corresponds to $\beta_x < 0.130 \, D_x^2$.

Two optical tunings have been studied which are represented in figure 2-a and figure 2-b. In the first tuning, optical functions are identical to those of the nominal tuning in the matching section (as far as QM02). The minimum uncorrelated energy spread which can be resolved is 6 keV.

By modifying the matching section by means of QM01 and QM02, a tuning can be found which allows a 3 keV resolution. With the quadrupole settings given in case (2) of table 2, condition (5) is largely fulfilled.

<table>
<thead>
<tr>
<th>case</th>
<th>QM01</th>
<th>QM02</th>
<th>QS01</th>
<th>QS02</th>
<th>$\beta_x$</th>
<th>$D_x$</th>
<th>$\beta_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>15.07</td>
<td>-11.9389</td>
<td>7.415284</td>
<td>-1.71916</td>
<td>0.138</td>
<td>0.905</td>
<td>9.951</td>
</tr>
<tr>
<td>(2)</td>
<td>16.54775</td>
<td>-12.2488</td>
<td>7.415284</td>
<td>-1.71916</td>
<td>0.069</td>
<td>0.905</td>
<td>9.96</td>
</tr>
</tbody>
</table>

Table 2- Nominal Quadrupole gradient $K$, for the nominal tuning, $K = \frac{1}{B \rho \frac{\partial B}{\partial x}}$

The sensitivity study presented in Tech Note LCLS-TN-05-16 is not reproduced here. Even if the quadrupole settings have slightly changed of the overall sensitivity is very similar.
Figure 3– (a) nominal tuning    (b) modified tuning for 3keV resolution

\begin{align*}
\delta = 3\text{keV} & \quad 22.85 \quad 20.1 \quad 30.44 \\
\delta = 6\text{keV} & \quad 22.85 \quad 40.2 \quad 46.26 \\
\delta = 10\text{keV} & \quad 22.85 \quad 67 \quad 70.12 \\
\delta = 40\text{keV} & \quad 22.85 \quad 268 \quad 269.12 \\
\end{align*}

Table 4- Contributions to beam sizes for the nominal tuning lattice

\begin{align*}
\delta = 3\text{keV} & \quad 16.1 \quad 20.1 \quad 25.79 \\
\delta = 6\text{keV} & \quad 16.1 \quad 40.2 \quad 43.34 \\
\delta = 10\text{keV} & \quad 16.1 \quad 67 \quad 68.95 \\
\delta = 40\text{keV} & \quad 16.1 \quad 268 \quad 268.63 \\
\end{align*}

Table 5- Contributions to beam size for the modified lattice for low resolution

III- Vacuum Chamber

A one inch pipe with 0.87” ID can be used in the SAB. Apart from the junction to pumps and gauges, and the standard cross for the YAG screens, only three special chambers have to be designed:

1- The intersection with the main linac line : an X-chamber is required

2- The bending magnet (BXS) chamber : an X chamber which will be compatible with the 28 mm magnetic gap of the magnet; one port is used for the PM detector; the second port will not be used at the early stage of the injector beamline

3- A special OTR chamber with an 17.5 degree OTR screen and an in-vacuum mirror ; this is described in the next paragraph
The envelope of the beam for the case of uncorrelated energy spread measurement is given in figure 4. The first two plots of figure 4 give the envelope of the beam after the BXS bend both vertically (left) and horizontally (right) in the case of the transverse cavity (TCAV) with 1MV and for a +/- 1MeV correlated energy spread. The beam envelope contains all the photo-electrons of the beam, assuming a hard-edge injection laser pulse. It is neither an rms or a FWHM quantity.

**Figure 4a: Vertical envelope**
With TCAV on (1MV)

**Figure 4b: Horizontal Envelope**
assuming +/- 1 MeV correlated energy spread

### IV- Diagnostics

#### List of Diagnostics

Table 6 describes the functionality of the diagnostics.

<table>
<thead>
<tr>
<th>Diagnostics</th>
<th>Description</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>YAGS1</td>
<td>YAG screen</td>
<td>1- electron beam imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2- Alignment laser – target pattern required</td>
</tr>
<tr>
<td>YAGS2</td>
<td>YAG screen</td>
<td>Energy Spread measurement</td>
</tr>
<tr>
<td>OTRS1</td>
<td>OTR monitor</td>
<td>High resolution energy spread measurement</td>
</tr>
<tr>
<td>BPMS1</td>
<td>BPM</td>
<td>Used for steering into spectrometer bend</td>
</tr>
<tr>
<td>BPMS2</td>
<td>BPM</td>
<td>Steering/ energy jitter measurement</td>
</tr>
<tr>
<td>BPMS3</td>
<td>BPM</td>
<td>Steering/ energy jitter measurement</td>
</tr>
<tr>
<td>PM</td>
<td>Photo-Multiplier</td>
<td>Detection Signal for Wire Scanners</td>
</tr>
<tr>
<td>IMS1</td>
<td>Current Monitor</td>
<td>Measures charge, meets the BCS requirements</td>
</tr>
<tr>
<td>FCS1</td>
<td>Faraday Cup</td>
<td>Measures charge, meets the BCS requirements</td>
</tr>
</tbody>
</table>

Table 6- Functionality of diagnostics

**YAGS1 and YAGS2 Screens**
The two YAG screens should be 20 mm in diameter and have a 100 µm thickness. They should include markings as described in PRD “Physics Spec. for the injector on-axis alignment laser”. The resolution of these systems has been specified in http://www-ssrl.slac.stanford.edu/lcls/prd/1.2-021-r0.pdf

OTRS1

OTRS1 screen cannot be positioned at 45 degrees like the other OTR screens. Indeed, for measuring the uncorrelated energy spread, the beam is extended in both planes, in the (H) plane, for energy/horizontal position correlation, in the (V) plane for time/vertical position correlation). The optics cannot accommodate a depth of field of 14 mm to image a 14 mm x 14 mm beam pattern on a screen at 45 degrees. With the screen oriented at 15 degrees from normal incidence, the depth of field needs only to be of 3.75 mm for a 14mm large image. Anyway the depth of field will not be an issue as the camera will be tilted by 15/M wher M is the magnification. The proposed geometry is presented in figure 5. The characteristics dimensions are given in table 7.

A special chamber will have to be built to accommodate the extraction mirror. This chamber is schematically represented in figure 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Angle</td>
<td>15 from normal</td>
<td>Degrees</td>
</tr>
<tr>
<td>Screen Size</td>
<td>16 x 16</td>
<td>mm x mm</td>
</tr>
<tr>
<td>Screen thickness</td>
<td>1</td>
<td>µm</td>
</tr>
<tr>
<td>Mirror Size</td>
<td>L=24</td>
<td>mm</td>
</tr>
<tr>
<td>Mirror location from OTR screen</td>
<td>z = 30, y = 15</td>
<td>mm</td>
</tr>
<tr>
<td>Mirror Angle</td>
<td>60 w.r.t vertical</td>
<td>Degree</td>
</tr>
<tr>
<td>Exit Window</td>
<td>&gt; 38 (diameter)</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 7 – Characteristics of OTRS1 chamber components

The exit window will be located at z = -35 mm from the OTR screen. A resolution of 7 µm has been specified for OTRS1 [4]. This resolution is very important to allow 3keV resolution measurement as described earlier in table 6. The depth of field required is then 4.8 mm over the 16 mm screen, but 3 mm over a typical 10-mm wide image. The light will be directed down. A 45° mirror will send the light horizontally such that the camera will not be in the line of sight of the window. The optics and camera of YAGS1, OTRS1, and YAGS2 will have to be shielded against radiation.
Wire Scanner Detector

A photomultiplier tube (PMT) is to be installed in the line of sight of the matching section wire-scanners at the exit of the BXS bend magnet. The PMT detects the bremsstrahlung radiation generated by the passage of the wire-scanner through the beam.

The radiation is predominantly gamma rays which should strike a metal converter target up to 1 radiation length in thickness to produce electron positron pairs. The relativistic fraction of these particles are then detected in a Cerenkov medium, typically air, and the light is detected by an adjustable gain photomultiplier tube (PMT). To prevent synchrotron radiation and scattered particles from striking the PMT it is usually mounted in a light-tight periscope directed below the plane of the beam line [4]. Similar detector arrangements have been used at SLAC in the FFTB and the SLC Final Focus where the stainless steel vacuum blanking flange acts as the gamma ray converter and the air in the light-tight periscope acts as the Cerenkov medium.

The cross section of the Bremsstrahlung in Eq. (6) shows that the distribution nearly drops at $1/\gamma$. The attempt to compute the number of photons emitted is to be taken with care, as this computation is not easy. The Count-rate requirement for the PhotoMultiplier is usually determined experimentally.

In formula (6), reproduced from [3], we used

\[ \lambda = 1 \]
\[ M = 183 \text{ (tungsten)} \]
\[ Z = 74 \text{ (tungsten)} \]
\[ z = 1 \text{ (electron)} \]

\[
\frac{d\chi}{d\omega d\Omega} \approx \frac{16}{3} \frac{Z^2 e^2}{c M c^2} \ln\left( \frac{2\lambda \gamma^2 M c^2}{h \omega(1 + \gamma^2 \theta^2)} \right) \left[ \frac{3\gamma^2(1 + \gamma^4 \theta^4)}{2\pi(1 + \gamma^2 \theta^2)^2} \right]
\] (6)
To detect more than 95% of the Bremsstrahlung, the angle $\gamma \theta$ should be larger than 1.7. The angle $\theta$ is +/- 6.4 mrad for $E = 135$ MeV ($\gamma = 264.18$). This value does not vary much with the photon energy from the keV to the multi-GeV range. Table 5 gives the distance from the Wire-Scanner to the Photo-Multiplier tube. We expect 54% more signal for the WS03 than WS01.

<table>
<thead>
<tr>
<th>WireScanner</th>
<th>Distance to PM</th>
<th>10 mm detector</th>
<th>% total photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS01</td>
<td>7.33</td>
<td>0.6821 mrad</td>
<td>30.5%</td>
</tr>
<tr>
<td>WS02</td>
<td>5.42</td>
<td>0.9225 mrad</td>
<td>39.5%</td>
</tr>
<tr>
<td>WS03</td>
<td>3.49</td>
<td>1.43 mrad</td>
<td>55.5%</td>
</tr>
</tbody>
</table>

Table 5 – Distance from the wire-scanner to the photo-multiplier tube

V- Wakefield Budget
The wakefield budget is not critical here as this beamline is a diagnostics beamline.

VI- Dump Requirements
To be linked with BCS document

VII – Vacuum Specifications
The average vacuum pressure requirement is $5 \times 10^{-7}$ torr, as in the adjacent linac.

References
References