FACET-II Diagnostics Overview

FACET-II Science Workshop
October 17 – 21, 2017

Nate Lipkowitz
Engineering Physicist
Diagnostics & Controls
FACET-II Stage 1 FY17-19

- **Goal**: Deliver compressed electron beam from S10 to experiments in S20
- **Major upgrade**: Electron beam photoinjector in Sector 10
- **Scope**: Injector, shielding wall in S10, bunch compressors in S11 (BC11) and S14 (BC14), beam diagnostics
Provide to linac a beam of known:
- Charge
- Arrival time
- Bunch length & distribution
- Energy, energy spread & distribution
- Transverse emittance (projected and sliced)

The most useful LCLS injector diagnostics are reproduced for the FACET-II injector

S-band TCAV
- 1.4 MV crest deflection
- 2 MW from klystron 10-5
FACET-II Diagnostics
Linac and Bunch Compressors

- 70 BPMs and 4 wire scanners exist and in use at FACET
- BC11 and BC14 have all-new diagnostics
- TCAV after BC14
- 9-foot instrumentation girders between sectors

Linac diagnostics will mostly be reused in place or repurposed from FACET
FACET-II Diagnostics
Linac L1, BC11 and BC14 Overview

BC11

135 MeV

e- from Injector →

11-1b 11-1c/d 11-2a/b 11-2c

L1-X linearizer

E spread screen

Bunch length
pyro

335 MeV

To L2 →

Tune-up dump

BC14

4.5 GeV

From L2 →

14-6d

E spread screen

Energy collimators

Bunch length
pyro

To L3 →

YAG screen at 15-9

Bunch compressors have longitudinal phase space diagnostics
Key BC20 / FACET Existing Diagnostics

X-band TCAV

E spectrum

2-4 wire scanners

W chicane and IP area diagnostics all new for FACET.
### FACET-II Stage 1 Diagnostics Overview

Standard e- beam diagnostics (*existing and new*)

<table>
<thead>
<tr>
<th></th>
<th>Injector</th>
<th>L1 &amp; BC11</th>
<th>BC14</th>
<th>L2 &amp; L3</th>
<th>BC20 &amp; IP</th>
<th>Total (Stage 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM</td>
<td>12</td>
<td>6 + 3</td>
<td>4 + 2</td>
<td>66</td>
<td>19</td>
<td>112</td>
</tr>
<tr>
<td>Toroid</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Wire scanner</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td>4 + 4</td>
<td></td>
</tr>
<tr>
<td>Profile monitor</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>TCAV</td>
<td>1 S</td>
<td>1 S</td>
<td></td>
<td>1 X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch Length</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Collimator</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FACET-II re-uses existing FACET e- beam diagnostics where possible
• **Goal:** Deliver compressed electron beam from S10 to experiments in S20

• **Major upgrade:** Positron damping ring

• **Scope:** Damping ring, positron bunch compressor & return line
FACET-II Diagnostics
Positron Transport Lines Overview

Positron Return Line – Sector 14

解放思想

335 MeV

e+ towards PDR

14-8a
14-8b
14-8c
14-8d

190 MeV

e+ from source

Diagnostics for e+ return system
optimize transmission and ring capture

Positron Return Line – Sector 10

解放思想

e+ to PDR

Vertical bend

Tune-up dump

Diagnostic waist

Horizontal bend

E spread screen

335 MeV

e+ from PRL
Positron Extraction and Compression – Sector 10-11

Provide to linac a beam of known:
• Charge
• Energy, energy spread & distribution
• Transverse emittance (projected)
• Bunch length

PEC diagnostics characterize positron beam before injection into linac at BC11
FACET-II Stage 2 Diagnostics Overview

Standard e+ beam diagnostics (existing and new)

<table>
<thead>
<tr>
<th></th>
<th>e+ source</th>
<th>e+ Return Line</th>
<th>Damping Ring</th>
<th>e+ Extraction</th>
<th>Stage 2 Total</th>
<th>Project Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM</td>
<td>46</td>
<td>62 + 35</td>
<td>28</td>
<td>22</td>
<td>193</td>
<td>305</td>
</tr>
<tr>
<td>Toroid</td>
<td>5</td>
<td>3 + 2</td>
<td></td>
<td>3</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>Wire scanner</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Profile monitor</td>
<td>4 + 1</td>
<td>2 + 5</td>
<td>5</td>
<td>17</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>TCAV</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Bunch Length</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Collimator</td>
<td>1</td>
<td></td>
<td>1</td>
<td>2</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

FACET-II re-uses existing FACET e+ beam diagnostics where possible
SYAG wiggler stripe spectrometer

Always-on, non-invasive energy spectrum measurement

Higher energy ➔

Max

-0.5°

-1.0°

-1.5°

-2.0°

Vertical Chicane Magnets

Dispersed Electron Bunch

Chirp scan, detuned compression

SLAC-PUB-16310
FACET-II Diagnostics
Beam Position Monitor Processors

BPMs are the primary diagnostic for monitoring, feedback and tuning
FACET-II Diagnostics
Relative Bunch Length Monitors

Coherent edge radiation monitor
- Mirror + pyrometer
- $f > 300$ GHz
- $I_{pk} > 300$ A

$\rightarrow$ BC11, BC14
$\rightarrow$ BC20 (existing)

Wall gap monitor
- Ceramic gap + diode
- $f < 300$ GHz
- $I_{pk} < 300$ A

$\rightarrow$ Injector, e+ system

Non-destructive, pulse-by-pulse bunch length monitoring, but need TCAV calibration
Bunch Length Monitors

Pyroelectric bunch length monitor modeled after LCLS BC1/BC2.

Relative diagnostic, works well for finding and maintaining peak compression.
FACET-II Diagnostics
Toroid Beam Charge Monitors

Resonant toroid current transformers with calibration winding

Typically:
- 8-turn signal
- 1-turn calib.
- $f \sim 50 \text{ kHz}$

CAMAC TCM module + SLAC preamplifier – used at FACET
- Rectifier to S&H circuit to 10-bit gated ADC
- $\sim 5\%$ absolute accuracy and precision at 3 nC

LCLS upgrade: low-noise preamp + twinax cable + 12-bit VME ADC
- $<1\%$ accuracy, $<0.2\%$ noise at 150 pC

Toroids in FACET-II monitor total beam charge at boundaries of functional areas
FACET-II Diagnostics
Linac Emittance Measurement

<table>
<thead>
<tr>
<th>Location</th>
<th>Sector</th>
<th>Energy [GeV]</th>
<th>σₓ (µm)</th>
<th>σᵧ (µm)</th>
<th># of wire scanners</th>
<th># existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>After BC11</td>
<td>Sector 11</td>
<td>0.335 – 1.0</td>
<td>145-215</td>
<td>110-215</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>End of L3</td>
<td>Sector 19</td>
<td>9.0 – 10.0</td>
<td>35-57</td>
<td>38-56</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

- Relocate wire scanners from Sectors 1 & 2 to FACET-II linac
- Replace standard 10-foot RF structures with modified 9.4-foot sections

Wire scanners characterize emittance preservation across linac-BC system
FACET-II Diagnostics
Guidelines behind diagnostic choices

BPM in every focusing magnet + key dispersive locations
Toroids upstream/downstream of every transport line + BC
At each BC:
  TCAV + relative BLM
  Energy spread screen/wire, BPM, collimator pair
Multi-profile emittance measurement brackets linac
  → Wire scanners after BC11, before BC20
x-y magnet mover at every sextupole
Questions
Key LCLS drive laser diagnostics:
- Transverse distribution (virtual cathode camera)
- Pulse length (cross correlator)
- Transport cameras → steering feedback
- Beam charge → intensity feedback, QE monitoring

Laser diagnostics reflect ongoing development and current practices at LCLS
Existing Linac BPMs

Existing linac CAMAC BPM processors date from SLC
- 70 BPMs in FACET-II linac – 8 per sector
- Broadband, external gate – can resolve bunches 60 ns apart

Existing BPMs are sufficient for interlaced e- / e+, but not co-accelerated beams
Ce:YAG scintillator crystal
Al/Ti OTR foil
Phosphor

- Transverse profile/emittance measurements
- Energy spread (BCs)
- Bunch length (TCAVs)

YAG: low E, dispersed beam
OTR: high E, focused beam

→ COTR is a problem for compressed bunches

Profile monitors are most efficient and intuitive transverse diagnostic available
FACET-II Diagnostics
COTR from compressed bunches - LCLS

- Upstream foil inserted
- Microbunching spoiled
- Incoherent OTR only

- Nominal compression
- Microbunching present
- Coherent OTR

- Max compression
- Microbunching enhanced
- Strong COTR

- Microbunched structure at optical wavelengths → coherent OTR emission
- Ways to mitigate this effect for YAG screens: screen tilt, fast camera gating
- Dispersed beams, e.g. E-spread or TCAV screens

Strong COTR from compressed bunches → use wire scanners after BC11 for focused beams
BC20 Diagnostics Controls

BPMs: 21 FFBT “NiTnH” CAMAC processors in FACET
- 24 in BC20E + BC20P + FFS
- Add 6 modules to existing crates

Toroids: 5 TCM CAMAC modules
- Add 2 modules to existing crates

YAG screen:
- Add camera & POE to spare camera server channel

Use existing controls for diagnostics - add channels and run cable if necessary
Bunch Length Monitors

Pyroelectric bunch length monitor modeled after LCLS BC1/BC2.

Relative diagnostic, works well for finding and maintaining peak compression.
FACET-II Diagnostics
Transverse RF Deflecting Cavities (TCAV)

- TCAVs put y-z correlation on beam.
- Measure bunch length with downstream profile monitor or wire scanner.
- Self-calibrating ($f_{RF}$ well known)

TCAVs before/after linac, BC14 for measurement of bunch length & distribution

---

Injector 55cm S-band TCAV
Designed for LCLS-II

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>Length [m]</th>
<th>$f_{RF}$ [MHz]</th>
<th>$\sigma_z$ [µm]</th>
<th>Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>TCAV0</td>
<td>0.55</td>
<td>2856</td>
<td>800</td>
<td>OTR04</td>
</tr>
<tr>
<td>After BC14</td>
<td>TCAV3</td>
<td>2.4</td>
<td>2856</td>
<td>30</td>
<td>15-9</td>
</tr>
<tr>
<td>End BC20</td>
<td>XTCAVE</td>
<td>0.5</td>
<td>11424</td>
<td>1</td>
<td>IP2B</td>
</tr>
</tbody>
</table>

$\sigma_z < 5 \mu m$
mapped

LCLS TCAV3
XTCAV horizontal at dump

Dump, TCAV off

$\sigma_y = 1185.3\ \mu\text{m}$

$\sigma_x = 356.0\ \mu\text{m}$

$rms\ X = 553.256\ \mu\text{m}$

$rms\ Y = 1459.84\ \mu\text{m}$

$Q = 1.99719\ \text{nC}$

Dump, TCAV on

$\sigma_y = 1185.3\ \mu\text{m}$

$\sigma_x = 629.8\ \mu\text{m}$

$rms\ X = 833.529\ \mu\text{m}$

$rms\ Y = 1459.75\ \mu\text{m}$

$Q = 1.99713\ \text{nC}$
2-jaw energy collimation in each bunch compressor:
- Beam quality / tails
- Potential high $I_{pk}$ mode (horn cutting)

Collimation in bunch compressors gives additional control of longitudinal distribution
SLM at arc - straight boundary:
- Transverse beam size
- Bunch length
- Damping times
- Instabilities

Synchrotron light monitor for transverse/longitudinal study of stored beam
FACET-II Diagnostics
Positron Damping Ring - BPMs

FACET NDR Tune spectrum
FACET NDR Current envelope

Tune monitor and envelope current monitor are derived from BPM signals
BC20 Stage 3 Beamline Layout

3D render in CAD application
- Existing stands and tables
- Models / bounding boxes of actual magnets
BC20 Diagnostics

- X-ray stripe (Wiggler + YAG) energy spectrum measurement
- Resonant toroid BCM at entrance and exit of chicane
- Stripline BPM near each focusing element
- TCAV relocated downstream to common line

Beamline diagnostic devices are largely re-used from FACET chicane
2-Bunch BPM Design

Signal on electrode:
- Proportional to $I_{\text{beam}}$, $x_{\text{beam}}$
- Normalize to bunch length monitor

Mix stripline signals with reference RF to resolve 2-bunch orbit in linac

\[
x^+ = \frac{1}{I^+ S_x} \left( \frac{R^+ - L^+}{R^+ + L^+} \right) \\
x^- = \frac{1}{I^- S_x} \left( \frac{R^- - L^-}{R^- + L^-} \right)
\]

\[
x_E = x^+ + x^- \quad \quad x_p = x^+ - x^-
\]
2-Bunch BPM Design

2-bunch resolution < 100 μm using LCLS/LCLS-II electronics

\[ Z(\omega) = Z_0 \frac{\alpha}{4\pi} \sin \left( \frac{\omega \ell}{c} \right) e^{\frac{i\pi}{2} \frac{\omega \ell}{c}} \]

\[ f_{RF} = 2856 \text{ MHz} \]

From RF

BPM

2856 MHz

Sum

Diff

Digitizer

Digitizer

250 MHz BPF

Digitizer

Digitizer

300 MHz AFE

300 MHz AFE

30m RG-232
FACET-II employs a mixture of legacy and modern controls with tools developed for FACET and LCLS to pass data back and forth.
Matlab/python scripts regulate beam parameters at individual key locations:

Energy and bunch length: upstream RF phase & amplitude

Orbit feedback: use 4 upstream correctors, stabilize \([x \ x' \ y \ y']\)

Simple feedbacks at key locations stabilize drift on 5-10 second time scale
Software developed for FACET (and LCLS) automates many standard tuning and setup tasks:

- Troubleshooting – correlation plot, jitter
- Characterization – profile monitor, wire scans, emittance, bunch length
- Corrections – dispersion, matching, phase scans
- Configuration changes – IP config, longitudinal setup

Matlab physics applications provide online analysis tools and iterative correction for fast, interactive tuning.
### FACET-II Diagnostics
**Recovered components from Sector 0-10**

<table>
<thead>
<tr>
<th>Beamline components:</th>
<th>Controls hardware:</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 wire scanners</td>
<td>116 CAMAC crates</td>
</tr>
<tr>
<td>40 stripline BPMs (PRL)</td>
<td>79 CAMAC PDU/STB (timing)</td>
</tr>
<tr>
<td>13 toroids (various)</td>
<td>13 FIDO (timing)</td>
</tr>
<tr>
<td>24 ion chambers</td>
<td>119 CAMAC DAC (magnet)</td>
</tr>
<tr>
<td>5 profile monitors (PRL)</td>
<td>179 CAMAC SAM (magnet, analog)</td>
</tr>
<tr>
<td>1 gap BLM</td>
<td>140 CAMAC 605 BPM</td>
</tr>
<tr>
<td>1 faraday cup</td>
<td>97 CAMAC 972 BPM</td>
</tr>
<tr>
<td>4 stoppers – tune-up dump</td>
<td>30 CAMAC TCM (toroid)</td>
</tr>
<tr>
<td>2 2-jaw collimators</td>
<td></td>
</tr>
<tr>
<td>2 fixed collimators</td>
<td></td>
</tr>
</tbody>
</table>
Linac Low-level RF – L1S

PAC & PAD:
- Phase & Amplitude Controller/Detector
- Feedback in IOC

Linac has installations at:
- L1S (2 stations)
- L1X linearizer
- TCAVs (2 stations)

PAC only installations:
- L2 phase reference
- L2 energy feedback
- L3 energy feedback

PAC/PAD LLRF control and feedback wraps around existing RF hardware