Advanced Beam Instrumentation supporting AARD at the A0-Photoinjector

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Agenda

• Motivation
• Overview on long. beam diagnostics
• OTR Introduction
• Ongoing Activities
  – Streak Camera
  – Martin-Puplett Interferometer
  – OTR Interferometer
  – EOM-based Time-of-Arrival

• Proposed New Activities
  – Long. diagnostics using CTR
  – Long. bunch profile using EOS
  – HOM signal processing
  – Beam tests of a cold ILC cavity BPM prototype
  – Waveguide pickups
**Motivation**

- Need a set of reliable basic beam instruments (upgrades required, see also Ray’s talk):
  - Intensity, position (orbit), transverse beam size (emittance)
- AARD demands advanced beam diagnostics, in particular in the longitudinal domain to study and observe the bunch dynamics in AARD experiments:
  - Bunch length
  - Longitudinal bunch profile
  - Bunch time-of-arrival (wrt. RF phase, or relative between two locations)
- No best “I can do everything” instrument available to fully characterize longitudinal bunch parameters
  - Calibration, measurement range (fs, ps) and time (single/multi shot), (non) invasive, resolution, reproducibility, etc.
## Longitudinal Beam Diagnostics

<table>
<thead>
<tr>
<th>Device</th>
<th>Applicable bunch lengths</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td><strong>Streak camera</strong></td>
<td>1 – &gt;100 ps</td>
<td>• Well understood, expensive commercial device</td>
</tr>
<tr>
<td>Ongoing activity, Bunch profile</td>
<td></td>
<td>• Single bunch, single pass capability (intensity limited)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dispersion effects dominate at short bunch length measurements</td>
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<tr>
<td></td>
<td></td>
<td>• Can provide arrival times and jitter</td>
</tr>
<tr>
<td><strong>Martin-Puplett Interferometer</strong></td>
<td>&lt; few ps</td>
<td>• Slow response, scanning using many macropulses</td>
</tr>
<tr>
<td>Ongoing, length</td>
<td></td>
<td>• Susceptible to upstream CSR and wakefields</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Missing phase information makes details of the bunch profile difficult to obtain</td>
</tr>
<tr>
<td><strong>CTR angular distribution</strong></td>
<td>&lt; few ps</td>
<td>• Parametric measurement of the bunch profile, bunch shape must be assumed</td>
</tr>
<tr>
<td>Proposed, length</td>
<td></td>
<td>• Scanning over many macropulses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Susceptible to upstream CSR and wakefields</td>
</tr>
<tr>
<td><strong>Electro-optical sampling</strong></td>
<td>100 fs – 2 ps</td>
<td>• Single shot capability, fairly expensive, needs a (high power) laser synchronized to the beam</td>
</tr>
<tr>
<td>Proposed, profile</td>
<td></td>
<td>• Must understand behavior of electro-optical crystal in the frequency regime corresponding to the expected bunch length</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Susceptible to upstream CSR and wakefields</td>
</tr>
<tr>
<td><strong>Waveguide pickups</strong></td>
<td>200 fs – 2 ps</td>
<td>• Inexpensive and simple, but calibration very difficult.</td>
</tr>
<tr>
<td>Proposed, length</td>
<td></td>
<td>• Does not give shape information, just rough bunch length</td>
</tr>
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</table>
(Optical) Transition Radiation

- Charged particles pass through a media boundary
- Monitoring of trans. beam profile (→ emittance), bunch length and energy
Streak Camera Principle

- Dual-sweep streak camera *Hamamatsu* C5680 (1.5 ps FWHM res.)
- Addition of M5676 synchroscan plugin module and the C6878 phase-locked delay box enabled new series of experiments at A0.

Based on VG by B. Yang for ANL/S35 review
Streak Camera Summary

- **Streak camera**
  - Views UV-visible light from a (intercepting or non-intercepting) conversion mechanism, e.g. OTR, OSR to observe the bunch.
  - Provides a 2-D bunch profile, allowing sliced measurements:
    - Vertical axis -> time axis
    - Horizontal axis: preserved (spatial, energy, spectral)

- **Features**
  - Synchroscan unit (81.25 MHz, phase-locked to master oscillator)
    - ~1 ps RMS jitter
    - Synchronous summing of micropulses (statistics, intensity)
  - Delay unit provides long term stability
  - Dual-sweep allows simultaneous observation of micropulses

- **Resolution**
  - 1.5 ps FWHM (monochromatic), larger for broadband light
• Bunch length elongation with micropulse charge and slice beam-size effects (50%) at 4 nC observed.
• Bunch compression and transit time changes for different momenta in double doglegs were measured.

The line is a fit showing that $R_{56}$ is $0.18$ m

Lumpkin, Ruan: BIW08
Emittance exchange results in bunch compression.
**Martin-Puplett Interferometer**

- **Martin-Puplett interferometer**
  - Needs many beam pulses to resolve the temporal convolution
  - Difficult to calibrate the detectors
MP Interferometer Results

- Measurement experiment 2008:
  - Using improved pyroelectric detector (DESY) with suppressed interference
  - Measured spectrum does not show interferences
- Bunch length measurement results (deflecting mode cavity on/off), and comparison:
  - Autocorrelation with ratio = 0.69
  - Reconstructed bunch ratio = 0.43
  - Streak camera ratio = 0.66
- **MP issues**
  - Detector response (low freq.) and calibration
  - Diffraction effects at lower wavelength

Emittance Exchange Cavity On

- Interferogram
- Spectrum
- Adjusted
- Raw

8/18/2008
A0-Photoinjector Review 12
MP Interferometer: Next Steps

- Plans
  - Calibration of the pyroelectric detector frequency response
  - Experiments with other detector types
    - Golay cell
    - Schottky detector
  - Reproduction and improvements of the MP interferometer hardware (borrowed from DESY).

Martin-Puplett Interferometer (borrowed from DESY)
OTR Interferometer (OTRI)

OTRI principle of operation.

OTRI normal incidence setup & optical readout.

• **OTRI features:**
  - Beam divergence measurement
  - Beam energy (better accuracy)
  - Single shot measurement (no scanning)

OTRI apparatus at the A0 Photoinjector.
OTRI Results

Measured (solid lines) and computed (dots) fringes for the Mylar (left) and Mica (right) -based interferometers at normal incidence, 16 MeV beam with the energy spread of 0.6% and the readout resolution of ≈0.9 mrad.

- **Next steps**
  - Experiment with thinner foils
  - Beam divergence measurements at higher beam energies
  - Measurements in the EEX line?!

- **Results**
  - Measurements taken with 2.5 µm Mylar and 6 µm Mica double foils
  - Mylar foils show very good agreement with simulation!
  - Beam divergence measurement accuracy ~ 15 %

The interference pattern obtained at 45° incidence setup with Mylar (left) and Mica (right) -based interferometers at the beam energy of 16 MeV.
To quantize long beam dynamics a sub-ps resolution bunch-by-bunch time-of-arrival measurement is required!

- An electro-optical modulator (EOM) fed by femto-second fiber laser pulses utilizes the sampling of a high slew-rate pickup signal.
- The bunch time-of-arrival is referenced to the RF master oscillator.

### Principle of the Beam Phase Monitor

<table>
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<tr>
<th>laser pulses from fiber link</th>
<th>EOM</th>
<th>beam pick-up</th>
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The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

### Time-of-Arrival to Modulation Voltage

- early
- correct
- late

Reference laser pulse

Modulate laser pulse with zero-crossing voltage from beam pickup.

courtesy F. Loehl, DESY
TOF Preliminary Results

- Initial results:
  - EOM setup established
  - First measurements taken
  - Resolution limited by
    - Noise & jitter sources (EMI, 81.25 MHz master)
    - Pickup response
    - Long cable runs (> 50 ft)
    - Fiber laser PLL lock
  - Resolution: ~3 ps (RMS)

- Next Steps
  - Identify and improve jitter source, improve system resolution (100-200 fs)
  - Improved beam pickup
  - New location with shorter cable runs (in the cave?!)
Long. Diagnostics using CTR

- Large target $D \gg \gamma \lambda$ and far field $L \gg \gamma^2 \lambda$
  - Angular distribution does not depend on frequency
  - Measurement using OTR (visible)
- Small target $D < \gamma \lambda$ and/or near field $L < \gamma^2 \lambda$
  - Angular distribution depends on frequency
  - Measurement using coherent TR (CTR) (far-infrared)
- Transition region $D \sim \gamma \lambda$
  - Angular distribution sensitive to bunch length
  - Tune $D$ as function of $\gamma$ and $\lambda$ to be in this transition region
  - Map angular CTR distribution of measure the bunch length

Proposal from R. Fiorito and A. Shkvarunets, University of Maryland

Diameter $D$

Coherent TR distribution for 16 MeV electrons at A0 for two bunch lengths

8/18/2008
Results from PSI-SLS (100 MeV)

Energy distribution of CTR

Single Gaussian bunch fit
0.69ps, RMS=5%

Double Gaussian bunch fit,
RMS=1.26%,
0.57ps, Am=1;
2.84ps, Am=0.2, Shift=1.53ps

Reference: paper WEPC21, DIPAC 07
Electro-Optical Sampling (EOS)

- All 3 single shot schemes are realized.
- Temporal decoding resolve bunch length <100 fs using Ti:sapphire laser and GaP crystal at DESY.
- At DESY, deflecting mode cavity proved the effectiveness of EO techniques.
- Most current EO experiments are done on high energy electron beams.
- Most current EO efforts are focused on electron bunch length less than 200 fs.

Three common single shot EO detection techniques to measure sub-ps bunch length.
Comparison of EOS Techniques

<table>
<thead>
<tr>
<th>Spectral Decoding</th>
<th>Temporal Decoding</th>
<th>Spatial Decoding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong>&lt;br&gt;• Simple laser system&lt;br&gt;• Single shot measurement&lt;br&gt;• High repetition rate</td>
<td><strong>Pros</strong>&lt;br&gt;• Large time window&lt;br&gt;• High resolution (110 fs)&lt;br&gt;• Single shot measurement</td>
<td><strong>Pros</strong>&lt;br&gt;• Simple laser system&lt;br&gt;• Single shot measurement&lt;br&gt;• High resolution (160 fs)&lt;br&gt;• High repetition rate</td>
</tr>
<tr>
<td><strong>Cons</strong>&lt;br&gt;• Limited resolution (200 fs)&lt;br&gt;• Distorted signals for e⁻ bunches &lt; 200 fs</td>
<td><strong>Cons</strong>&lt;br&gt;• Complex laser system (mJ laser pulse energy)&lt;br&gt;• Low repetition rate</td>
<td><strong>Cons</strong>&lt;br&gt;• Complex imaging optics&lt;br&gt;• Good for clocking, but tough to get the e⁻ bunch information</td>
</tr>
</tbody>
</table>

- For the current A0 research requirements and laser availability we will focus on the spectral and spatial decoding techniques.
1. Measure longitudinal bunch information of low energy electron beams

$$EO \text{ resolution} \Leftrightarrow \frac{2R}{\gamma c}$$

Here R is the distance between crystal and electron bunch center

- What will happen when $\gamma$ is low?
- Can we deconvolute the signal?

Current energy in A0 and upgraded A0 is a very good fit for this study

2. Investigate the use other laser wavelengths, via fiber lasers, for EO sampling at these bunch length.

<table>
<thead>
<tr>
<th>Ti:Sa Laser</th>
<th>Fiber laser</th>
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<tbody>
<tr>
<td>Cost</td>
<td>High</td>
</tr>
<tr>
<td>Transport</td>
<td>Free space</td>
</tr>
<tr>
<td></td>
<td>Complicated</td>
</tr>
<tr>
<td>EO study</td>
<td>Successfully Done</td>
</tr>
</tbody>
</table>

Recent simulations show that a fiber laser based EOS is feasible!
HOM Signals for Beam Monitoring

• **HOM as BPM**
  - $\text{TE}_{111-6}$ narrow band read-out
  - Beam-based calibration data, to orthogonalize the polarization planes of the excited eigenmodes per SVD algorithm.

• **HOM as phase monitor**
  - Comparison of the leaking 1.3 GHz fundamental ($\text{TM}_{010}$) to the first monopole HOM ($\text{TM}_{011}$)
  - Broadband Scope analysis
  - $<0.1^0$ @ 1.3 GHz resolution (equiv. ~200 fs RMS)
HOM Development & Analysis Plans

- Develop read-out hard- and firmware for HOM Analysis
  - Narrowband System:
    - Low-noise, high-IP3 downmix hardware based on SLAC/KEK/DESY ILC collaboration experience
    - Try to incorporate flexibility, tunable to downmix different dipole and possibly monopole bands
    - Low cost per channel custom VME digitizers, capable of processing the HOM signals using the onboard FPGA
  - Broadband system: High-speed oscilloscope

- HOM Analysis
  - The above instrumentation can be used to provide beam position, trajectory, and phase measurements to optimize performance.
  - Because the HOM spectrum is a function of the cavity shape, the observed modes provide a powerful cavity diagnostic for study and simulation.
Other Activities

• Cold L-Band cavity BPM
  – ILC collaboration activity
  – Beam test of a prototype
  – Verify tuning, signal orthogonality and levels, resolution, reproducibility

• Waveguide Pickups
  – Horn antenna, waveguide & diode detector assembly
  – Available frequency range: 90-900 GHz
  – Simple setup for relative bunch length estimation (SLAC ESA, CERN CLIC)
Summary

• Advanced beam instruments play a mission critical role to characterize the beam parameters when performing current and future A0-Photoinjector AARD experiments.

• A comprehensive, challenging A0 instrumentation plan is proposed, it has some focus in the longitudinal domain:
  – Utilizing advanced optical, electro-optical and microwave state-of-the-art technologies.
  – Continuing ongoing developments, i.e. streak camera, \textit{MP} interferometer, OTRI, and time-of-arrival diagnostics.
  – Start of new activities, i.e. CTR, EOS, HOM, cavity BPM, and waveguide pickup instrumentation.

• Local and international collaborations are established, and are crucial for the success of the program!