Optical Techniques for Ultra-Short Bunches
Rasmus Ischebeck
Let's first have a look at the object of study, the beam. This beam can be represented by the particle distribution in the six-dimensional phase space, extended by transverse coordinates x and y, transverse angles x' and y', time t and energy delta. When we speak about the longitudinal phase space, we mean the projection on these last two dimensions, and in particular the time, which is very difficult to measure with femtosecond accuracy.

There are ways to transform the beam in phase space. No diagnostics exists for the entire distribution. We can only measure projections into one or two of these dimensions. Additional beam line elements, such as quadrupole magnets and transverse deflecting RF cavities can then be used to do phase space transformations, which allow us to see dimensions that are not easily accessible, and we can use mathematical reconstruction algorithms to infer 3d information.
Phase space transformation with RF deflecting cavity
Reference for all longitudinal diagnostics
Shown here: installation in LCLS
(1) mapping of the time axis onto the vertical angle by the transverse deflecting structure, (2) variation of the horizontal phase advance between the deflector and the profile monitor by adjusting the quadrupole lenses, while keeping the vertical phase advance approximately constant such that a vertical angle is transformed into a vertical position, and (3) measurement of the horizontal beam size in several slices of the beam.
Measurements of full phase space possible!
Femtosecond resolution, depending on:
— emittance
— streak strength
When designing an accelerator, we can carefully choose an instrumentation suite that lets us
> set up the accelerator
> measure beam properties
> control the stability of the machine via feedbacks

Thus, let us distinguish longitudinal and transverse diagnostics. It is not a clear distinction, as we can transform the phase space dimensions, but it’s a start.

Let’s start with direct time domain methods.
Streak camera
Rasmus Ischebeck > Optical Techniques for Ultra-Short Bunches

Hence, we employed the RFDEF to diagnose a 30 fs electron bunch of SACLA. The bunch-length measurement system, as shown in Fig. 26, comprises a C-band rf deflector (RFDEF), a beam drift space, and a high spatial resolution SCM, as mentioned in the previous section. This RFDEF operated at 5712 MHz is driven by a high-power rf source including a 50 MW pulse klystron.

The operating principle of the RFDEF is as follows. The RFDEF is a backward traveling-wave structure at the operation rf mode of HEM11. When the electron beam is injected into the structure at an rf zero-cross phase, the RFDEF pitches the beam bunch around its center to project an image of a longitudinal bunch structure on the screen of the above-mentioned SCM. The relation between the deflection voltage, \( V_y \), and the projected bunch length on the screen, \( l_y \), is given by

\[
V_y = \frac{l_y L_d}{k_c z_e k_a C^2 z_e};
\]

where \( L_d \) is the drift length between the RFDEF longitudinal center and the surface of the SCM screen, \( k_a \) is the wave number of the RFDEF, \( z_e \) is the bunch length, and \( p_z \) is the longitudinal momentum of the electron bunch.

\( V_y \) must be 40 MV in the case of \( L_d = 5 \) m to obtain a bunch-length measurement sensitivity of 200 fs = mm on the screen of the SCM with a spatial resolution of less than 2.5/\( C_{22} \) m.

To realize this measurement system, a special backward traveling-wave accelerating structure with the HEM11-\((5/6)\) transverse mode at 5712 MHz was developed, as shown in Fig. 27. This accelerating structure has racetrack-shape rf coupling irises to prevent rotation of the deflection plane of the HEM11 mode. The main parameters of this backward traveling-wave accelerating structure are tabulated in Table II, and the dispersion relations of the X and Y modes in a fabrication model of the accelerating structure are depicted in Fig. 28. In the figure, the X and Y modes are sufficiently separated by the iris. Furthermore, even though the \((5/6)\) mode is employed, a group velocity, \( v_g \), of about 0.02 \( c \) in the accelerating structure is achieved. These rf characteristics guarantee stable high-power rf operation of the accelerating structure.

<table>
<thead>
<tr>
<th>TABLE II. RF specifications of the RFDEF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total deflecting voltage ( V_y ) 40 MV</td>
</tr>
<tr>
<td>rf deflecting phase ( /C_{30} ) a 0 degree</td>
</tr>
<tr>
<td>Fractional bunch length for x-ray oscillation ( /C_{27} z_e ) 200 fs</td>
</tr>
<tr>
<td>Beam energy at the deflector ( p_z ) c 1.45 GeV</td>
</tr>
<tr>
<td>Resonant frequency ( f_a ) 5712 MHz</td>
</tr>
<tr>
<td>Type of structure CZ</td>
</tr>
<tr>
<td>Resonant mode HEM11</td>
</tr>
<tr>
<td>Phase shift per cell ( /C_{12} D ) 5/( C_{25} = 6 ) rad</td>
</tr>
<tr>
<td>Group velocity ( v_g ) = ( c/ C_{0} 2 ) 16%</td>
</tr>
<tr>
<td>Filling time ( T_f ) 0.27/( C_{22} ) s</td>
</tr>
<tr>
<td>Unloaded ( Q_0 ) 11500</td>
</tr>
<tr>
<td>Transverse shunt impedance ( z_y ) 13.9 M/( C_{10} = m )</td>
</tr>
<tr>
<td>Length of structure ( L ) 1.7/( C_{22} ) m</td>
</tr>
</tbody>
</table>

A sub-picosecond time resolution can be achieved with a streak camera. Shown here: a measurement at SACLA
Another method to achieve sub-picosecond resolution is to probe directly the transverse electromagnetic field of the electron bunches. An electro-optical crystal, i.e. one that exhibits the Pockels effect, is introduced into the vacuum chamber, and the change in birefringence is probed by a short laser pulse.
Cross-correlation with an external laser pulse
Pockels effect allows to cross-correlate coherent THz fields with laser
Reflectivity change allows to cross-correlate X-rays with laser
Measure:
Bunch arrival time
Bunch length
Also known as “Electro-optical effect”
Electric field induces birefringence in crystal
Birefringence can be probed with a polarized laser
Pockels Effect can probe down to time scales of 10…100 fs
Effect is totally reversible
Possible materials
ZnTe
LiNb
GaP
The setup has been transformed from an experiment to a reliable diagnostics. Shown here: electro-optical monitor at the ANKA storage ring, designed in a KIT–DESY–PSI collaboration.
Beware of wake fields!
Measurements with this monitor for different compression (middle), and for different bunch charges (right). To the left, a comparison with a streak camera measurement.
Limitations: resonances in crystal, and available laser pulse length.

Two-pulse Cross-FROG:
Electro-optic sampling with sub-pulse width time-resolution
> Sampling with 500fs FWHM transform limited probe
> ReD-FROG with sum- & difference frequency sidebands
=> Retrieve electric field profile as obtained with 45fs FWHM probe
Another possibility: put the electro-optical crystal in a box outside the accelerator vacuum, and transmit the EM field through cables. 

—> Possibility to measure arrival time
Another possibility: ignore the phase of the spectrum of the bunch, and measure only spectral amplitude

→ Stabilization for feedbacks
Reminder: bunch compression
Calculated spectrum, assuming Gaussian bunches, for different compression stages, and for different operation modes of SwissFEL. Note logarithmic scales on both axes!
Careful! Ignoring the phase of the radiation means that generally, you cannot reconstruct the bunch length from the spectrum. Take a look at this spectrum: it peaks at 550 nm, so you may be lead to believe that the pulse is 1.8 fs long.

In fact, this is the spectrum of the sun. Pulse length = age of the sun: 4.6 billion years! — almost 32 orders of magnitude off…
Setup at LCLS
Detection of coherent edge radiation from the bunch compressor
Signal peaks at maximum compression
Similar setup at SACLA (free electron laser at SPring8 in Japan)
I will now show a comparison of CSR measurement with bunch length measurements using transverse deflecting cavity
The bunch length observed with the CSR monitor was calibrated by using the RF-deflector's data. Electron beam was bypassed through BC3. Bunch length was changed by the RF phase of the S-band accelerating structures. Estimated bunch length measurement sensitivity is about 6% at a bunch length of 170fs.
CSR intensity as a function of the RF Phase of the C-band accelerating structures before BC3
CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3.
Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of the RF deflector.
Coming back to the power distribution of CSR, we see that we could improve resolution if we detect selectively near an edge.
Setup installed at the SwissFEL Injector Test Facility
Beam splitters, then using grids as edge pass filters
Indeed, sensitivity to X-band phase changes (i.e. compression changes) increased when using only high-frequency radiation.
SwissFEL has very low charge operation modes, thus we are looking especially into sensitive THz detectors. Here: Schottky diode with spiral antenna for broadband sensitivity
This detector is very fast: detection of two bunches separated by 28 ns easily possible
Similar idea: detect different frequency components. Here: five channels separated by waveguides, for GHz frequencies (SACL after first compression)
Dependency of different frequency signals on compression
Each stage acts as dispersive element + filter for next stage

- Parallel readout
- 4 Stages cover one order of magnitude in $\lambda$

THz spectrometer with 120 channels implemented at DESY, for FLASH
Photo of the setup
Parallel readout of a total of 120 channels in pyro detector arrays
Reconstruction with Kramers–Kronig relation.
Keep in mind: this is the shortest pulse compatible with the spectrum. The spectrum in itself is also compatible with a bunch length of 4.6 billion years!
Optical Techniques for Ultra-Short Bunches
Rasmus Ischebeck

> Thank you for slides, graphics, photos, movies and plots provided by:
> Franziska Frei
> Joe Frisch
> Nicole Hiller
> Patrick Krejcek
> Hirokazu Maesaka
> Yuji Otake
> Volker Schlott
> Stephan Wesch
> ACST GmbH
> AFS Inc.
> BBC
> Wikimedia Commons

Slides available at: http://www.ischebeck.net

rasmus.ischebeck@psi.ch