Laser pulse shaping for high brightness electron source

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• The control of the laser pulse geometry is required in order to minimize the space charge non linear forces and implement effective emittance compensation schemes

• Laser optimal 3D distribution **beer can** or uniform filled **ellipsoid**

• Other qualifying laser parameters:
  – high energy, at the proper wavelength
  – limited jitters and fluctuations
  – Reliability
  – repetition rate

• The beer can shape is obtained with
  • Flat top time shape
    • Pulse duration $10^\circ$ RF resolution (rise time) better than $1^\circ$ RF, ripple
  • Uniform hard-edge circular spot

• Combined spatial and temporal shaping for ellipsoidal shape
• Incomplete overview of the laser pulse shaping approaches
• Generation of flat top time pulse
  • Programmable frequency domain IR shapers
    – Liquid crystal mask spatial light modulator
    – Acusto Optic Programmable Dispersive Filter DAZZLER
  • Multi-stage pulse shapers
    – IR filters + UV shaping
    – UV dazzler
• Time domain flat top
  – Un-coherent pulse stacking
  – Coherent pulse stacking
• Laser transverse shaping
• Strategy for the generation of uniformly filled ellipsoidal laser
• Conclusions
• The electro-optical devices can control the laser pulse at sub-ns resolution
• Spectral amplitude and phase manipulation for time shaping at sub-ps resolution
• Large bandwidth source is desirable to high fidelity control the pulse profile: Ti: Sa. This systems are limited by repetition rate.
• Spectral amplitude and/or phase modulation through programmable filter
Programmable liquid crystal (LC) array placed in the Fourier plane of a 4f system. Here, focused spectral components can be selectively attenuated or phase shifted when an external voltage is applied to the liquid crystal.

Alignment difficult and limits for tunability

Using LC SLM phase modulation driven by a genetic algorithm, Yang et al. significantly improved the emittance.


A co-propagating acoustic generates a transient Bragg grating in a birefringent crystal, to diffract selectively the optical wavelengths.

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programmable</td>
<td>Efficiency &lt; 50%</td>
</tr>
<tr>
<td>Alignment</td>
<td>$\lambda = 650-1650$ nm</td>
</tr>
<tr>
<td>Tunability</td>
<td>Eth=0.1GW/cm$^2$</td>
</tr>
<tr>
<td>Phase &amp; amplitude</td>
<td>Max duration 10 ps</td>
</tr>
<tr>
<td>Reliability</td>
<td>Rep rate 1 KHz</td>
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</tbody>
</table>

$\Delta T=10\text{ps} \quad r_t=1\text{ps}$

$\lambda =800$ nm

Dazzler by Fastlite

C. Vicario et al, proc EPAC 2004

P. Tournois et al., Opt: Comm., 140, (1997), 245
Amplification and UV conversion

- The IR pulse shapers should pre-compensate the distortions experienced by the flat pulse in the amplifier and the harmonic conversion.
- Amplifier distortions: red-shift, gain narrowing and high order phase can be effectively compensated.
- Harmonics distortions:
  - High efficiency implies small bandwidth
  - The spectrum can be strongly modified especially for short IR pulse.
  - Tilting of the non-linear crystal determines asymmetry in the harmonic spectra.
  - The harmonic generation increase the ripples and worse the rise time.

Two stages time shaping: implemented at SPARC

The long rise time could be improved by properly clipping the tails of the UV spectrum. This was accomplished by the UV stretcher in order to have allow spectral masking and variable pulse length. Pulse shaping IR DAZZLER and UV stretcher.

Also starting from a gaussian spectrum (no IR shaper) and a proper cut is possible to achieve a flat top like profile in the stretcher.

Simulations
UV pulse shaping for FERMI

MAIN FEATURES:
- Fourier-domain shaping based on transmission diffraction gratings
- 2-element deformable mirror (DM) with multilayer coating
- Amplitude band-pass filtering by knife edges
- The version shown below starts from a short UV pulse and includes variable stretching, a lower loss version (in use now) starts with a long UV pulse and does not include the stretching

Cross-correlation traces of flat-top pulses with different duration

Miltcho Danailov, FERMI Trieste
Laser system layout SwissFEL

Amplified Ti:SA laser 780-845nm
DAZZLER and MAZZLER loop for wavelength tuning and transform limited pulse 25 fs @ 100Hz

UV pulse stretcher: four prism setup capable of stretching to 3-10ps, without significant losses
The UV pulse wavelength is spanned between 260-280 for best thermal emittance
UV DAZZLER for temporal manipulation
Wavelength tuning

Thermal emittance measurements

Exp. Cond.:
Q < 1 pC; 5.2 MeV
σ_{t,laser} = 4 ps rms;
DC field 25 MV/m
Commercial AODPF UV DAZZLER based on KDP crystal to work in the 250-410 nm range. Resolution 0.1 nm, rep.rate 1 KHz, maximum pulse length 5 ps with 7.5 cm crystal. Limit of the maximum input energy due to limited useful area in the crystal and to two photon absorption phenomenon. Pulse shaping on un-diffracted beam. Time domain pulse shaping for alternative high efficiency approach.
• The flat top distribution can be obtained by overlapping several delayed replica of a short pulse.
• N Michelson-like interferometer cascaded for the generation of $2^N$ replicas.
• The rise time and the ripples depend on the input pulse, the final length by $n$ replicas.
• ps input required: laser alternative to the Ti:SA
• Output interference between pulses is avoided by cross polarization and eventually chirped.
• Reduced losses
• Alignment can be difficult.

OPTICAL SETUP

Electron beam for different input length

M. Y. Sheverdin, Proc. PAC07 LLNL
Tomizawa, Quantum Electronics 37, 697 (2007)
Pulse stacking using bi-refringent crystal

Use crystal birefringence to generate delayed replicas along the ordinary and extraordinary axes. The time separation depends on the crystal length and on $\Delta n$:

$$t_d = t_o - t_e = \frac{n_o L - n_e L}{c}$$

$\alpha$-cut YVO$_4$ for ($\lambda>400$ nm) and $\alpha$-cut BBO ($\lambda>190$ nm).

Low losses for AR coated crystal. Poor flexibility.

$\alpha$-BBO

1 stage, 2 pulses

2 stages, 4 pulses

3 stages: 8 pulses

Coherent pulse stacking: DESY approach

XFEL demands for flat top at MHz repetition rate drive laser

The pulse shaping is done by stacking of ps IR pulses that interfere at the output polarizer

Pulse length depends on the number of crystals and the rise time and ripples depends on the input pulse length and the programmed phase

Relative interpulse phase control is accomplished by tuning the crystals temperature with accuracy of 0.03 °C

I. Will et al.; Optics Express 16 (2008) 14922
I. Will; NIM A 594 (2008) 119

Ingo Will, Guido Klemz, Max-Born-Institute Berlin, in cooperation with DESY
Stacked pulse for different pulse length

Low total transmission 10% but it can work with CsTe$_2$ cathode
Defined polarization output polarization for the harmonic generation
Shaper suitable for high repetition rate
Programmable through the temperature control

Ingo Will, Guido Klemz, Max-Born-Institute Berlin, in cooperation with DESY
REFRACTIVE HOMOGENIZER

An input UV Gaussian beam can be mapped into a top hat spot by means of a proper aspheric telescope. Very limited losses, commercial available systems.

Limitation:
- Sensitive to misalignment
- Difficult optic fabrication
- Perfect input mode is not always available
- Beam transport difficult

OVERFILLED APERTURE

A perture selects the most uniform part of the beam and which is imaged to the cathode. A spatial filter or a capillary can be used for clean the higher spatial frequencies.

This method is intrinsically lossy but is the most simple and widespread for photoinjector application.
Deformable mirrors are formed by 2D array of movable elements. The device is used to compensate wave-front aberration. Flat top has been demonstrated using genetic algorithm to drive a 37 elements mirror. Reflectivity at 260 nm 70% Commercially available Complex optimization

Micro lenses array to image different parts of the input beam over the same output spot. Potentially it is not influenced by the input dis-homogeneities larger than the lenslets. Optimal results at short focal distance (20 cm). UV optics available.

Never tested in a photoinjector due to the difficulties to transport the beam.
The most desired electron distribution is ellipsoidal shape

Fully linear phase space for complete emittance compensation can be achieved using ellipsoidal laser geometry

Very challenging to combine spatial and temporal control the laser profile

\[ \varepsilon_{\text{projected}} = 1.02 \text{ mm-mrad} \]

\[ \varepsilon_{\text{projected}} = 0.58 \text{ mm-mrad} \]
ELECTRON BEAM SHAPING

- Using a pancake laser, the electron beam evolves to ideal ellipsoid (Serafini-Luiten)
- Not big effort to generate 50 fs UV laser pulse
- This scheme has been recently demonstrated up to 50 pC charge, distortion at higher charge

Brightness $10^{14}$ A/m²
The ellipsoidal shape can be approximated by pulse stacking different laser beam size michelson interferometer like

Energy losses 75%

Easy idea, bit complex implementation
Fiber bundle and deformable mirror have been used to generate ellipsoidal-like laser geometry.

Limitation: short focal length demands for transmissive cathode and long tails in the time profile.

H. Tomizawa
Use chromatic aberrations

- The chromatic focal shift from a lens can be used to generate the ellipsoidal shape
- Program $\omega(t)$ and the $A(t)$ through a DAZZLER
- Top hat beam at the lens with IRIS

\[ \delta f = -\frac{f_0}{n_0 - 1} \chi \delta \omega \]

Proof of principle at 800 nm

**EXP**

**SIM**

Simulations indicate the depression in the center is due to diffraction effect by iris

Li & Lewellen, PRL 100, 078401(2008)
Li & al, PRSTAB 12, 020702 (2009)
Conclusions

Spectral domain pulse shaping demonstrated to be able to produce flat top pulse
- Energy losses are in general significant for UV shapers
- Repetition rate limited to few KHz (due to laser and shapers)
- Demonstrated rise time about 1 ps at 10 ps pulse length and ripples of few percent

Pulse stacking for flat top profile
- Good efficiency (except for coherent stacking)
- High repetition rate is possible
- Not very flexible output shape (birefringent crystal) fine control of interference

Transverse homogeneity
- Overfilling an aperture is still the most widespread approach
- Deformable mirror has complex but still possible implementation

Uniformly filled ellipsoidal laser
- Variable size beam pulse stacking
- Pancake evolution demonstrated for low charge
- Deformable mirrors + fiber bundle long tail shape and require backward illuminated cathode
- Lens aberrations scheme needs further exploration
- Future schemes: 3 dimensional holography??
Acknowledgments to
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Hollow cathode Geometry:
- DLC Coating
- Exchangeable Cathode Insert (Al, Cu, Mo, Nb, …, FEA)

DLC coated Hollow Cathode (> 150 MV/m)
Quantum Efficiency versus Material & Wavelength

- Reproducibility of QE for same material (& preparation) = 50 %

\[ \text{Exp. Cond.:} \]
\[ 30 < Q < 200 \text{ pC}; 5.2 \text{ MeV} \]
\[ \sigma_{t,\text{laser}} = 4 \text{ ps rms}; 25 \text{ MV/m} \]

QE reduces by a factor 2 over 20 nm
LCLS pulse shape