MAX IV PHOTOCATHODE GUN LASER SYSTEM SPECIFICATION AND DIAGNOSTICS

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Abstract

The MAXIV injector has two guns - a thermionic used for ring injections, and a photocathode used for short pulse facility operation. A commercial Ti:sapphire laser from KMLabs drives the copper based photocathode gun. It has been running without major issues for more than 3 years. The laser delivers up to 500 µJ on the cathode at the third harmonic, 263 nm, via a vacuum laser transport system. To achieve the desired pulse duration of 2–10 ps the laser pulses, originally 100 fs long, are stretched with a prism pair and the resulting 1.5 ps pulses stacked by a series of birefringent α-BBO crystals. Diagnostics consist of photodiodes, spectrometers, and cameras. Longitudinal pulse characterization is done with a cross correlator and a UV FROG.

INTRODUCTION

MAX IV operates a 3 GeV linac for full energy injections into two rings with 1.5 GeV and 3 GeV electron energies [1]. In addition there is a linac based short pulse facility (SPF) for time resolved experiments [2]. A thermionic gun is enough for ring injections, but the electron bunches for SPF experiments have higher requirements (mainly synchronization and emittance) and a photocathode gun is needed.

Here a 2.9985 GHz, 1.6 cell, BNL/SLAC derived [3], photocathode gun is employed to service the SPF. See [4] for more information on the performance of the gun. It has a copper photocathode, with a photoelectric workfunction of ~4.5 eV, setting an upper wavelength limit for the driving laser of around 270 nm. The pulse duration has to be short enough that the RF phase does not vary significantly during the pulse and long enough that the Coulomb repulsion of liberated electrons does not blow the beam up. For a 3 GHz linac this means a useful range of 2–10 ps. These conditions are a good fit for the third harmonic of a Ti:sapphire laser, where the fundamental wavelength is ~800 nm.

LASER SYSTEM

A commercial Ti:sapphire laser system from KMLabs, Colorado, is used as the gun drive laser. The system is based on chirped pulse amplification (CPA) and has two amplification stages. The amplifier crystals are pumped by DPSS (diode pumped solid state) YAG lasers and are cryogenically cooled to reduce the effects of thermal lensing. See table 1 for basic laser parameters.

To ensure that the laser is kept synchronized to the same part of the 3 GHz RF cycle in the gun, it is locked to the 39th subharmonic of the linac master RF source by controlling the cavity length of the modelocked oscillator running at 76.9 MHz. The experiment lasers at the SPF are also locked to the same reference to make pump-probe experiments possible.

When running the oscillator for long continuous periods the power level drops over the course of a few days. This is due to damage on the surface of the Ti:sapphire crystal caused by build-up of contaminations and assisted by the high optical fields there. To reduce this problem we have installed a clean air system that filters the air in the oscillator box. Now the laser can run for a full week before the power drop is too large and needs to be addressed.

Table 1: Laser Specifications

Central wavelength	790 nm
Pulse duration	50 fs
Pulse energy	7.5 mJ
Repetition rate	1 kHz

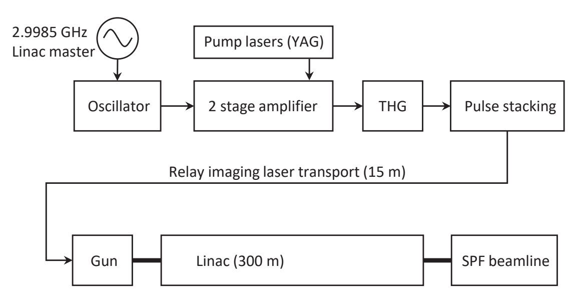

Figure 1: Laser system overview.

While the pump lasers are always running at 1 kHz, the repetition rate of the amplified beam is lowered by a pulse cleaning Pockels cell to the linac frequency (<100 Hz). This helps increasing the life time of various components, such as the copper cathode, compressor gratings, and UV optics.

The amplified bandwidth is 20 nm, supporting 50 fs pulses, but the compressor is slightly detuned for optimized UV pulse generation.

Third Harmonic Generation

After compression to <100 fs the IR laser pulses are frequency tripled to 263 nm central wavelength with β-BBO crystals (type I second harmonic generation + type I sum frequency generation). By using thin crystals, 0.2 mm thick-

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ness, a large 1.5 nm bandwidth in the third harmonic is generated. This opens up for further spectrum based pulse shaping, see [5].

Pulse Shaping

The generated UV pulses are too short to be useful in the gun. To get to the desired ps range they are stretched in two steps. First a double passed prism stretcher adds a frequency chirp to the pulses, resulting in a 1.3 ps FWHM duration. Then a set of α-BBO crystals stacks the chirped pulses to either 3 ps or 6 ps quasi flat-top. α-BBO is highly birefringent (n_e = 1.73, n_o = 1.59 at 266 nm) and transparent down to 190 nm, but, as opposed to β-BBO, it is centrosymmetric and has no second order nonlinear effect. The crystals, 2 mm and 4 mm thick, are placed at alternately 45° to the polarization axis of the laser. The resulting pulse will have a complicated polarization structure, but since we are hitting the cathode at normal incidence the effect on electron emission should be small.

Beam Transport

The laser is located in a temperature and humidity controlled lab next to the linac tunnel. After adjusting the UV beam pulse duration, it transported to the gun in a vacuum pipe system. The cathode is located ~15 m from the tripling crystal. If the beam was free propagating this distance the spatial profile would be very non-uniform. Instead an iris just after the tripling crystal is imaged onto the cathode with 1:2 demagnification through a set of relay imaging lenses. The resulting spatial profile resembles a cut Gaussian.

DIAGNOSTICS

The overall health of the laser is overseen by the usual set of diagnostics.

- Beam samplers and photodiodes are used for online monitoring of energy levels of pump lasers, oscillator, and amplified beams.
- GigE cameras monitor pointing and spatial mode of the IR and UV beams. Ce:YAG crystals are used to convert from UV light to visible.
- Spectrometers for bandwidth measurements.

Cross Correlator

The short wavelength of the UV pulses makes it difficult to use SHG or similar up-converting autocorrelation schemes to measure the longitudinal pulse profile. One alternative is to instead mix with a longer wavelength and use difference frequency generation (DFG). For this purpose short, ~30 fs, low energy, ~2 nJ, IR pulses are split off from the oscillator pulse train and overlapped with the UV in a 0.2 mm thick β-BBO tuned for type I phase matching.

The short IR pulses are then scanned through the UV while measuring the resulting 395 nm DFG signal with a photodiode to build up a cross correlation trace. Since the DFG process is polarization dependent, only one polarization direction at a time can be measured. The complicated polarization structure from the stacked UV pulses means that they are preferably measured in two steps, with a half-wave plate flipping the UV polarization by 90° in between, and then summed. A nice feature with the cross correlator is that since the measurement is done against an independent pulse (from the oscillator), instead of against itself as would be the case for an autocorrelation, there is an absolute time zero to which separate measurements can be related. See fig. 2 for a measurement of the stacked pulse train.

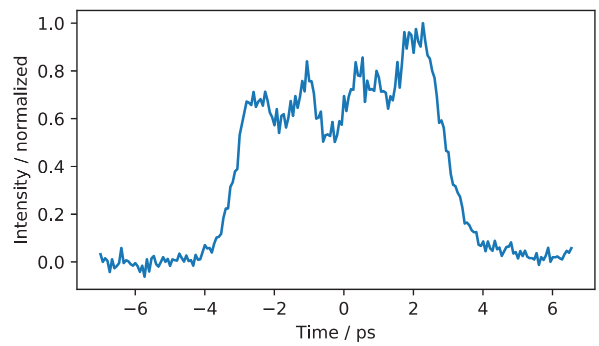

Figure 2: Cross correlation plot of four stacked pulses.

FROG

The main downside with the cross correlation measurement is that it only gives the intensity and not the phase structure of the pulse. To completely characterize a pulse and diagnose various alignment issues the phase information is needed. A common technique to achieve this is the frequency resolved optical gating, FROG [6]. There are various FROG configurations but common to all is that a spectrally resolved nonlinear autocorrelation intensity trace is measured. Some, such as SHG, are not suitable for UV, but there are several that are. Here we have selected the transient grating (TG) technique which provides a sensitive, automatically phase matched, measurement.

TG is a three beam geometry, in which two overlapping beams are focused in a nonlinear medium to induce a transient refractive index grating through the optical Kerr effect. A good choice of medium is regular fused silica glass which is widely transparent, amorphous, and has a large Kerr coefficient. Bragg diffraction of the third, time delayed, beam then leads to the appearance of a fourth signal beam that can be spectrally resolved in a spectrometer. The expression for the signal field becomes

$$E_{sig} = E(t) E^*(t) E(t-\tau)$$

The three input beams are arranged in the boxcars geometry, i.e. in the corners of a square, with the signal beam emerging in the fourth corner. The main difficulty with this geometry is finding the overlap in space and time of all three beams. Here it was done by increasing the pulse energy high enough that self-phase modulation could be observed even for two overlapping beams so that each beam could be overlapped in turn.

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The spectrometer needs to have enough resolution that all features in the signal spectrum are resolved. That means better than ~0.1 nm considering the 1.5 nm bandwidth of the UV beam. We have built a simple grating based spectrometer that uses the focused interaction spot in the medium as the entrance slit, resulting in a 0.05 nm resolution. A Jai CM-140GE-UV camera, sensitive down to 200 nm, is used as the detector.

To record a FROG trace one of the beams is put on a delay stage and scanned in time with a spectrum measured for each delay. The resulting spectrogram uniquely determines the electric field structure of the pulse and can be inverted through an iterative retrieval algorithm. The algorithm is based on generalized projections between the measured data and the mathematical expression for the nonlinear interaction. See [7] for details. We have implemented a CPU version of the algorithm in `numpy` and also a GPU version using `pyopencl` giving a ~5x speedup. A single iteration with the CPU version takes around 0.1 s for a 256x256 frog trace on a desktop i7 PC, with 10–20 iterations needed for a moderately complicated pulse.

While it is possible to reconstruct the stacked pulses with the FROG, it is quite difficult to get a good trace. In general the cross correlator is more suitable for these pulses.

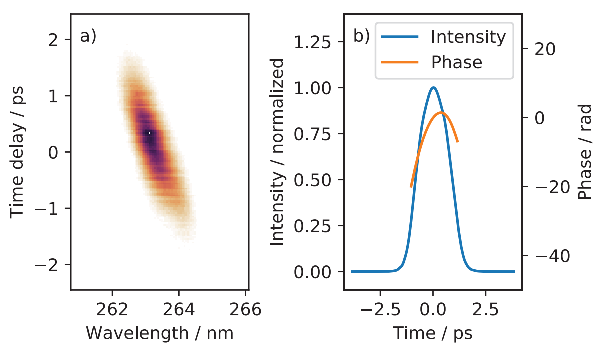

Figure 3: UV FROG pulse trace of the beam after the prism stretcher. The measured spectrogram is shown in panel a, with a clear tilt representing a frequency chirp in the pulse. In panel b, the reconstructed trace is plotted. The pulse duration is 1.3 ps FWHM and the chirp is evident as a quadratic phase curve.

CONCLUSION

The gun laser at MAX IV was installed in 2012 (at the old Maxlab) and is now a stable work horse running more than 100 hours per week. A set of diagnostics are used to monitor the laser health and, in combination with the `tango` control system for long term trending of parameters, helps ensuring high uptime by early detection of anomalies. In addition, longitudinal pulse diagnostics are used to characterize the UV beam.

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