Component description	Pharos Injector Laser for VEGA System
Component manufacturer	Light Conversion
Component manufacturer P/N	PH1-06-1500-02-42
Component part number	LO000024
Component serial number	L191325
Component ID	ES:LS000
Customer	IFIN-HH / ELI-NP
Test date(s)	02/2020 – 01/2021
Test engineer(s)	John Khaydarov
Reference documents	SP000125 Injector Laser System Specifications TR000002 Light Conversion Pharos Fat Report SN L191325 GD000003 Light Conversion Pharos Installation Report SN L191325 DR000007 ELI-NP VEGA FINAL TECHNICAL DESIGN REPORT

1 Component description

The injector laser generates electron bunches in the RF electron source by illuminating a photocathode with ultraviolet picosecond laser pulses. The injector laser is a PHAROS system produced by Light Conversion. The Pharos laser for VEGA system has been customized for oscillator locking to the required repetition rate.

Figure 1: Photograph of the Pharos injector laser head.

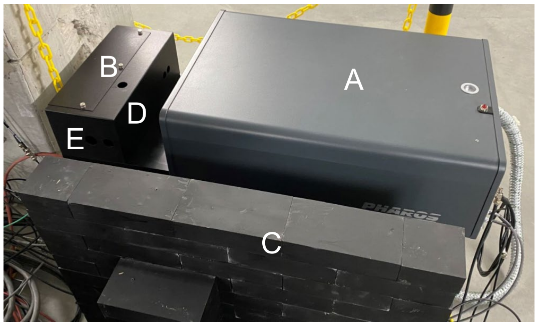

Figure 2: Photograph of the Pharos injector laser head installed as part of the RF electron source test setup behind a lead brick wall. A: Pharos laser head; B: first part of the UV Transport Assembly (second part is near the RF electron source and is connected to the first one by a tube enclosing the UV beam); C: protective lead wall (part of RF electron source test setup), D: position for the power meter head to measure UV power directly at the laser output; E: position for the power meter head to measure UV power after 4 mm aperture.

Figure 3: Photograph of the Pharos injector laser electronics rack with power supply (center) and chiller (bottom).

2 Test setup

WARNING: This laser, when operating, is a Class 4 Laser. Laser safety measures and procedures must be implemented and followed to.

The test setup (Figure 4) consist of

1. IR and UV cards (visualizers)
2. Oscilloscope
3. Spectrum analyzer
4. Power/Energy meter
5. Laser Beam Profiler (LBP). Broadband attenuator, regular and UV-sensitive cameras, beam profiling software

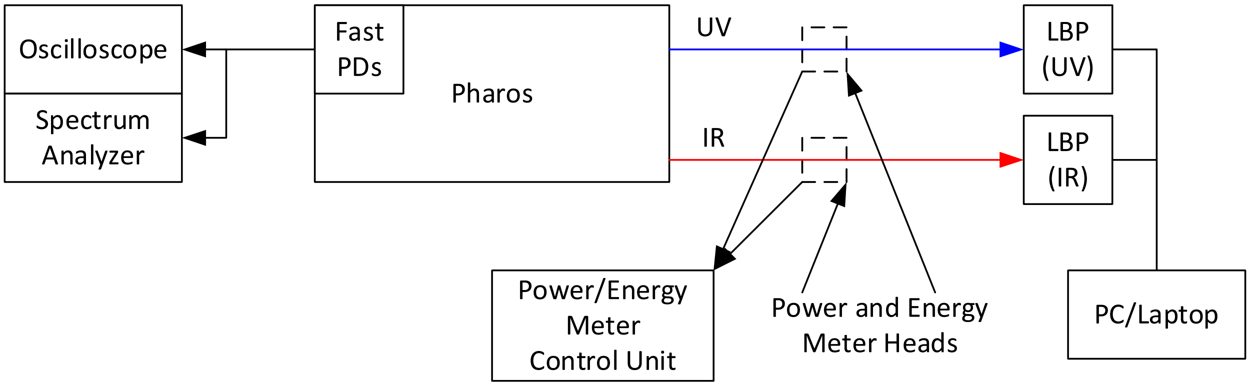

Figure 4: Test setup

The Pharos laser has three fast photodiodes on board. The panel with the direct connectors to photodiodes is shown on Figure 5 below. Also listed other control ports.

1. PD OSC – Oscillator monitor (EOT ET-3500, >12.5 GHz)
2. PD RA – Regenerative amplifier monitor
3. PD OUT – Laser output monitor (IR)
4. Direct connection to Fast Piezo
5. Direct connection to Slow Piezo
6. External control interface connector

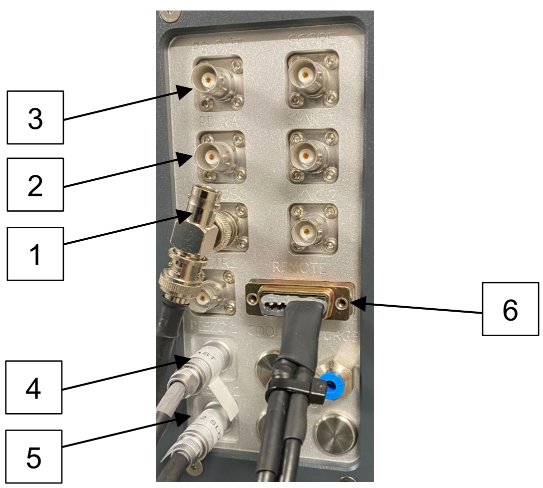

Figure 5: Pharos user output and control panel.

3 Test results

3.1 Summary

Table 1 lists specifications and test results for the Pharos injector laser:

Table 1: Summary of injector laser specifications and test results

Param	Unit	Information	LTI Specification	Pharos value / test result	See Section
λ_{IL}	nm	Injector laser wavelength	255 - 265	257.5	n/a (by design)
$E_{h\nu}$	eV	UV photon energy	4.68 – 4.86	4.815	n/a (by design)
f_{OSC}	MHz	Oscillator repetition rate	64.91 / 71.40*	64.9091*	3.2
E_{IL}	μJ	Injector laser pulse energy	0-135 (min)	0-145	3.3
τ_{IL}	ps	Injector laser pulse width	5	2.7-22	3.4
f_{IL}	Hz	Injector laser repetition rate	Single shot – 50 Hz	Single shot – 1080 Hz	3.5
d_{OP}	mm	Beam diameter on photo- cathode during operation	4 Truncated at w=2 mm	4.7 (hor) x 4.3 (vert) **	3.6

* Oscillator repetition rate: f_{OSC} = 64.91 MHz for LTI test setup, f_{OSC} = 71.40 MHz for VEGA system. See Sec. 4.2. ** Beam will be truncated to 4 mm by aperture in the UV transport assembly.

3.2 Oscillator repetition rate

The Injector Laser Oscillator repetition rate required for VEGA system operation is 71.4 MHz (2856 MHz / 40). However, testing of the RF electron source will be done at Lyncean with the oscillator repetition rate of 64.9 MHz (2856 MHz / 44 = 64.9(09) MHz), compatible with the existing test setup at Lyncean. After the electron source is tested and delivered to ELI-NP, the oscillator in the Pharos laser will be replaced with the new one operating at 71.4 MHz. At the time of VEGA commissioning, the laser will be tested again against specifications and system requirements.

3.2.1 Test at 64.9 MHz (repetition rate of LTI test setup for RF electron source)

Oscillator operation is monitored using a built-in fast photodiode (EOT ET-3500, >12.5 GHz bandwidth). This photodiode was installed in the Pharos laser oscillator per Lyncean request. A wide bandwidth is required because its signal is used for locking oscillator to the system frequency of 2856 MHz. Signal from photodiode is observed on the fast oscilloscope (Tektronix TDS7104, 1 GHz bandwidth, 10G samples per second) and its frequency measured using spectrum analyzer (Keysight 8593E Spectrum Analyzer, 9 kHz to 22 GHz).

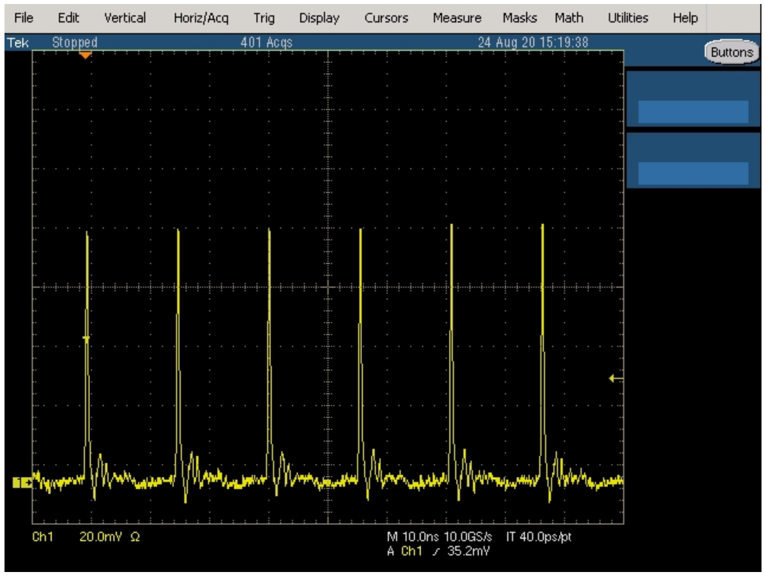

Figure 6: Oscilloscope trace of the 64.9 MHz pulse train from oscillator

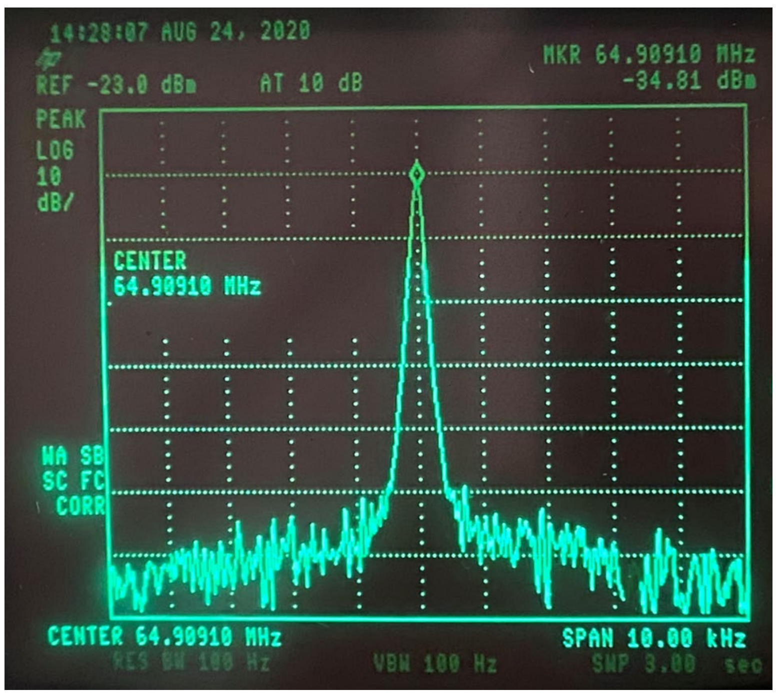

Figure 7: Spectrum analyzer trace of the oscillator pulse train spectrum. Oscillator is locked to the system frequency of 2856 MHz. Peak frequency is at 64.90910 MHz.

3.3 Injector laser pulse energy

Output pulse energy was measured using Coherent LabMax-TOP meter with two sensors:
LM-10 HTD – power meter head, and
J-10MB-LE – energy meter head.

Measurements were done at RA frequency of 1080 Hz – operation condition for VEGA system and two output frequencies 1080 Hz and 24 Hz. Measurements at 1080 Hz were done only with power meter head because energy meter does not work at higher frequencies.

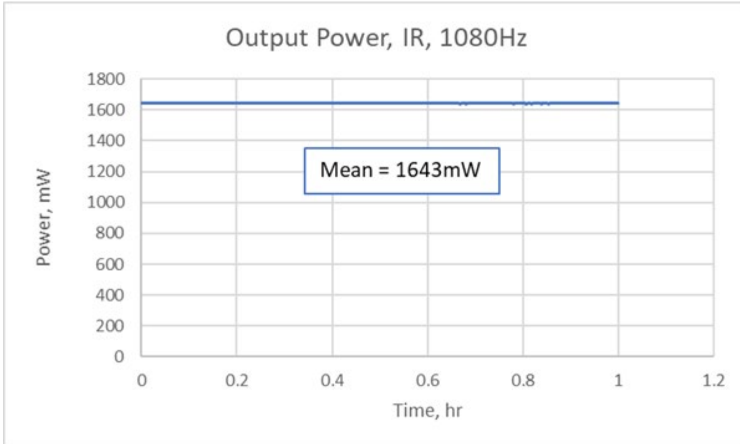

Figure 8: IR output power of the Pharos laser measured at RA repetition rate 1080 Hz. This power corresponds to pulse energy of 1.52 mJ per pulse (1643 mW / 1080 Hz).

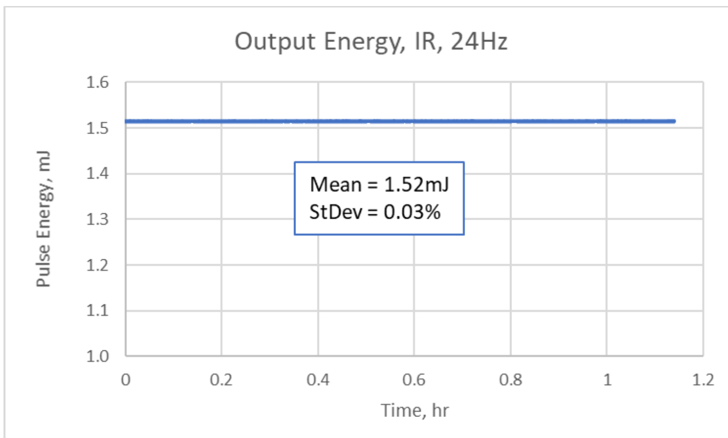

Figure 9: IR pulse energy at output rate of 24 Hz (RA rate is 1080 Hz, PP divider is 45). Standard deviation of this measurement is 0.03%

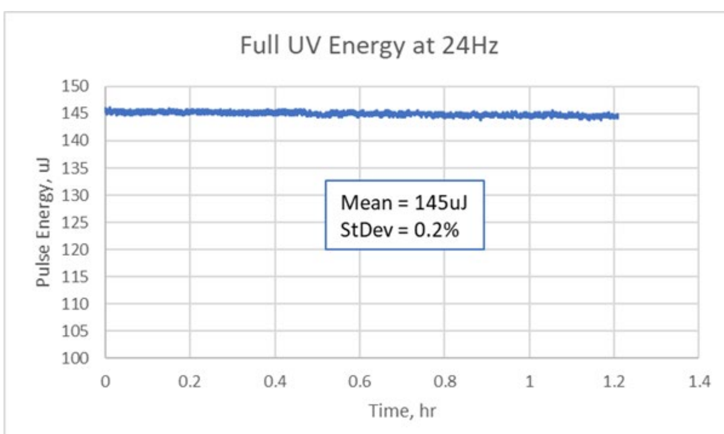

Figure 10: UV pulse energy at output rate of 24 Hz (RA rate is 1080 Hz, PP divider is 45). The pulse energy is approximately 145 μJ. The standard deviation is 0.2%.

The energy at the laser output can be varied using a pulse picker (PP). It is an Electro-Optic device (based on a Pockels Cell) located between the Regenerative Amplifier and Pulse compressor. It is shown on diagram in the Pharos manual (LTI document number GD000002; Figure 8 on page 23). The electron bunch charge generated in the RF electron source depends on the UV pulse energy on the photocathode, and the PP is used for controlling the charge. Photocathode cleaning also requires UV pulse energy optimization, and variable PP transmission is used for this purpose also.

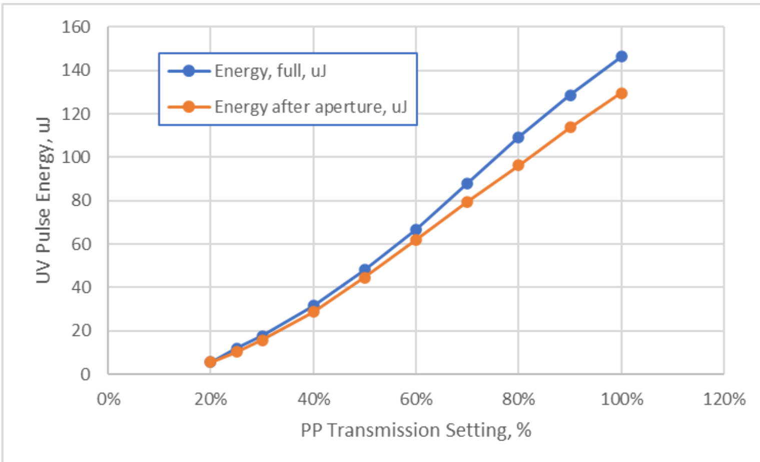

Figure 11: UV pulse energy before and after 4 mm aperture in UV transport assembly as a function of the Pulse Picker Transmission setting. Power meter head positions for both measurements are shown in Figure 2 (items D and E)

Figure 11 shows the UV pulse energy before and after the 4 mm aperture that is integrated into the UV transport assembly. Please note that the pulse picker always operates in IR, not in UV. Pulse picker transmission is linear in IR, but after 4th harmonic conversion UV pulse energy as a function of pulse picker transmission deviates from linearity.

3.4 Injector laser pulse width

This parameter was measured in IR by Light Conversion and is documented in their Factory Test Report (LTI document TR000002) on pg. 7-10.

The laser contains pulse stretcher before regenerative amplifier (RA) and pulse compressor (both diffraction grating-based) after RA. This allows to reduce pulse peak intensity and prevent optical damage in amplifier at higher energies. After the RA pulses are re-compressed to desired duration. Compressor has motorized stage that allows changing output pulse duration. The factory test shows measurements that were done with shortest output pulse duration. Duration of the compressed pulse slightly depends on the RA repetition rate and are shorter at a lower RA rate. This effect can be seen on the factory data on pages 7-9. The pulse elongation is mostly affecting shortest output pulses, for the longer ones (>5 ps) change in duration is minimal.

Figure 12 (plotted from table in Sec. 2.1 in Light Conversion FAT report) shows how output pulse duration depends on the compressor motor position. In this Pharos unit pulse duration varies from about 2.7 ps to 22 ps. Operation of the electron source in VEGA system requires pulse duration to be about 5 ps. Thus, motor position for operation was chosen to be 34500 that corresponds to about 5 ps pulse duration.

Please note that pulse duration was measured using autocorrelator in infrared only. Autocorrelators for UV spectral range are not commercially available yet. So, pulse duration of the UV pulses illuminating photocathode will be optimized during system commissioning based on the system performance.

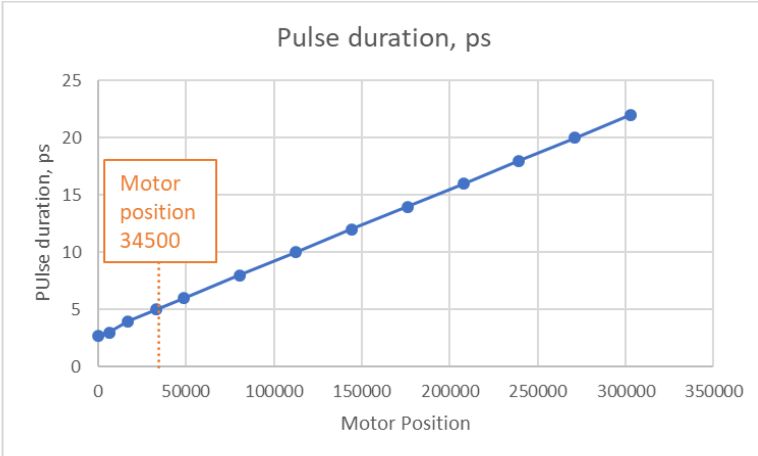

Figure 12: Pulse duration as a function of the motor position in pulse compressor

3.5 Injector laser repetition rate

RA can operate with repetition rate in the range from 1000 Hz up to 200 kHz. The minimum repetition rate of 1000 Hz is due to performance limitation of RA at low rates. For the VEGA system, the RA will operate at a fixed repetition rate of 1080Hz. Pulse after RA goes through the electro-optical pulse picker (PP) that transmits only certain pulses to output. It can be done internally by dividing RA rate by the whole number (for example to obtain pulses at 24 Hz from the 1080 Hz train the divider must be 45). It can also be done using PP external trigger. For this test RA was operating at 1080 Hz and we used internal PP divider to generate pulse train with lower repetition rate.

Injector laser performance at different output pulse rate was evaluated using digital oscilloscope with lower bandwidth (Tektronix TDS 2014B, 100 MHz). Oscilloscope with lower bandwidth was used to be able to visualize short pulses with large duty-cycle. Below are screenshots of oscilloscope traces obtained with signal from PD OUT BNC connector (IR pulses)

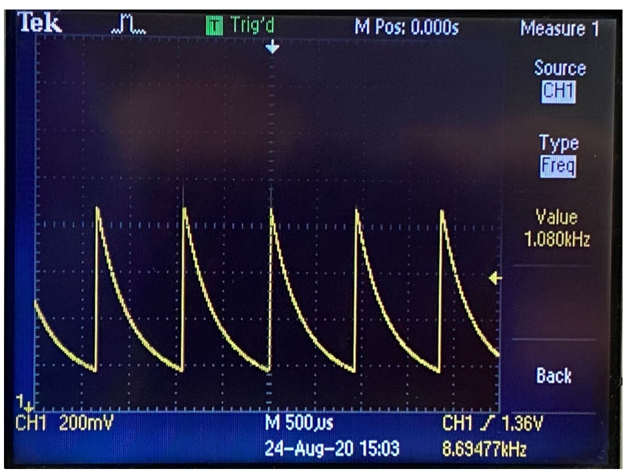

Figure 13: Pulse train at 1080 Hz (PP divider = 1)

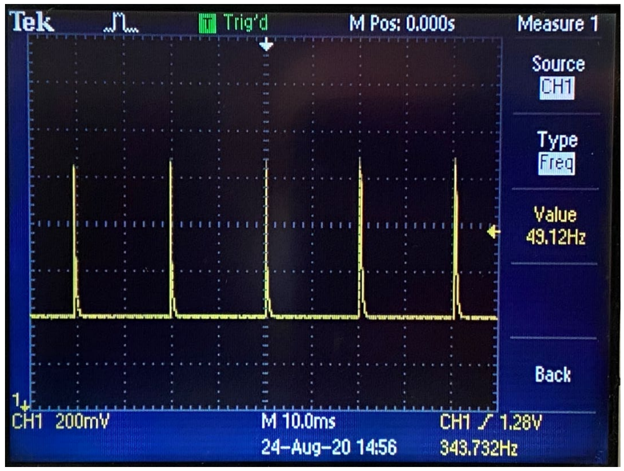

Figure 14: Pulse train at 49 Hz (PP divider = 22)

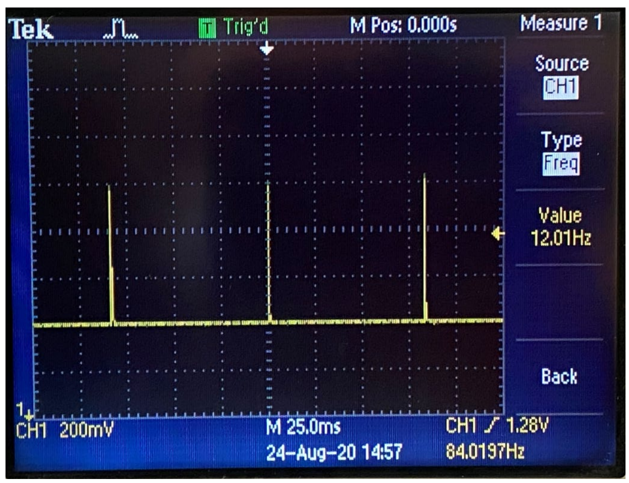

Figure 15: Pulse train at 12 Hz (PP divider = 90)

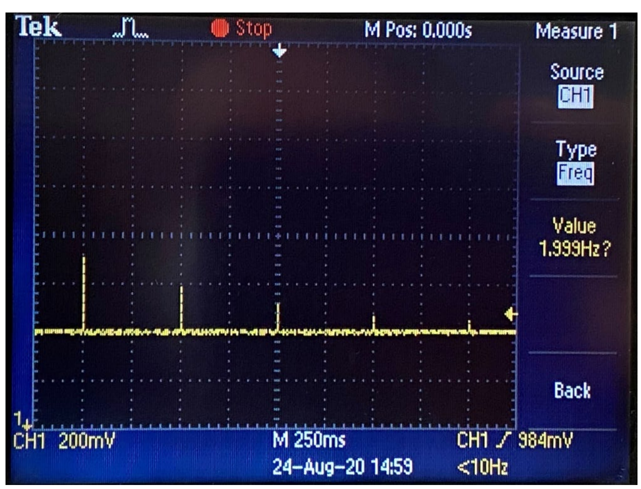

Figure 16: Pulse train at 2 Hz (PP divider = 540). Pulses vary in height because of digitization

3.6 Beam diameter on photo-cathode during operation

Figure 17 shows beam measurement setup in the near field. Pelin Broca Prism (2) is used to separate UV beam from the green and IR residuals. Camera sensitivity is much higher at the green and IR wavelengths than at the UV wavelength. Pelin Broca prism separates all three beams by refracting them in different directions. UV beam passes through the prism with low losses as it has horizontal polarization and crosses all prism surfaces at Brewster's angle.

UV beam after the prism is reflected by the optical wedge (3). Reflected by the front and rear surface of the wedge beams propagate in separate directions and the camera (4) detects only one reflected from the front surface. There are two filters in front of the camera sensor: UV bandpass filter and neutral density filter (metal coating on SiO2 substrate).

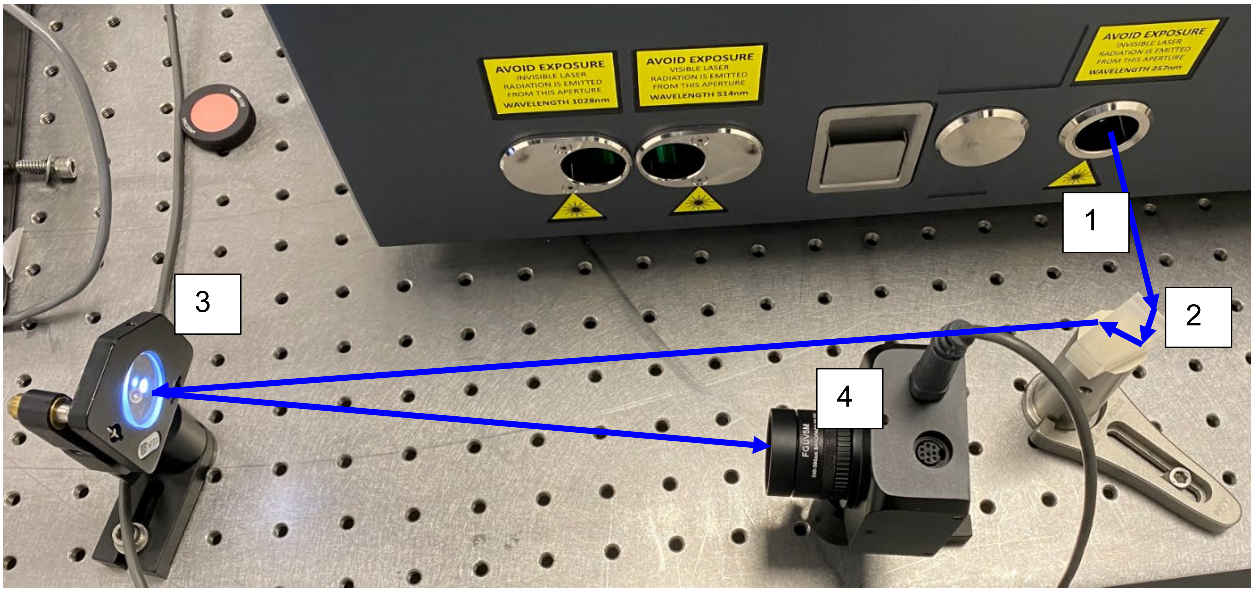

Figure 17: Beam measurement setup. (1) UV beam; (2) Pelin Broca Prism; (3) Wedge (BK7); (4; (4) UV-sensitive camera (with UV filter)

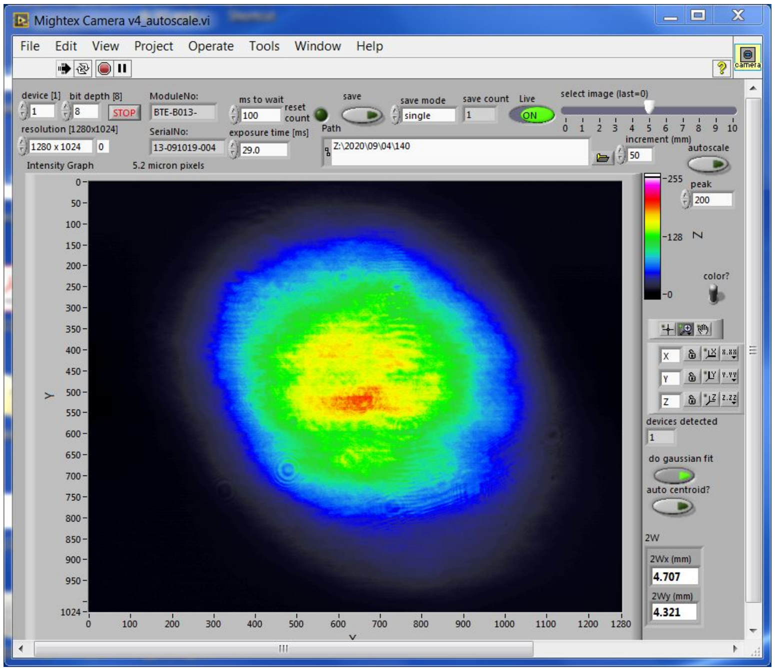

Figure 18: Software screen showing UV beam profile at 60 cm from the front laser panel.

Figure 18 shows beam profile in the window of the proprietary beam profiling software. Gaussian diameter in horizontal plane is 4.7 mm, and in the vertical plane 4.3 mm. In the VEGA RF electron source assembly, the beam will be truncated to 4 mm using an aperture integrated into the UV transport assembly. Please note that values for the diameter listed here come from the cross-section fit to the Gaussian profile. In reality, 4th harmonic UV beam is not Gaussian anymore but closer to the flat-top.

The purpose of truncating the beam on the cathode is to cut off undesired wings and to make the beam shape closer to top hat. This has been shown to improve emittance (F. Zhou et al., Phys. Rev. ST Accel. Beams 15, 090701 (2012), https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.15.090701). The beam size of 4 mm diameter has been optimized by Lyncean to get both intensity efficiency and good emittance. Beam truncation leads to some energy reduction of the UV pulses compared to the direct laser output (as shown in Figure 11).