PHIN

CTF3 photo-injector laser amplifier construction

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Abstract

Rutherford Appleton Laboratory (RAL) has performed the design of the CTF3 photo-injector laser system. However, construction of the system was not completed before shipment to CERN in 2006. In this report, the status of the laser power amplifiers is described. The power measurement technique is outlined. The major problems so far encountered are explained and forthcoming studies are discussed.

1. Introduction

Following the difficulties encountered by RAL, the PHIN laser project was transferred to CERN. In an attempt to reduce the workload to CERN, informal collaborations were established with INFN Frascati and University of Milano, partners of PHIN but not previously involved in the CTF3 photo-injector, to fill the gap.

INFN Frascati, who are developing a photo-injector for the SPARC project, have experienced laser scientists, and accepted to send them to CERN to help commissioning the laser amplifier chain. One of the authors (from INFN) now has a fellowship contract at CERN. He is working on the laser system in order to optimize at best its characteristics and reach the requested performance.

University of Milano accepted to take responsibility for investigating the feasibility of the phase coding scheme proposed by RAL that makes use of Custom Off-The-Shelf fiber optics components for telecommunications.

After the delivery of the components from RAL to CERN, and after initial setting-up of the system, a number of hardware problems were encountered which hampered progress:

- problems with the oscillator / pre-amplifier system
  (pump diode broken, external synchronization not operational, etc.)
- problems with the drivers (power supplies) for the Nd:YLF amplifier's pump diode lasers (erratic behavior, different error messages produced without apparent reasons, communication problems with controls software, etc.)

This succession of problems led to delays of several months during 2007. There is good hope that much of these hardware issues are now resolved - the major remaining issue concerns the synchronization.

In this report, the status of the laser system as of May 2008 and the performance of the laser power amplifiers are described.

2. The CTF3 photo-injector laser system

The photo-injector laser system designed to produce the CTF3 drive beam is described in this chapter. A schematic layout is given in Figure 1. Further details can be found in Refs. [1,2,3].

A Nd:YLF oscillator[1] produces vertically polarized pulses at a repetition rate of 1.5GHz (~ 666ps between two consecutive pulses) with an average power of P~300mW, a central wavelength λ~1047nm and with a pulse time width of τ~8ps. These pulses are first amplified by a Nd:YLF "pre-amplifier"[2] required to increase the average power up to P~10W. The pulses delivered by the pre-amplifier have the same characteristics (τ~8ps (FWHM) and λ~1047nm). In between the oscillator and the preamplifier a dedicated device called "Phase Coding" will be placed. This equipment provides a special time distribution of the pulses necessary to produce electron bunches with a distribution in time as required for the CTF3 delay loop.

[1] High Q Laser Production GmbH model *pico*TRAIN IC-1047-10000-ps Nd:YLF 1.5GHz Sync
[2] High Q Laser Production GmbH model *pico*TRAIN

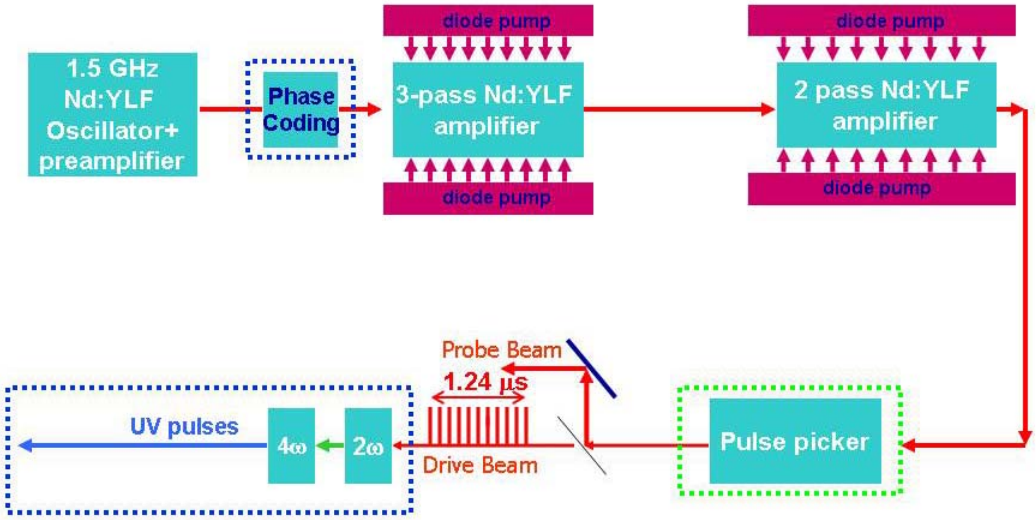

Figure 1: CTF3 photo-injector laser system

After these first stages, the laser beam is injected sequentially into two powerful Nd:YLF amplifiers: the first one is made up of a $L_1 = 8$ cm long Nd:YLF rod with $d_1 = 7$ mm diameter aperture pumped by 5 stacks of diode lasers symmetrically arranged around the rod. The total diode pump peak power is 15 kW and its amplification window is τ_1~400 µs. The second amplifier has a rod length $L_2 = 12$ cm and diameter $d_2 = 10$ mm; it is diode-pumped by 5 diode arrays symmetrically arranged around the rod, the pumping peak power is 17 kW and its amplification window is τ_2~200µs. This amplification starts with a delay of 200 µs with respect to the starting time of the first amplifier. In some measurements a longer amplification window (τ_2~250 µs) was applied with correspondingly decreased delay between the first and second amplifiers.

Both amplifiers are designed to work at a repetition rate in the range of 5 −50 Hz.

Figure 2 shows a picture of the amplifier layout; in Figure 3 the two amplifiers are shown in their operational set-up in the CTF3 laser room. Figure 4 shows the Nd:YLF rod mounting scheme [4] .

After the second amplifier, a Pockels cell allows to select the pulse train length, according to the requirements of the CTF3 RF gun. Ultimately, the CTF3 drive beam will require a 1.272 µs long train of pulses at 1.5 GHz, with a repetition rate of up to 50 Hz. Presently, a repetition rate of 5 Hz is being used.

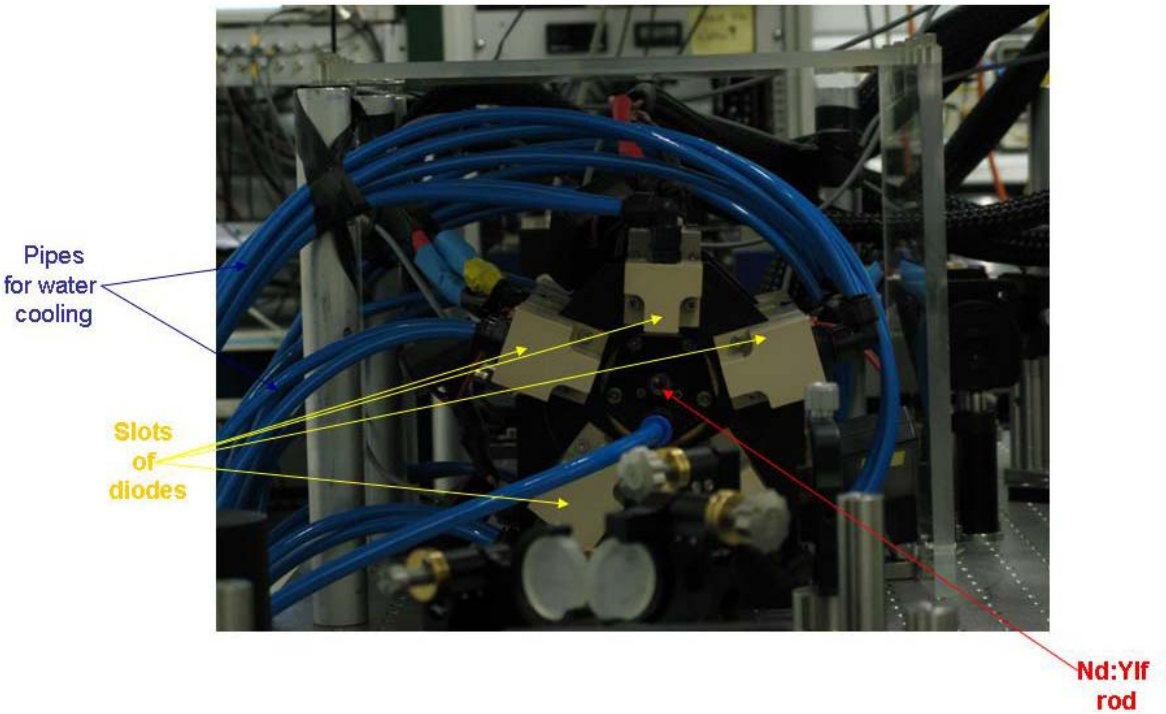

Figure 2: Photo of amplifier 1: The blue pipes are water cooling pipes needed for the pumping diodes. The diode stacks are enclosed in the white boxes (pointed out by the yellow arrows). The five diode stacks are arranged symmetrically around the Nd:YLF rod (red arrow).

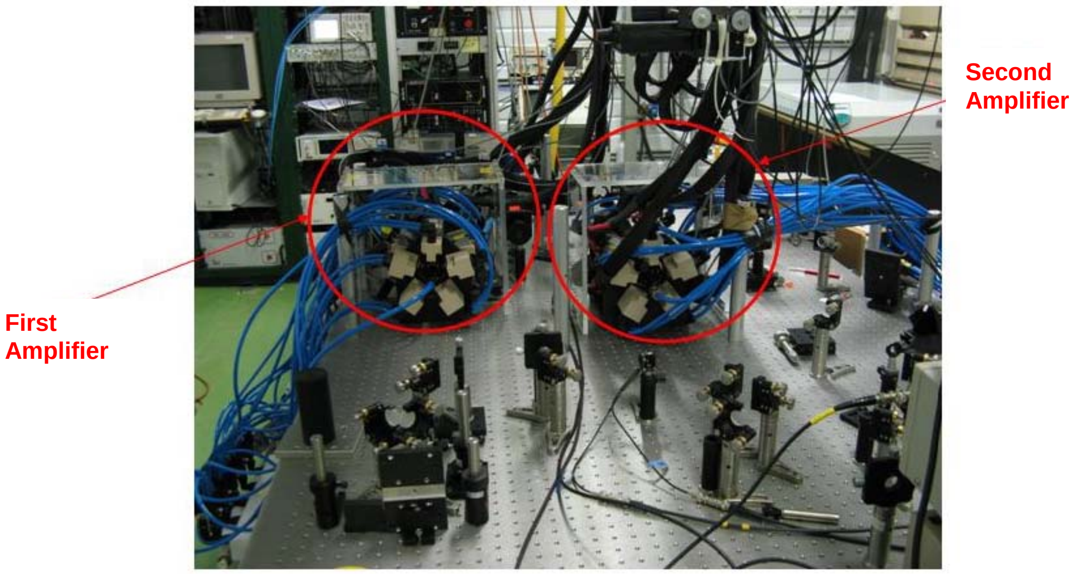

Figure 3: CTF3 laser optical table: The first amplifier is placed on the left, the second amplifier on the right hand side.

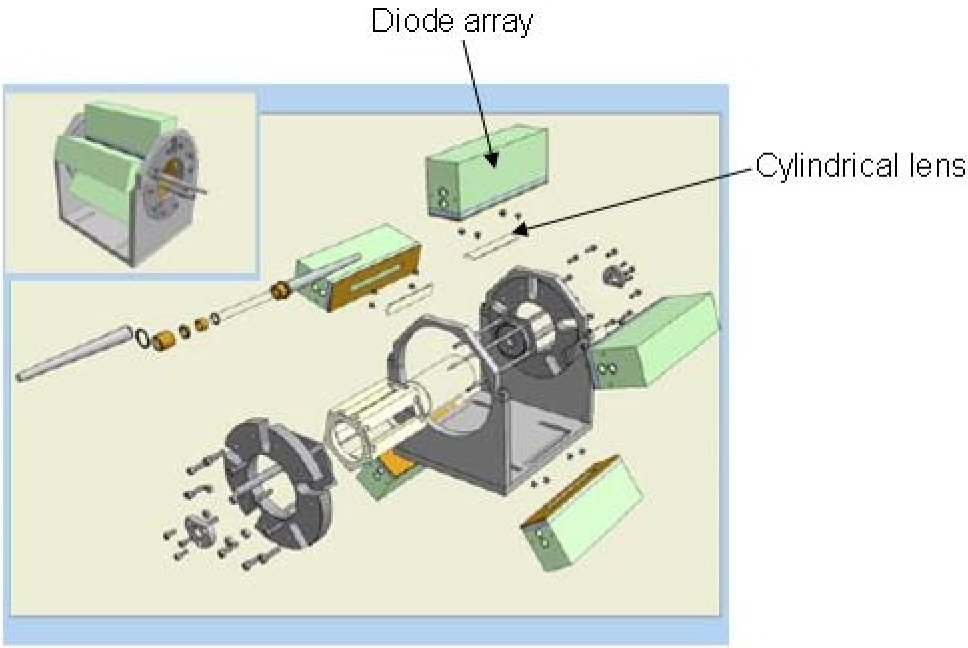

Figure 4: The Nd:YLF rod mounting system scheme is shown (from Ref. [4]). The design of the amplifier is based on long vertical stacks of diode bars which match the length of the Nd:YLF rod. Cylindrical lenses are used to match the diode pumping laser beam into the laser rod. The glass tube which contains the coolant for the laser rod is partially aluminum coated on the outside to couple transmitted light back into the rod (The cylindrical mirrors in the second amplifier are not installed, in order to try to use all the active volume of the rod).

3. Laser power measurements

Laser power measurements corresponding to the time structure of the macro-pulses from the first and the second amplifier have been recorded using the procedure described in this chapter. Results are shown in chapter 4.

In order to measure the time dependence of the amplified laser pulse, a semiconductor photodiode with about 1 ns time resolution[3] is coupled by BNC cable to an oscilloscope[4] (2GHz of bandwidth and 50 Gs/s). To obtain a signal below saturation of the photodiode (output voltage < 1 Volt), the laser beam is sent along an optical path which contains a mirror with 99% reflectivity (about 1% of signal is transmitted to the photodiode). Alternatively, the laser beam is reflected by some wedges (some percent of the beam intensity is reflected to the photodiode, while most of the intensity is transmitted and sent onto a beam stopper). A lens is used to focus the low intensity beam onto the photodiode's sensor. If additional reduction of intensity is needed, filters can be placed along the beam path. An example of a trace recorded in this manner is schematically shown in Figure 5.

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[3] Thorlabs Model Det 10A/M
[4] LeCroy : Waverunner 204Xi 2GHz oscilloscope 10GS/s

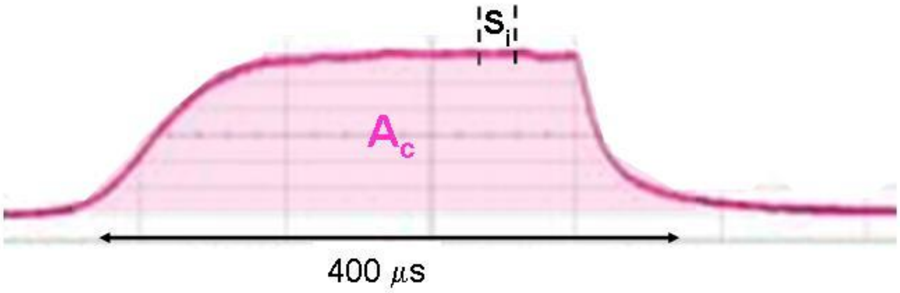

Figure 5: Laser macro-pulse produced by laser amplifier 1. Signal measured by the photodiode-oscilloscope arrangement. The quantities A_c and S_i, used in the text, are indicated.

The average laser power is measured by a commercial power meter[5]. Such instruments have inherently long time constants, well above the 5 Hz repetition rate of the laser amplifiers. Therefore, the power measured is an average of the none-amplified laser pulses (typical power levels of 8 W) between the macro-pulses and the 400 μs long macro-pulses themselves. For this reason it is necessary to de-convolute the macro-pulse curve obtained by the photodetector-oscilloscope set-up with the power obtained by the power meter. In this way, the real laser beam power for any given time interval in the amplified macro-pulse can be obtained. This de-convolution is briefly explained below.

The laser beam is sent into the power meter and the power values at nominal diode drive current is measured (P_{out}, obtained with I_{drive} = 90A). The non-amplified power value is also measured at the same location along the laser beam path (P_{base}, I_{drive} = 0A). The difference between these two values divided by 5Hz (repetition rate of the amplifier) corresponds to the energy within the macro-pulse from the amplification:

$$E_{amp} = \frac{\mathrm{P_{out}} - \mathrm{P_{base}}}{5} \; [W \cdot s].$$

The area under the curve (A_c) measured by the photodiode - oscilloscope set-up is calculated (e.g. by built-in software of the oscilloscope) and the ratio between E_{amp} and A_c gives the calibration value (Cal) needed to convert the amplitude S_i of photodiode signal within each slice of the trace recorded by the oscilloscope into the real power of the pulse:

$$Cal = \frac{E_{amp}}{A_c} \; [\frac{W \cdot s}{V \cdot s}] \; .$$

In order to obtain the real macro-pulse power (P_{fi}), each value of the oscilloscope trace (S_i) is multiplied by this “Cal” value:

$$P_{f_i} = S_i \cdot Cal \; [V \cdot \frac{W}{V}] \; .$$

[5] Gentec : PTM-300 with head Gentec UP55N-400W-H9-DO; or
Coherent : Laser Power/Energy metre LabMax Top with head Power Max model PM30

Note that, due to the averaging of the power meter, any light present in the intervals of ~660 ps between the micro-pulses will also be included in the power measurement. Such "background", which might be due to the amplified spontaneous emission (ASE) e.g. in the first amplifier, can not be eliminated in the laser power measurement.

In summary, the effective power of the 400 μs macro-pulse is obtained by two measurements: (1) the average power obtained from the power meter and (2) the signal level and shape obtained with the photodiode-oscilloscope set-up. Dividing the peak power by the pulse repetition rate 1.5 GHz, the energy in a micro-pulse is obtained. However, values obtained in this way may be higher than the effective micro-pulse energy if there is an undesired laser beam background (such as ASE) between the micro-pulses.

4. Present performance of the amplifiers

Power measurements after the first and second amplifier stage have been performed in standard operating conditions. A macro pulse peak power level P_{p1} in the plateau corresponding to the saturation of the first amplifier of P_{p1}~3.5 kW. This is achieved when the five pumping diodes are driven by the nominal current of 90 A. The resulting calibrated power vs. time is shown in Figure 6.

The peak power level P_{p2} after the second amplifier is P_{p2}~8 kW, in operating conditions aimed at long diode lifetime, i.e. with its pumping diodes driven by 90 A current (the maximum current specified is 120 A). The measured calibrated power spectrum is shown in Figure 7. The final peak power achieved corresponds to a micro-pulse energy of E_m=5.3 μJ. This should be compared to the value in the laser system specifications, E_m = 10 μJ.

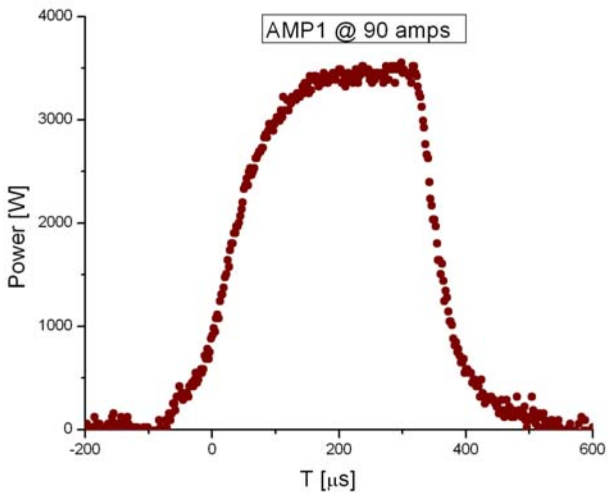

Figure 6: Time dependence of the macro-pulse power at the output of the first amplifier: the peak power (at saturation) is ~3.5 kW and the saturation time is ~ 250 μs. Data taken with photodiode-oscilloscope arrangement, vertical scale is calibrated as discussed in chapter 3.

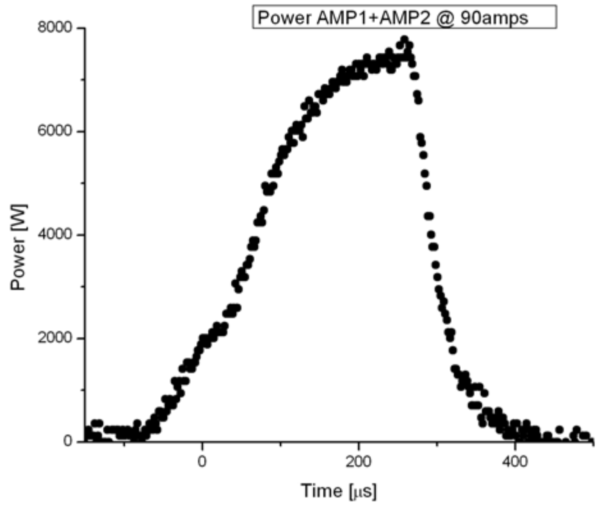

Figure 7: Temporal shape of the macropulse at the output of the second amplifier. Pumping pulse window τ_2 = 250 µs, delayed by 150 µs with respect to that of first amplifier. The peak power is ~ 8 kW, the saturation is not reached. Data taking and calibration as for Figure 6.

As explained in chapter 3, above, the observed performance of the amplifier chain must be carefully analyzed. In fact, a halo has been observed in the laser beam at the exit of amplifier 1. This observation can be an indication of unwanted parasitic (outside micro-pulse) laser light being amplified. In addition, the poor conversion efficiency observed in first attempts to transform IR laser light to green and then to UV light [5] also indicate that the measured laser energy is not concentrated in the micro-pulses, but is partly due to background ("noise") between the pulses.
Recent observations indicate that the first amplifier is indeed introducing a significant level of ASE which is affecting the transverse beam profile (halo) as well as the time profile and the micro-pulse peak power. In an attempt to confirm this hypothesis, we have measured the average power in the laser beam with and without the halo. A first measurement, in which an iris diaphragm has been placed after the first amplifier along the beam path in order to remove an important fraction of the halo, shows a reduction of average power by ~2 W. The observed reduction of average power corresponds to a loss of ~1 kW in the peak of the 400 µs macro-pulse. This in turn implies that amplifier 1 does not deliver in fact the specified value of 3 kW.

The presence of such a strong ASE signal must be avoided, since it can also manifest itself as "noise" in the time structure of the laser beam, i.e. undesired stochastic laser pulses can be present (in time) between the wanted micro-pulses. This might lead to electron bunches produced outside the RF pulse of the gun (introducing dark current, lowering the lifetime of the photocathode). In addition, these parasitic laser pulses will deplete to a significant amount the stored energy from the Nd:YLF rod e.g. in the first amplifier, and less energy will be available to amplify the main laser beam pulses.

Additional insight concerning the ASE contribution has recently been obtained from a series of measurements using a fast photodetector[6] and a sampling oscilloscope[7]. The 400 μs macro-pulses arriving at 5 Hz repetition rate are sliced to 20μs by a Pockels Cell installed after the second amplifier. This laser beam is attenuated and sent via optical fiber to the 25 GHz detector which is coupled to the 50 GHz digitizing oscilloscope. The preliminary measurements carried out show that with the first amplifier diodes driven by a current level above 70 A (~11 kW peak pump power according to the diode laser specification), the signal from the micro-pulses degrades considerably and background between the pulses increases. In Figure 8 is shown the scope trace (in "persistence mode") of the laser signal when the first amplifier diodes are driven by 65 A current (~9.6 kW), and in Figure 9 is shown for comparison the signal observed (also in "persistence mode") when the first amplifier diodes are driven by 85 A current (~14 kW). These measurements have been carried out with the second amplifier switched off. Special care has been taken to keep the same signal level at the output of the photodiode to make sure that the observations made are not affected by the experimental conditions (signal vs. trigger level).
One observes in Figures 8 and 9 that the points which form the micro-pulse signal have more time jitter in the case of high current on the amplifier diodes. This can be a consequence of the fact that the trigger signal is less stable in time than for lower driven current. The origin of such time jitter in the measurement with the sampling oscilloscope is likely the presence of undesired high level spikes outside the 1.5 GHz micro-pulse structure.

Finally, the ASE halo is affecting also the M^2 value, a quality indicator for the transverse beam parameters [6]: It has been measured that this value decreases (improves) when an iris cutting the halo along the beam path (M^2~1.8), with respect to the standard configuration without the iris (M^2~2.5).

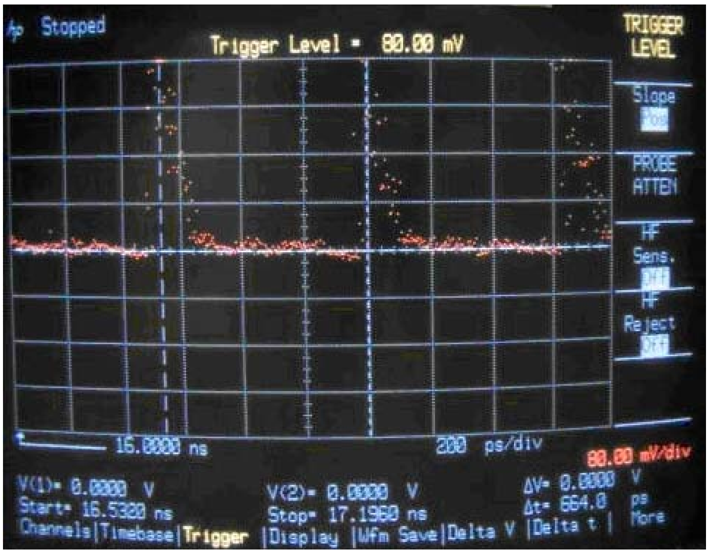

Figure 8: Laser signal after the Pockels Cell (gate = 20 μs) when diodes are driven by a current of 65 A (~9.5 kW). The horizontal scale is 200 ps per unit. The 666 ps distance between micro-pulses is confirmed.

[6] New Focus Model 1024 12ps IR Photodetector
[7] Hewlett Packard : Digitizing Oscilloscope Mainframe 54120B with 4-input and trigger module 54124A DC to 50 GHz Four Channels Test Set

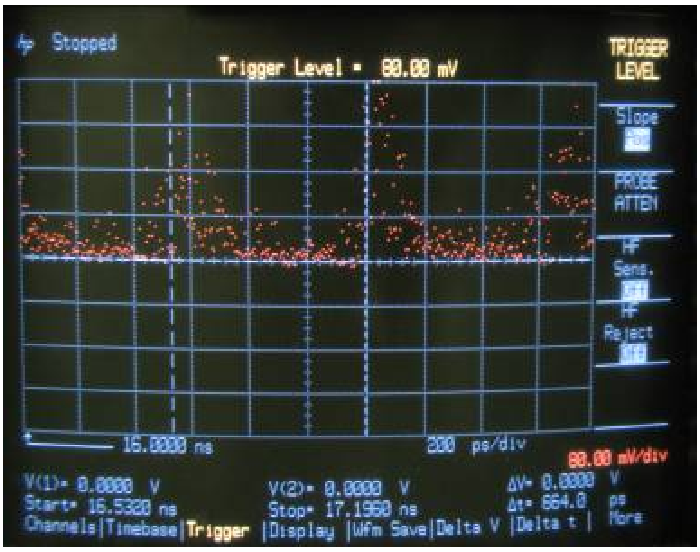

Figure 9: As Figure 8, but for a higher diode drive current of 85 A (~14 kW).

5. Future Studies

In the immediate future, the laser beam from the first amplifier with improved pulse structure (diode pumping current of 65A, see Figure 8) will be used to investigate the behavior of the second amplifier with this beam characteristics. In addition, the conversion efficiency from IR to green and then to UV will be measured with this improved micro-pulse structure.

As soon as possible, however, a more drastic improvement program for the performance of the first amplifier has to start. The aim is to remove the ASE component and to be able to operate this amplifier without significant ASE at nominal diode pumping current of 90 A.

Presently, the second amplifier is giving half of the nominal peak power when its diodes are driven by 90 A current and the beam from the first amplifier has peak power of P_{p1} ~3.3 kW. However, it is likely that the macro-pulse peak power value out of the second amplifier is affected by the bad performance of the first amplifier. Therefore, once the first amplifier has a much improved performance, the second amplifier will have to be optimized in order to reach the nominal peak power P_{p2} =15 kW with the lowest possible pumping power (to preserve diode lifetime).

Finally we believe that much better M^2 values will be achieved once the performance of the amplifiers has been improved, and that the conversion efficiencies to green and UV will approach the calculated values.

6. Summary

After a series of hardware problems which hampered progress, the CTF3 photo-injector laser system is now operational. An important ASE component from the first amplifier is presently hampering the performance of the system, which is therefore not producing laser beam within specifications. A number of improvements are under way, which should help to remedy these problems. Once the performance of the first amplifier is improved, re-tuning of the second amplifier and of the conversion to UV can be pursued.

Acknowledgements

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