# WP3 Ultrafast laser front-end development

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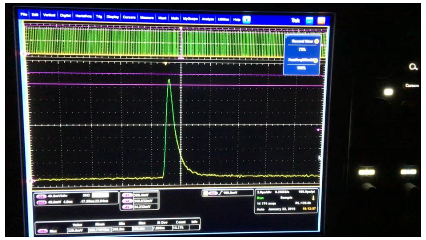
AMP

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 687880

# Work Package 3 Overview

- Objective: Develop ultrafast laser frontend for further amplification to a 500-W and 1-kW average power femtosecond laser
- Achievements in period:
  - 200-W laser performance before compression demonstrated
    - BUT: problem for long term operation because of accelerated ageing of component at high power
  - Laser control
    - Proof of concept of free triggering (but impossible to implement in short time)
    - Flexible laser control based on Amplitudes recent industrial platform + secondary signal for thin disk multi-pass amplifier



- Involved partners: AMP, USTUTT

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# WP3 – Task 3.2: 200-W, ~500-fs laser >1MHz at 1030nm

- partners involved: AMP, USTUTT, AMO
- Achievements:
  - Hybrid fiber-seeded/crystal-amplifier architecture based on Tangor platform
  - 200W output power achieved from amplifier
  - 160W output power with <450-fs pulses @ 1MHz
  - Higher energies: >140W, 330kHz, 430µJ
  - Beam quality: $M^2$~1.25 @ 200W
  - Long term testing

- Demonstration of aimed parameters in M21 OK, but: problems in stress tests => delay for demonstrator delivery (mitigation plan)

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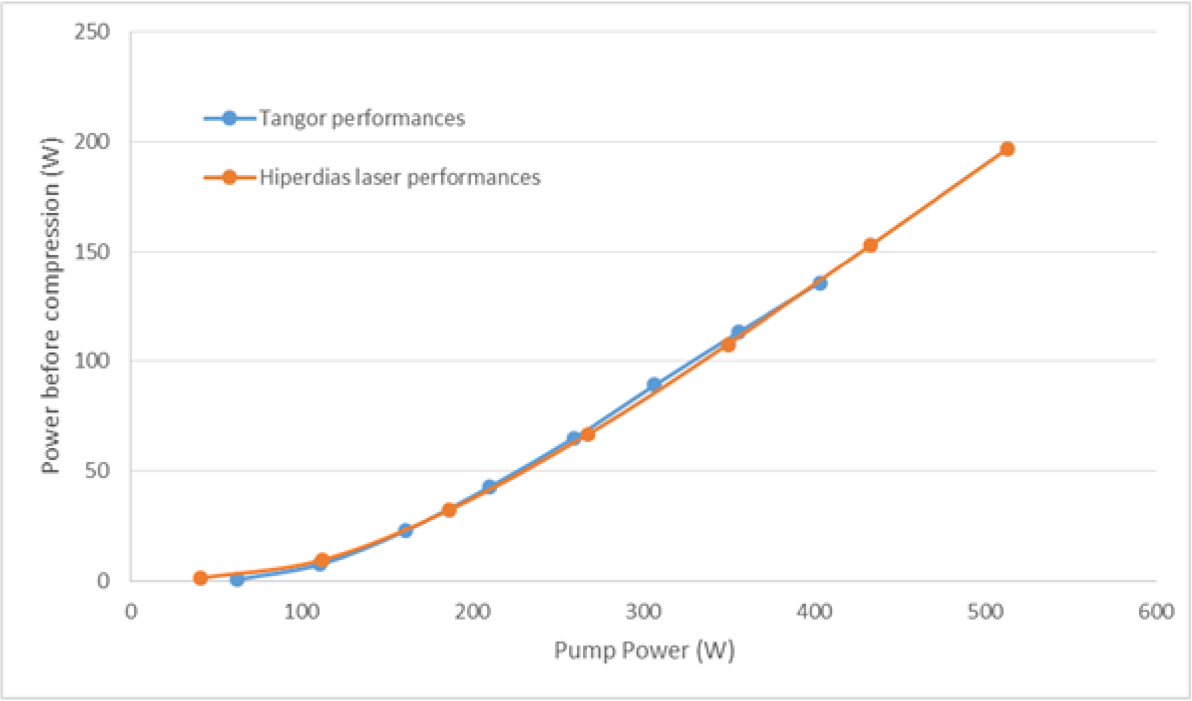
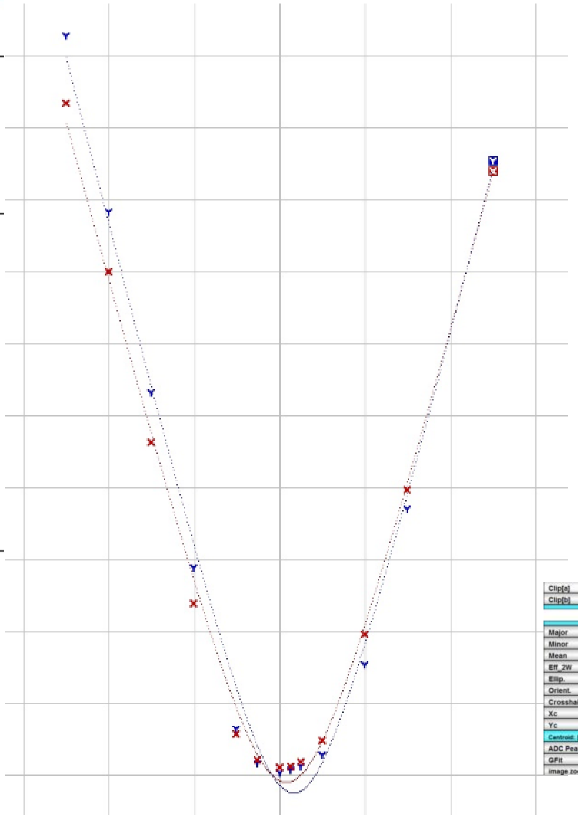
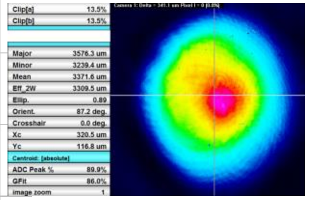
# WP3 – Task 3.2: **200-W**, ~500-fs laser >1MHz at 1030nm




| | Current | Units |
|---|---|---|
| —Quantitative—4 Sigma— | | |
| Total | 13,637,707 | |
| Peak | 1.938e+03 | |
| Min | -6.000e+00 | |
| Width X | 5.699e+02 | um |
| Width Y | 5.767e+02 | um |
| Z Location | 350.00 | mm |
| —Laser— | Automated Stepping | |
| Waist Width X | 3.201e+03 | um |
| Waist Width Y | 3.241e+03 | um |
| Divergence X | 5.102e-01 | mrad |
| Divergence Y | 5.058e-01 | mrad |
| Waist Loc X | 1444.37 | mm |
| Waist Loc Y | 410.56 | mm |
| M² X | 1.260 | |
| M² Y | 1.250 | |
| BPP X | 4.131e-07 | mm mrad |
| BPP Y | 4.098e-07 | mm mrad |
| Rayleigh X | 6200.02 | mm |
| Rayleigh Y | 6407.67 | mm |
| Astigmatism | 0.16 | |
| Asymmetry | 1.01 | |
| —After Lens— | | |
| Number in Run | 13 | |
| Waist Width X | 1.453e+02 | um |
| Waist Width Y | 1.377e+02 | um |
| Divergence X | 1.137e+01 | mrad |
| Divergence Y | 1.191e+01 | mrad |
| Waist Loc X | 301.50 | mm |
| Waist Loc Y | 303.22 | mm |
| Rayleigh X | 12.78 | mm |
| Rayleigh Y | 11.56 | mm |
| Astigmatism | 0.14 | |
| Asymmetry | 1.06 | |





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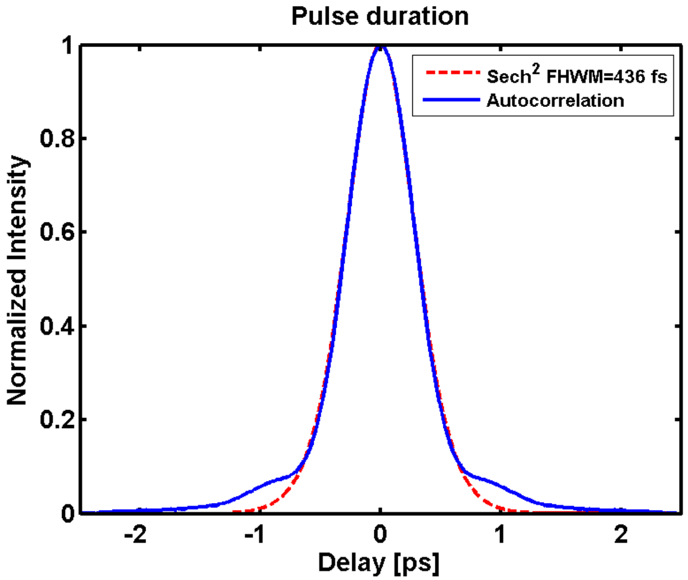
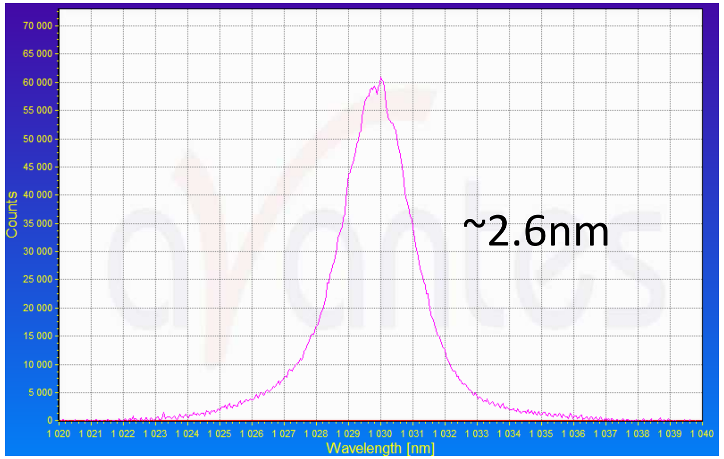
# WP3 – Task 3.2: **200-W, ~500-fs laser >1MHz** at 1030nm

160W, 440fs, 1MHz (160µJ); pulses ~bandwidth limited




Operation at higher pulse energies:
330kHz, 430µJ, >140W

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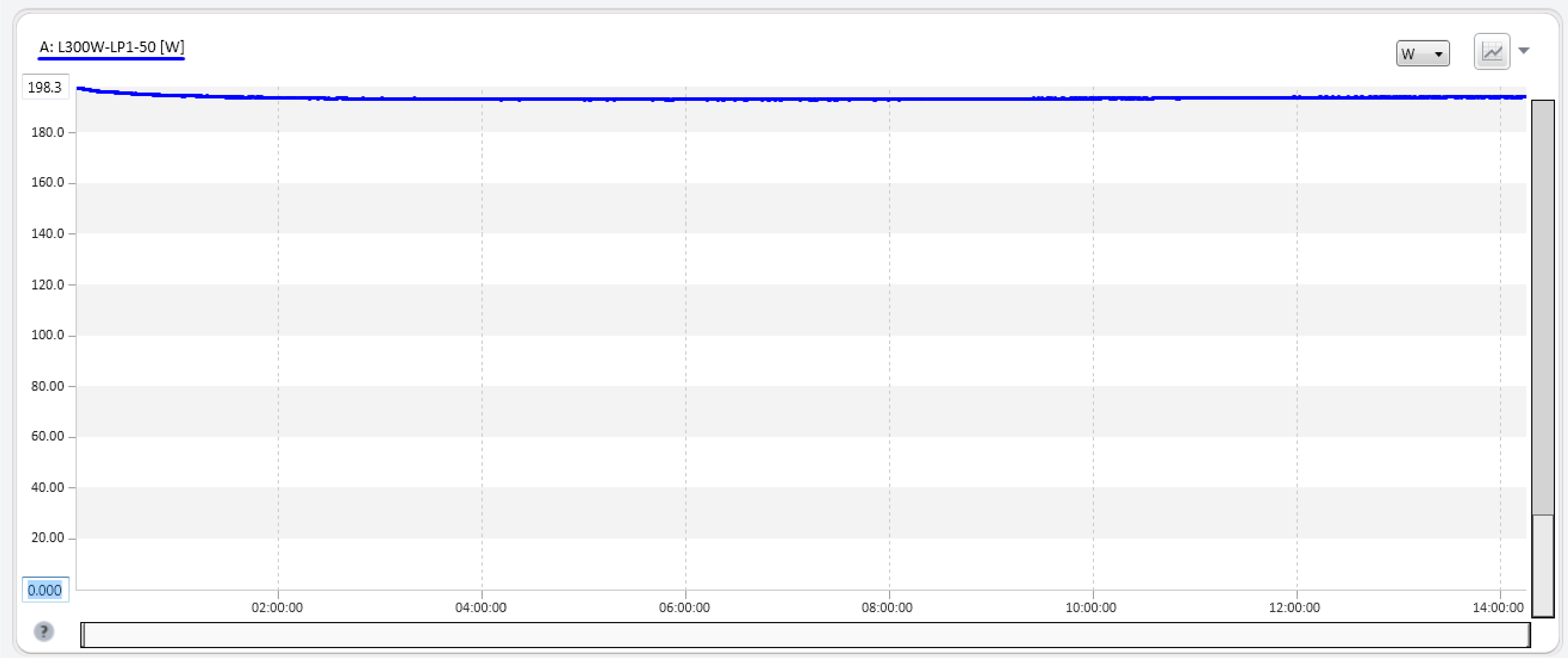
# WP3 – Task 3.2: 200-W, ~500-fs laser >1MHz at 1030nm

Long term testing




Amplifier output ~200W

Good stability over >14h

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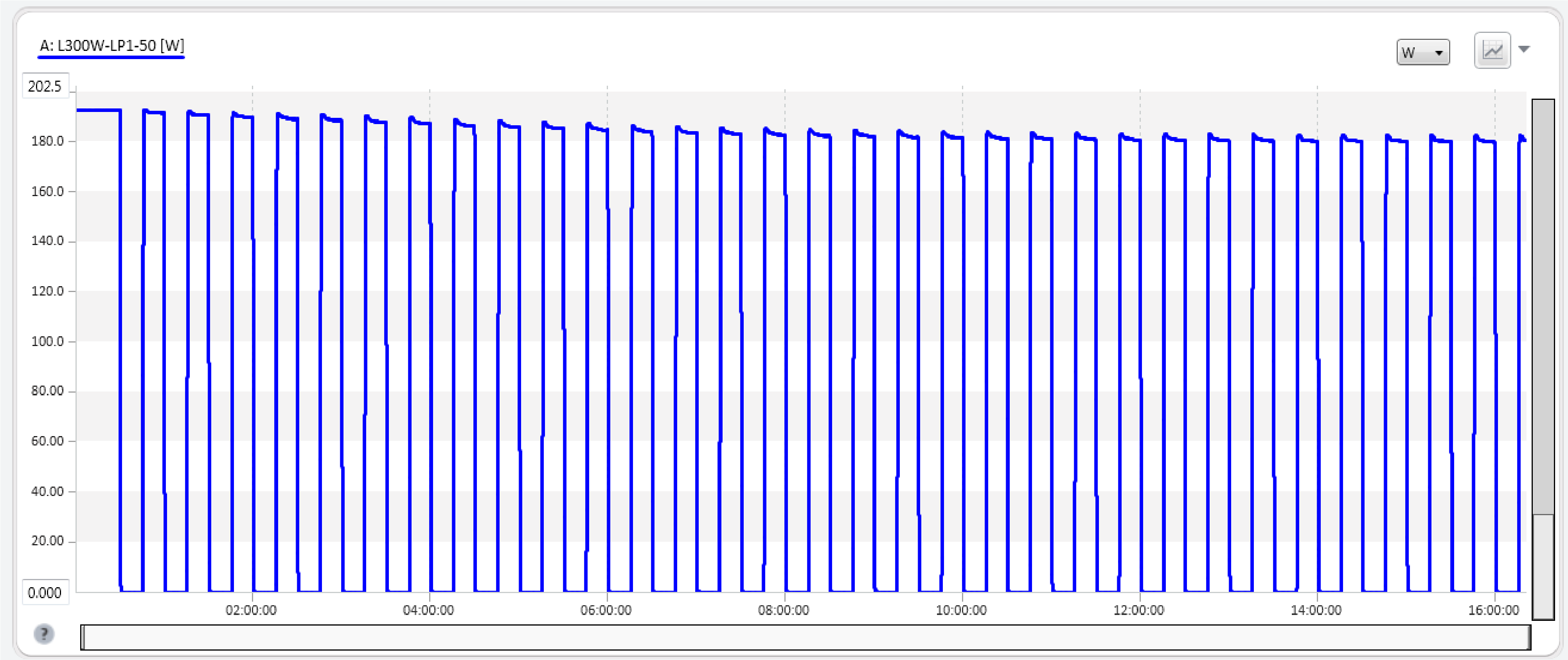
# WP3 – Task 3.2: 200-W, ~500-fs laser >1MHz at 1030nm

Stress testing




Amplifier output ~200W

Accelerated ageing Under ON/OFF cycling

=> Improvement necessary before delivery

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# WP3 – Task 3.3: Flexible user interface including high speed modulation a high power pulse train

- Overview:
  - The objective of the task is nicely summarized in its title
  - User requirements out of the consortium are taken into account
  - modulating the high power thin disk multi-pass amplifier with secondary signal (during “Gate OFF” phases) is taken into account and implemented
  - Burst mode operation can be implemented (including shaped bursts)

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# WP3 – Task 3.3: Flexible user interface including high speed modulation a high power pulse train

- partners involved: AMP, all other partners for interface discussions
- Achievements:
  - Different concepts worked on
    - 1: based on existing user interface, but introduced new options for externally triggering the pulse picker (and not only the GATE) to allow synchronisation with the scanner. This concept works up to 2MHz with the GATE and up to 13MHz (fOsc/3) with only the pulse picker.
    - 2: proof of concept of new modulator/gain limiter concept to gain higher flexibility than option1 for certain cases. Advantages:
      - Higher speed possible (but only relevant for higher repetition rate oscillators, not the case in Hiperdias)
      - Easily extensible to higher average powers (multi-100-W concepts)
    - Both concepts are compatible with burst mode operation
    - Generation of amplitude-shaped bursts
- Concept 1 will be integrated into the 200-W laser

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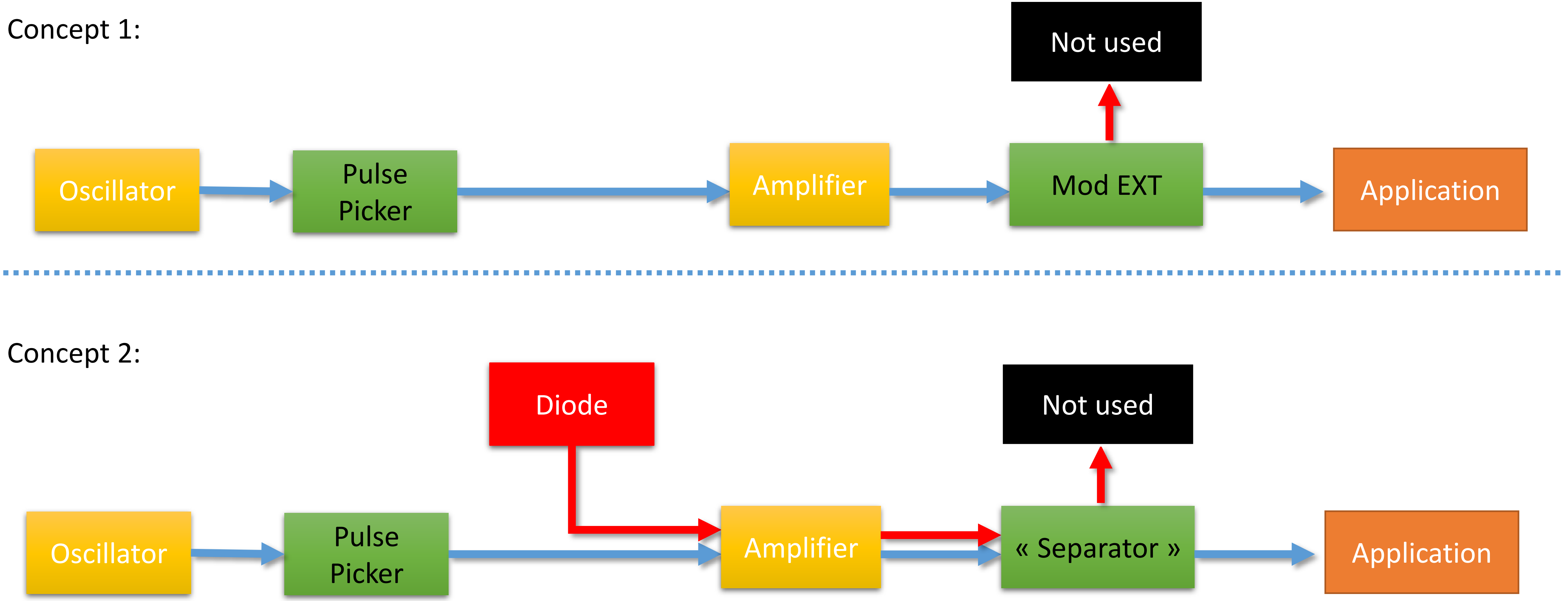
# WP3 – Task 3.3: Flexible user interface

Schematics of the modulation concepts:

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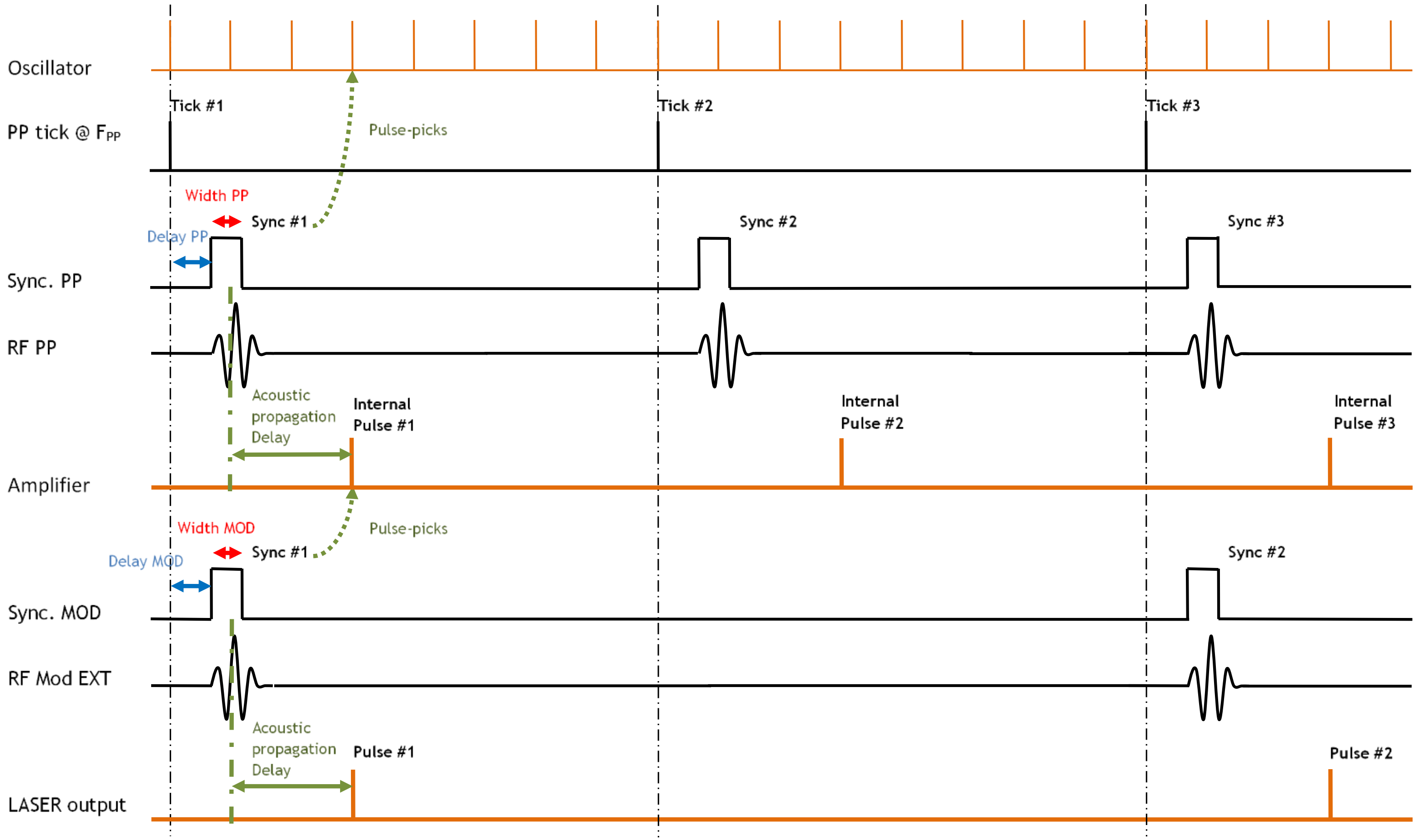
# WP3 – Task 3.3: Flexible user interface

## Concept 1: Synchronisation scheme with pulse picker and external modulator:




Oscillator: 40MHz
PP: up to 13MHz (fOsc/3)

- PP signal can be generated internally or applied externally by user

Attention:

- Latency of AOMs to be taken into account! (acoustic propagation)
- AOM2 (Mod EXT) is limited to 2MHz (by rise time)
- If PP and ModEXT are used in external mode, then the user has to provide ALL TRIGGER signals!

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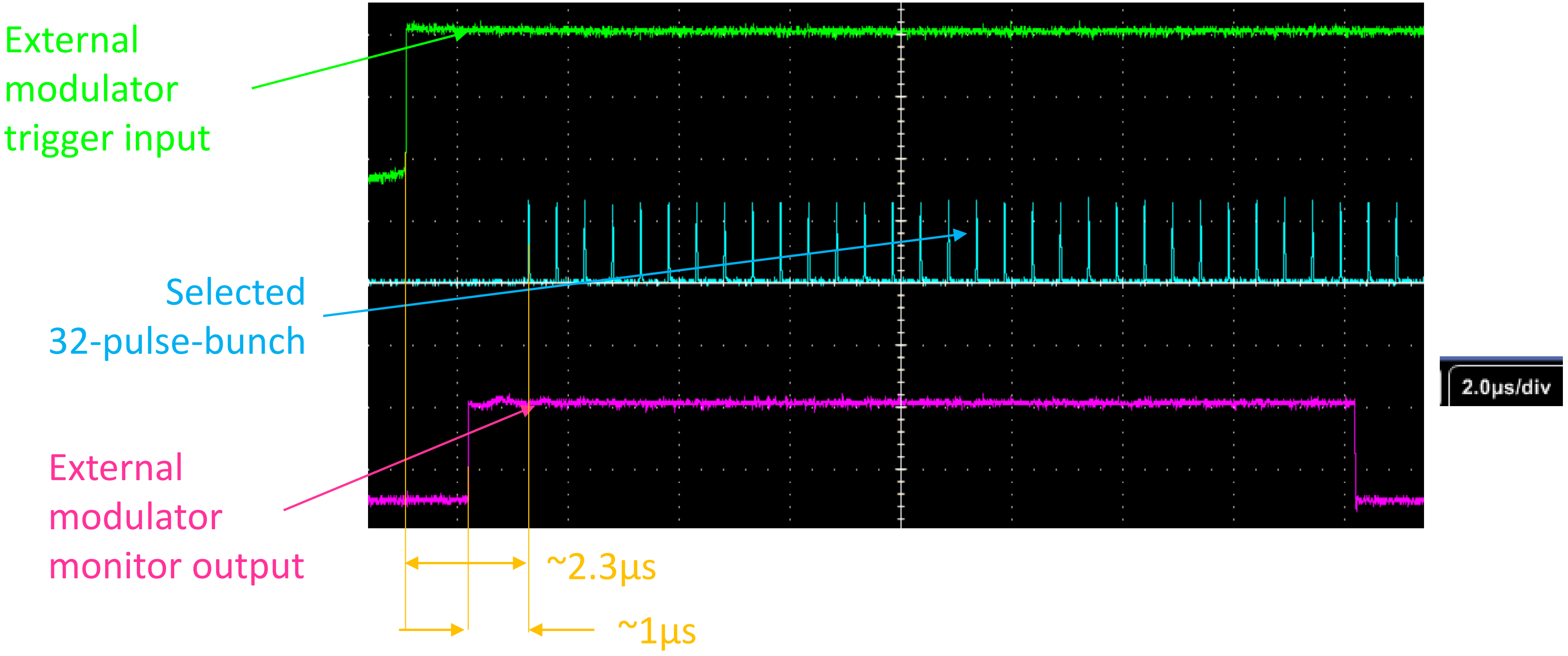
# WP3 – Task 3.3: Flexible user interface

Visualisation of latency:

- ~2.3µs between User trigger signal (ext. modulator) and output pulse at laser exit (@1MHz PP frequency: Latency ~ $T_{PP}$+1.3µs)
- ~1µs between Monitor output signal (ext. modulator) and output pulse at laser exit @ 1MHz ($T_{pp}$)

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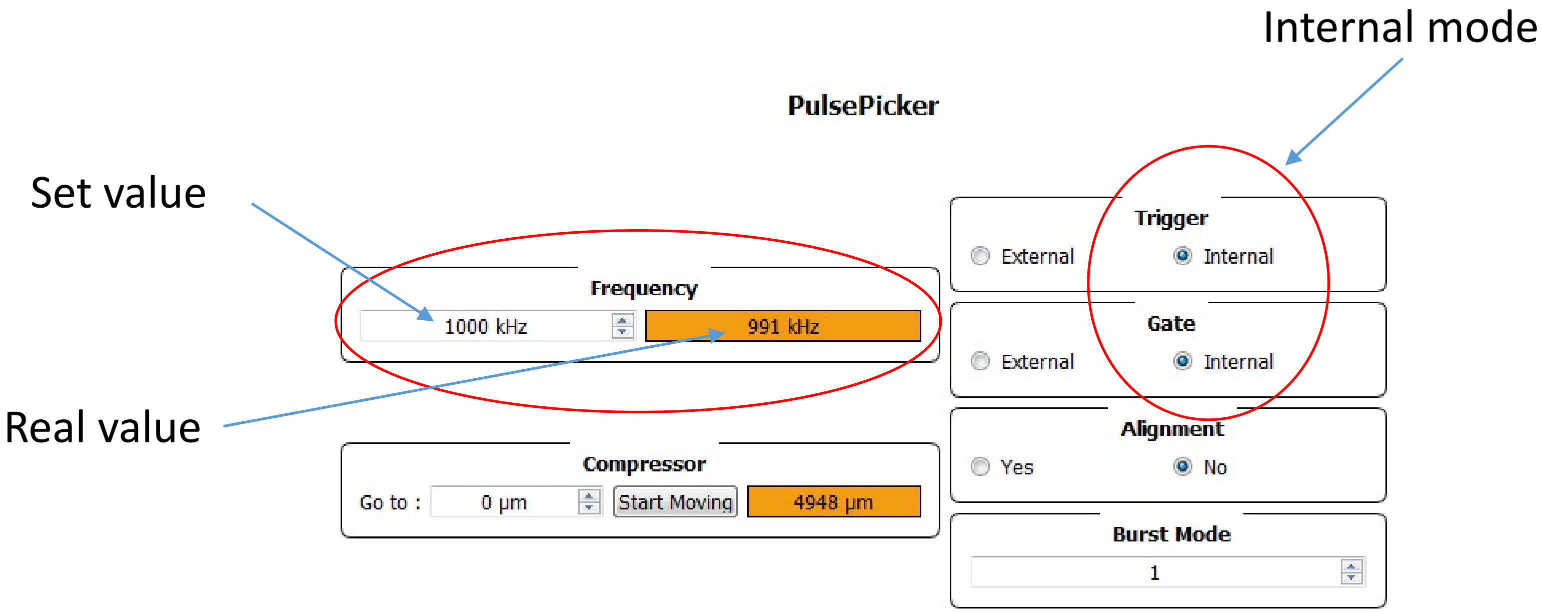
# Tutorial: How to get an exact number of laser pulses (bunch) from the TANGOR laser

<u>1st step</u>: PP frequency in "Internal mode"

Internal mode means that the laser internally (via FPGA) synchronizes the pulse picker frequency to the clock of the mode-locked oscillator

- Via the user interface, set the desired PP frequency fPP




Note that the real PP frequency may slightly vary from the set PP frequency, because only PP frequencies that are integer divisions of the oscillator pulse repetition rate are possible. The control electronics of the laser calculates and realizes the PP frequency closest to the set (desired) value.
In this specific case: 991kHz for a set value of 1MHz, because the oscillator frequency is 40.63MHz

- ➢ 991kHz = 40.63MHz/41, division factor k=41.

The exact value of the individual oscillator frequencies is given to the user by the Certificate of Conformance (CoC) of the corresponding laser.

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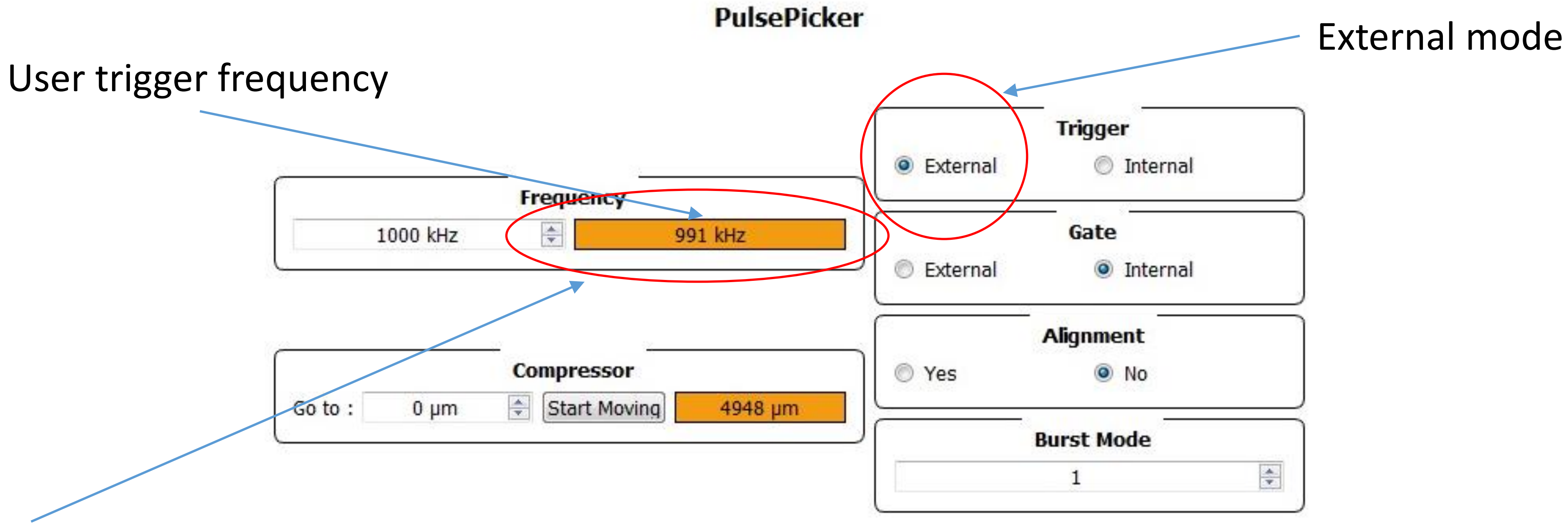
**1st step alternative:** PP frequency in "External mode" :

- In "External mode" the **user must provide the trigger signals for the pulse picker** (via the "Trigger PP" input of the user interface).
- A user trigger signal that is not synchronized to the oscillator necessarily causes a timing jitter of one oscillator period.
- **The user trigger signal can be used to resynchronize the laser with the application with a temporal resolution of the oscillator period**. BUT: gain dynamics in the amplifier chain must be considered and may result in measurable pulse energy fluctuations, e.g. in case the time interval between two PP pulses changes significantly.
- The **internal laser security loop remains active**, i.e., the laser will switch into a safety failure mode if the time interval between two trigger signals is larger than the inverse of the minimum allowed PP frequency (typically 330kHz in the TANGOR laser, corresponding to a max. time interval of ~3µs)




The user interface will indicate the pulse repetition rate or frequency of the external trigger signal provided by the user.

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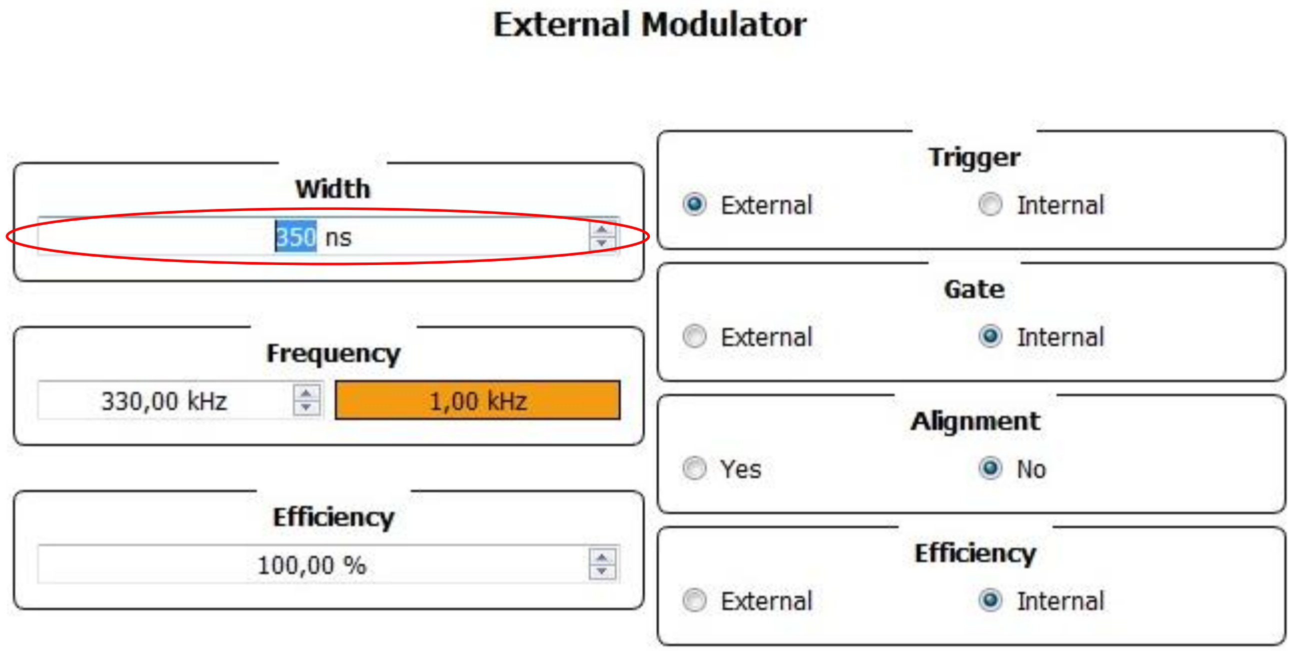
**2nd step:** Adjustment of the External Modulator to create bunches of pulses

- By using the “Width” parameter of the External Modulator the user can choose a selected number of pulses (bunch) out of the pulse train amplified at the PP frequency.
- The “Width” value to be set in order to obtain a single output pulse with good contrast is reported in the CoC of every individual laser. The value is 350ns in case of the laser below.
- These 350ns are part of the system-inherent times mentioned on slide 4.




**Examples of bunches follow on the next slides**

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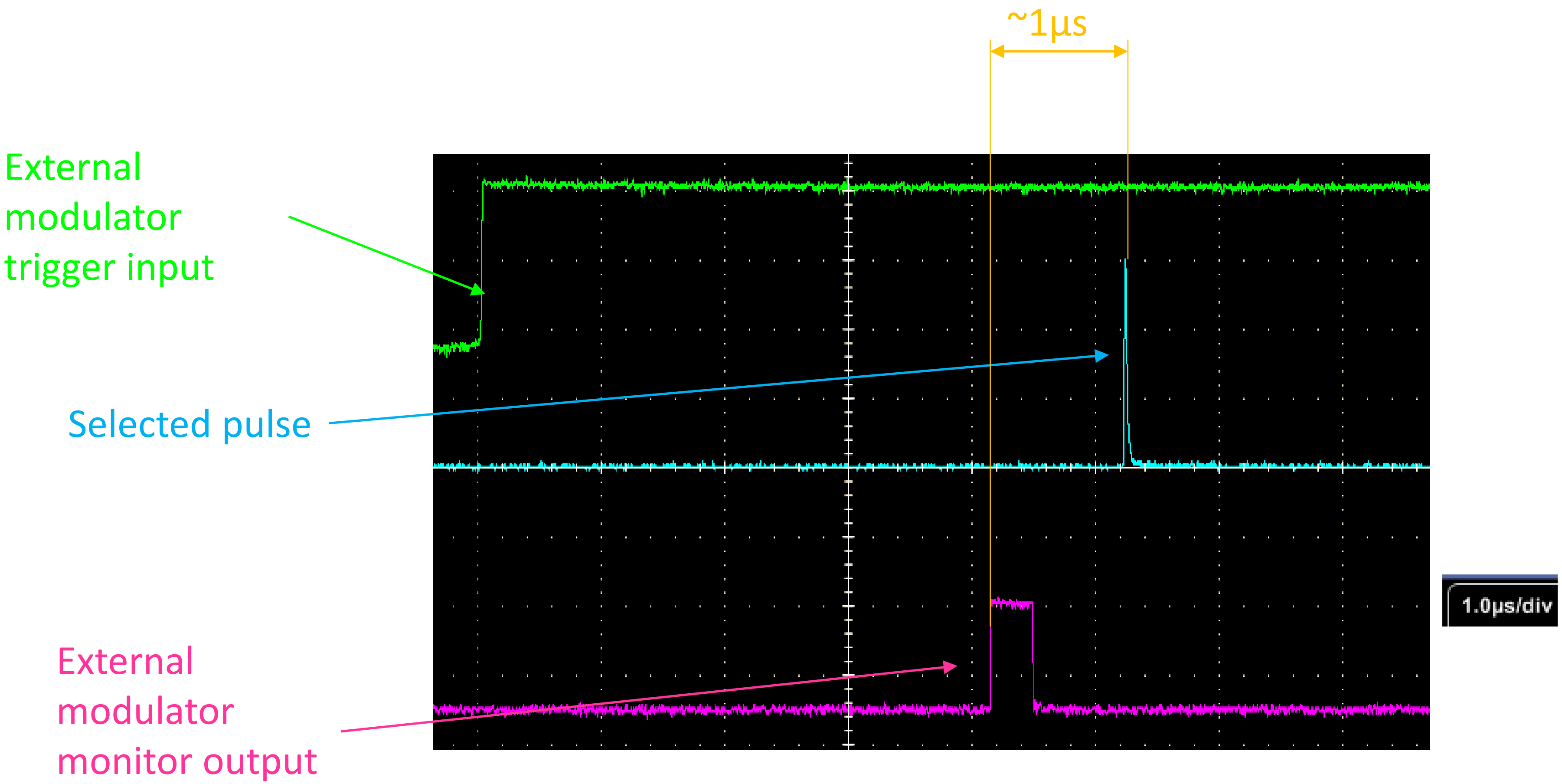
# Measurement example for selecting 1 pulse

- Set the “Width” value corresponding to a single pulse:
  - This value is reported in the CoC of the laser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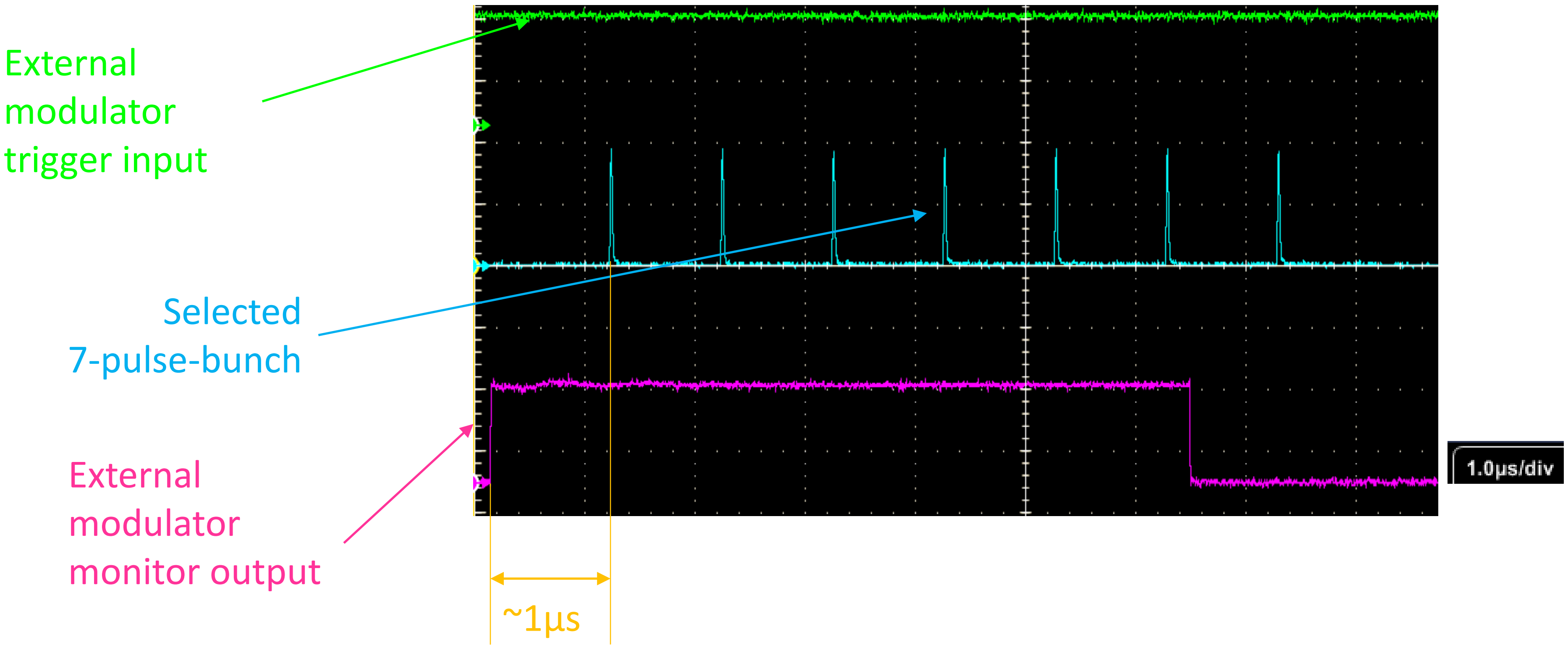
## Example for creating a bunch of 7 pulses

- For creating a **bunch of n pulses** at the PP frequency, an amount of (n-1) PP periods must be added to the “Width” value of a single pulse. PP period TPP=1/fPP with fPP=991kHz.
- For **7 pulses** : Width=350+(**7**-1)*1/991*1E6=6405ns: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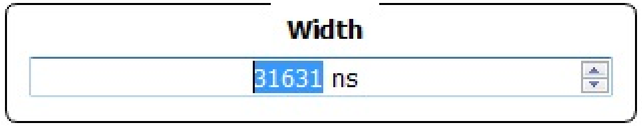
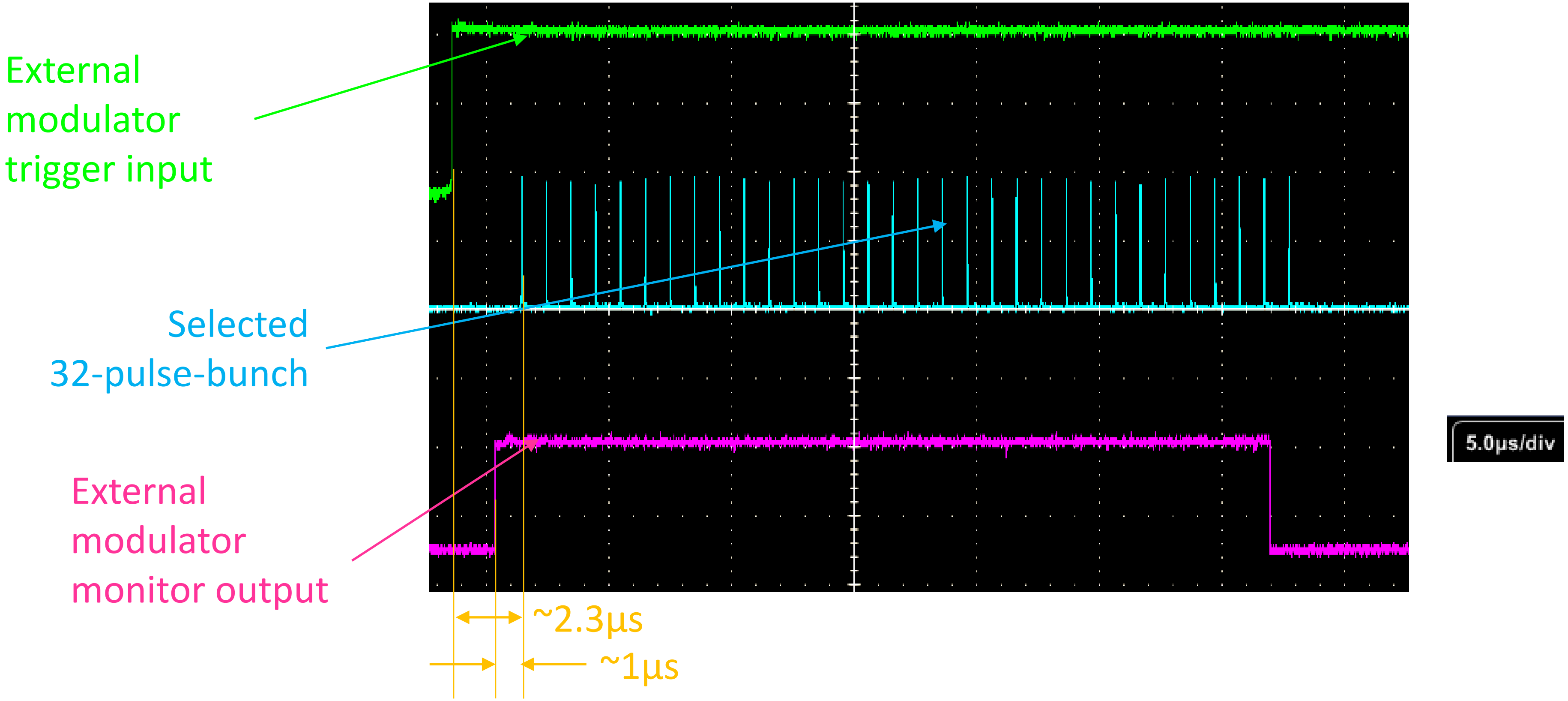
## Example for creating a bunch of 32 pulses

- For creating a bunch of n pulses at the PP frequency, an amount of (n-1) PP periods must be added to the “Width” value of a single pulse. PP period TPP=1/fPP with fPP=991kHz.
- For **32 pulses** : Width=350+(**32**-1)*1/991*1E6=31631ns:

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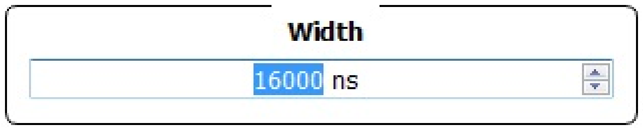
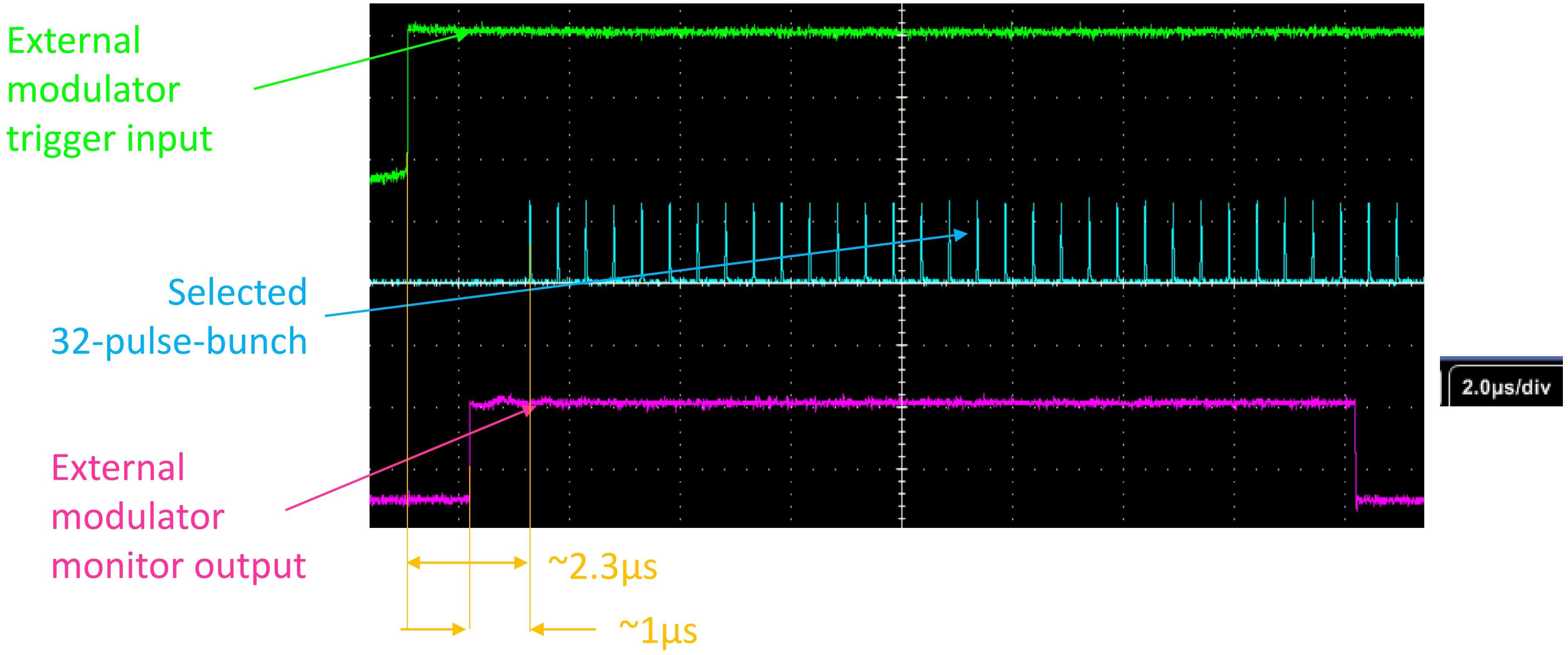
## Bunch of 32 pulses but fPP=1981kHz

- For creating a bunch of n pulses at the PP frequency, an amount of (n-1) PP periods must be added to the “Width” value of a single pulse. PP period TPP=1/fPP with fPP=1981kHz.
- For **32 pulses** : Width=350+(**32**-1)*1/1981*1E6=16000ns:

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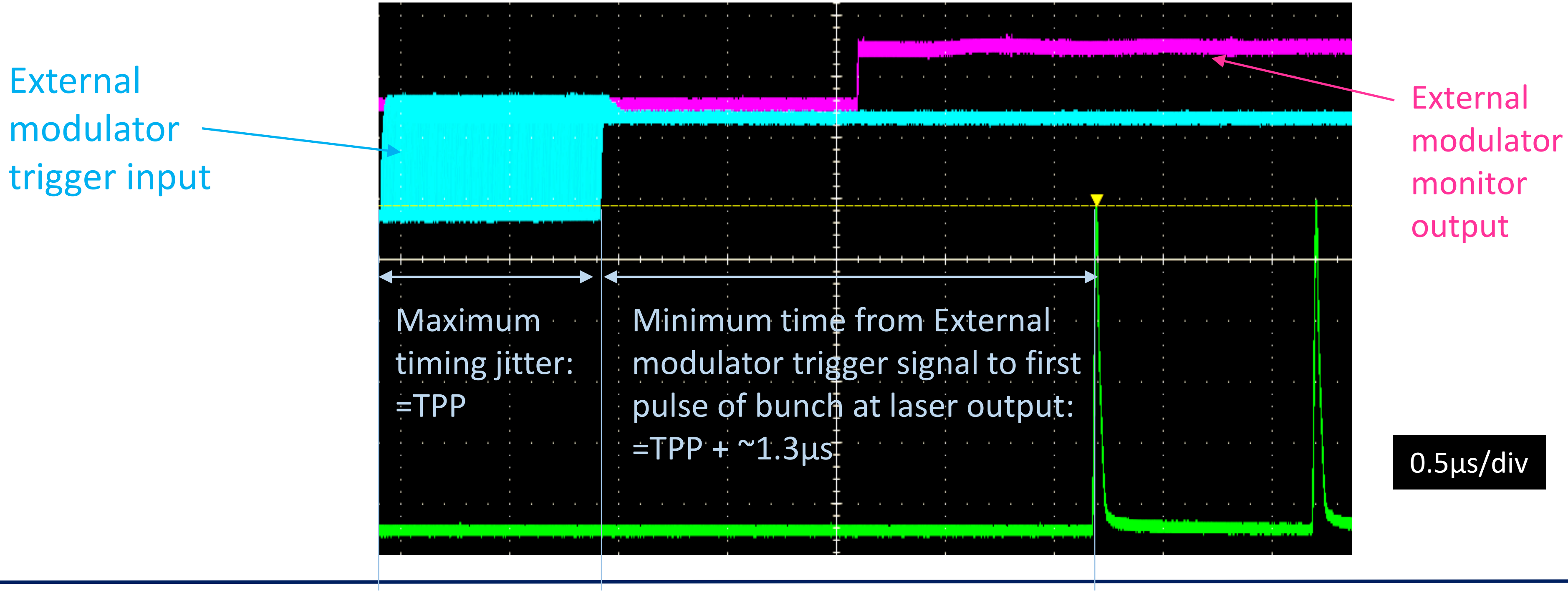
## Bunch of 32 pulses, timing jitter

- The figure below visualizes the **maximum timing jitter** in case of a trigger signal to the External modulator that is **not synchronized** to the oscillator and the PP frequency.
- This **maximum timing jitter** amounts to **one PP period** (TPP=1/fPP). ~1µs for fPP=991kHz.
- The minimum timing jitter is ~0 and is obtained if the user trigger is synchronized to the PP, e.g. via the Monitor PP output signal.
- The timing jitter can also be reduced to one OSC period (TOSC=1/fOSC=~25ns) if the user trigger is resynchronized to the oscillator master clock.
- **The figure visualizes as well the minimum time it takes from the External modulator trigger signal to the amplified pulse at the output of the laser: 1 TPP + ~1.3µs**

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## Summary and discussion

- *Bunches with exact number of pulses* can be programmed and triggered with the TANGOR laser via its user interface
- The *timing jitter* of the output pulse train relative to the user signal for the External modulator depends on the usage of the laser and the trigger signals:
  - If the laser is operated in “Internal” or “External” mode for the Pulse Picker PP and the External modulator trigger signal is **not synchronized** at all, **the timing jitter amounts to one Pulse Picker period TPP** (TPP=1µs for a PP frequency of 1MHz).
  - If the laser is operated in “Internal” mode for the Pulse Picker PP and the External modulator trigger signal is **synchronized to the PP frequency** and the oscillator (which are related by a fixed division factor), the **timing jitter is ~0**.
  - If the laser is operated in “External” mode for the Pulse Picker PP and the External modulator, and both trigger signals, for the PP as well as for the External modulator, are **synchronized with respect to each other AND to the oscillator**, the **timing jitter** can be reduced to **one oscillator period** TOsc (~25ns). **Note:** in this case, the PP period varies, in case the resynchronization with the application requires a dynamic change of the division factor k between fOsc and fPP. In this case, the energy of the pulse amplified within the varied PP period may slightly vary because of the different energy storage time in the amplifier chain before amplification and extraction of the desired pulse. With proper timing, it should be possible to shift this pulse to the OFF-phase of the External modulator.

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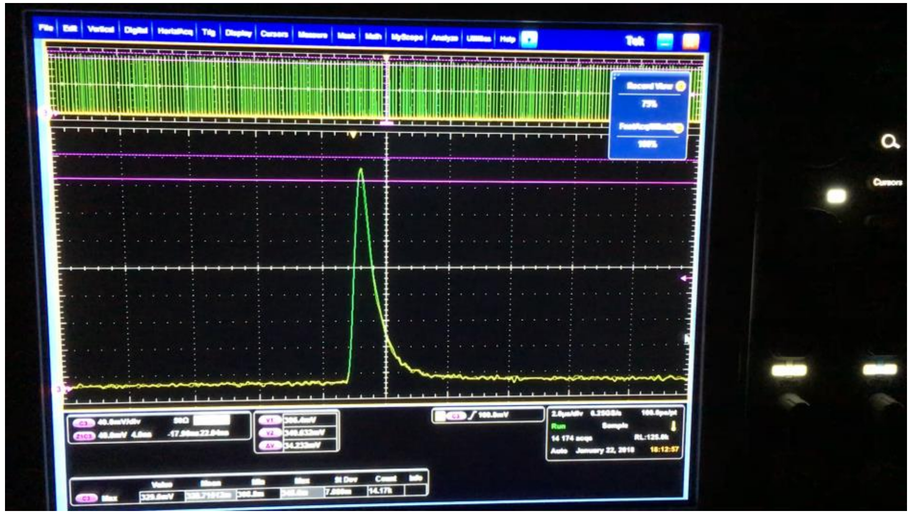
# WP3 – Task 3.3: Flexible user interface

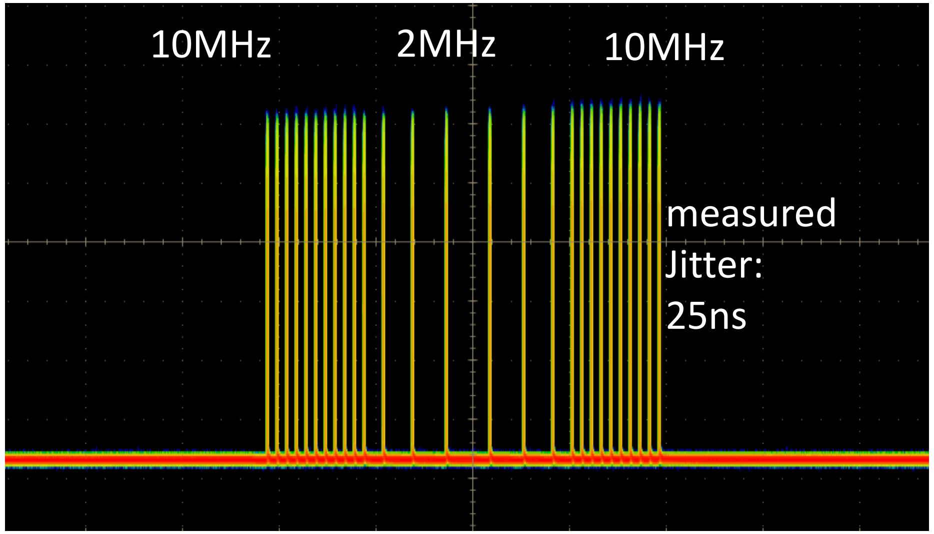
Proof of concept of Concept 2 for “free triggering” (also known as “Pulse on demand”)

- User defines wanted energy for process
- Laser can be Free triggered (**FemtoTrig**) with 25ns jitter
- Video:
    - Pulse periods from ms to 100ns (4 magnitudes!)
    - Pulse energy stable!



**REDUCING DEAD TIMES:**

- User case showing deceleration from 10MHz to 2MHz and acceleration back again
- Timing jitter: 25ns

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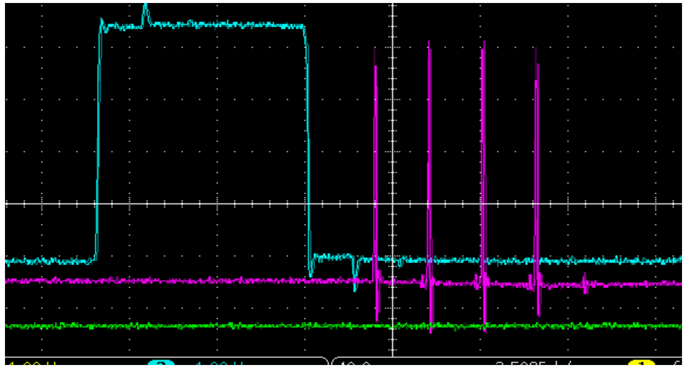
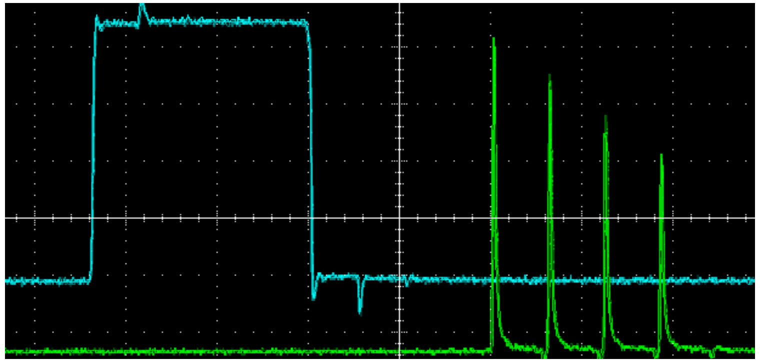
## **FemtoBurst:** *shaped burst envelopes*

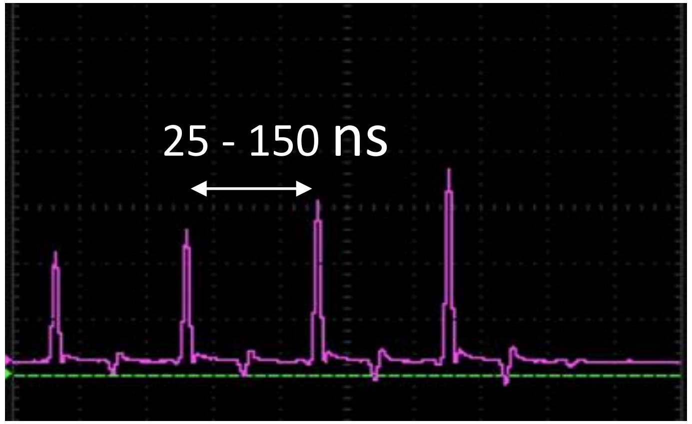
Before amplification



After amplification



**Amplitude shaping** with **Pulse Picker**





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# WP3 – The next six months…

- Tasks 3.2: 200-W, ~500fs laser, >1MHz @ 1030nm
  - Deliver additional 100-W laser to partner C4L for materials processing foreseen in project (means higher investment from Amplitude's side than originally foreseen!)
  - Finalize 200-W laser with optimized components and deliver to partner USTUTT for kW laser development in Sept/Oct 2018.

- Task 3.3: Flexible user interface including high speed modulation
  - Implement concept with second output beam during "Gate OFF" to the 200W demonstrator
  - Burst modes necessary?

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# WP3 - Deliverables

| Deliverable title | Due date | Status |
|---|---|---|
| D3.1 50-W, 300-fs, >1-MHz laser for seeding an Yb:YAG amplifier (1) | M09 – October 2016 | ✓ |
| D3.2 50-W, 300-fs, >1-MHz laser for seeding an Yb:YAG amplifier (2) | M09 – October 2016 | ✓ |
| D3.3 200-W, ~500-fs, >1-MHz laser for seeding an Yb:YAG amplifier (1) | M21 – November 2017 | **Demonstration: ✓**<br>**Demonstrator: NON** |
| D3.4 200-W, ~500-fs, >1-MHz laser for seeding an Yb:YAG amplifier (2) | M21 – November 2017 | **(✓)** |

Mitigation plan for D3.3:

1. Delivery of an additional R&D Tangor prototype with ~100W average power to C4L in Mai 2018
2. Optimization of demonstrator and demonstrator delivery to USTUTT in Sept/Oct 2018

=> **WP3 didn't end in M21 as foreseen but more likely will end in M32/33**

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# WP3 - Milestones

| Milestone title | Due date | Status |
|---|---|---|
| MS8 A 50W, 300fs at >1 MHz seed laser | M09 – October 2016 | ✓ |
| MS23 A 200W, sub500fs, >1MHz laser system | M21 – November 2017 | ✓ |

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