Ultrashort pulse lasers compatible to the FEL pulse structure

Ingo Will, Max Born Institute Berlin

G. Klemz, DESY

Material included from: H. Redlin (DESY),

M. Kalashnikov (MBI) and others

Ti:Sa laser versus OPCPA systems

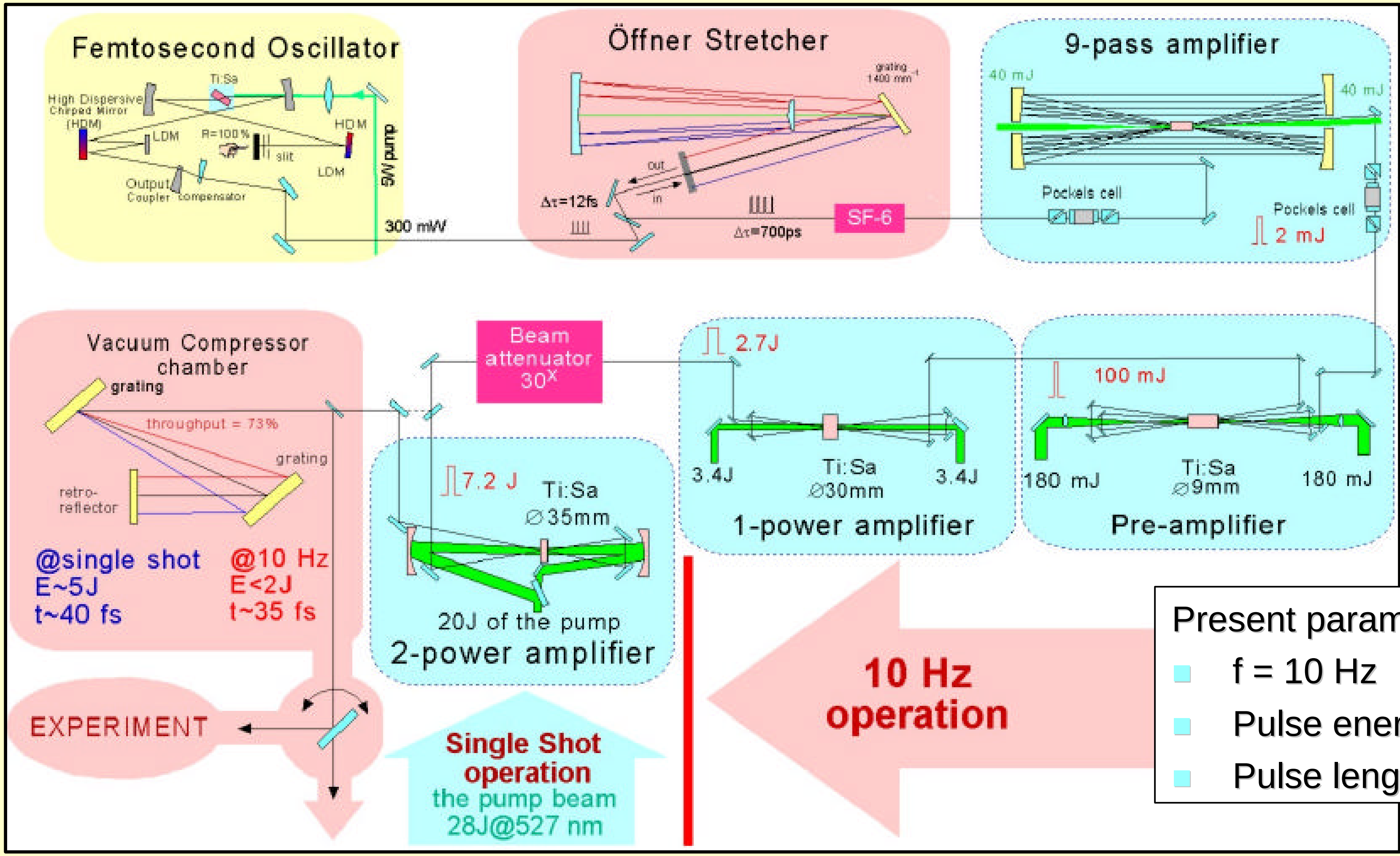
- **Ti:Sa lasers running at 10 Hz**
- **Limited usefulness of high-frequency CW-pumped lasers**
- **OPCPA burst-mode system in operation at FLASH, possible upgrades**
- **Feasibility of a Ti:Sa laser running in burst-mode**

Overview on the available laser parameters

operational mode	single pulse laser f = 10 Hz		CW with high rep. rate (f ³ 250 kHz)		Special Burst-mode laser (present Pump-Probe laser at FLASH)	
laser type	Ti:Sa	OPCPA	TiSa	OPCPA	Ti:Sa	OPCPA (presently at FLASH)
energy per micropulse	**5 J, up to 10 J**	**several J**	**20 mJ**	**?**	**unknown**	**0.5 mJ**
energy per train (600 ms long)	**single pulse**	**single pulse**	**0.003 J**	**?**	**unknown, 0.1 ...1 J estimated.**	**~ 1 J (presently at FLASH: 0.1 J)**
pulse duration	**£ 25 fs**	**> 15 fs**	**25...160 fs**	**> 20 fs (?)**	**~ 25 fs**	**100 fs**
wavelength [nm]	**800 nm**	**600...1500**		**600 ... 2000**	**800 nm**	**800 nm (600 ... 2000)**
availability	**commercial**	**home-made, under development**	**commercial: f < 200 kHz**	**home-made, under development**	**home-made, under development**	**home-made, working at FLASH**
comments		Outperformed by Ti:Sa for τ > 20 fs, E < 10 J	**very few pulses (< 0.5%) coincide with pulses from the FEL**		**Development neccessary**	

Single-pulse Ti:Sa lasers

Example: MBI high-power laser system built in 2002…2005



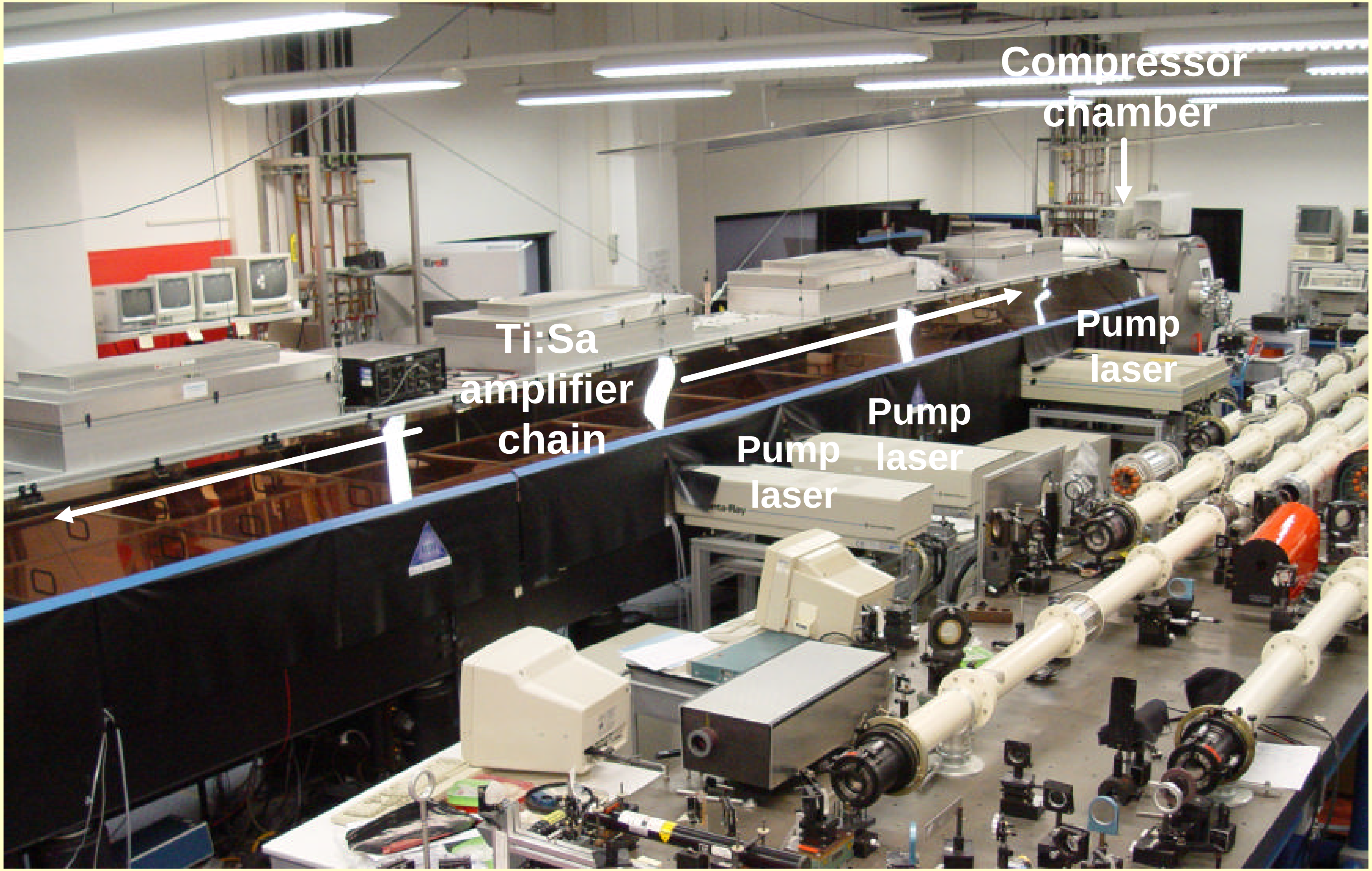
Present parameters:

- f = 10 Hz
- Pulse energy E ~ 3.5 J
- Pulse length: τ ~ 30 fs

- Similar systems are now commercially available from different companies (e.g. Thales, Amplitude, KLM labs …)

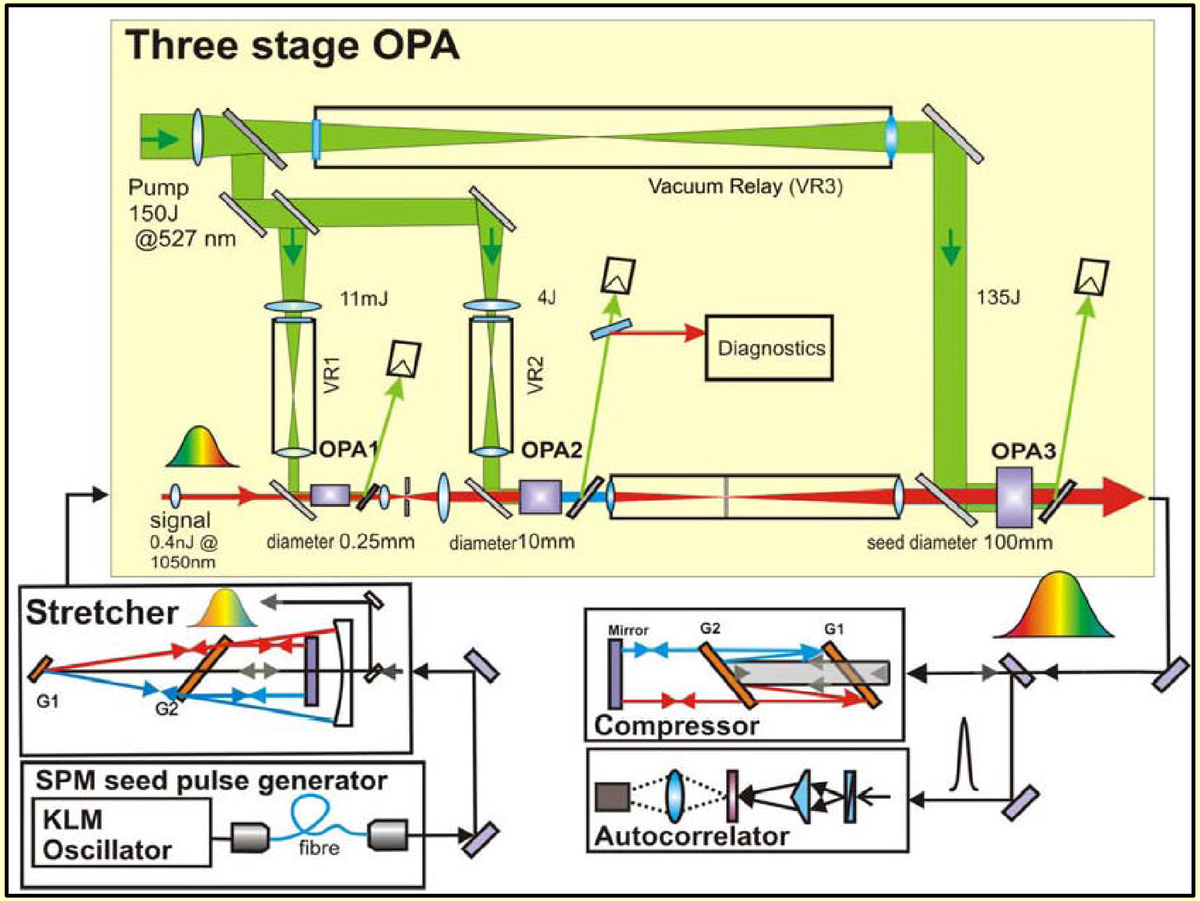
Single-pulse Ti:Sa lasers

Example: MBI high-power laser system built in 2002…2005



Single-pulse OPCPA systems

Example: VULCAN 10 PW OPCPA laser project (RAL Rutherford)



Reference: High energy broadband ultrashort pulse OPCPA system (O Chekhlov, J L Collier, I N Ross, P Bates, M Notley, W Shaikh, C N Danson, D Neely, P Matousek, S Hancock), Central Laser Facility Annual Report 2004/2005

- Being developed for very high pulse energies (e.g. RAL Rutherford)
  - Current parameters
    - E > 35 J (before compressor)
    - duration τ > 85 fs (FWHM)
    - Rep-rate: << 0.01 Hz (Nd:Glass pump laser)
  - Difficulties:
    - Huge systems
    - very low repetition rate
- Ti:Sa systems outperform the OPCPA systems for the following parameters
  - f = 10 Hz
  - Pulse duration τ > 20 fs
  - Up to 5 J pulse energy

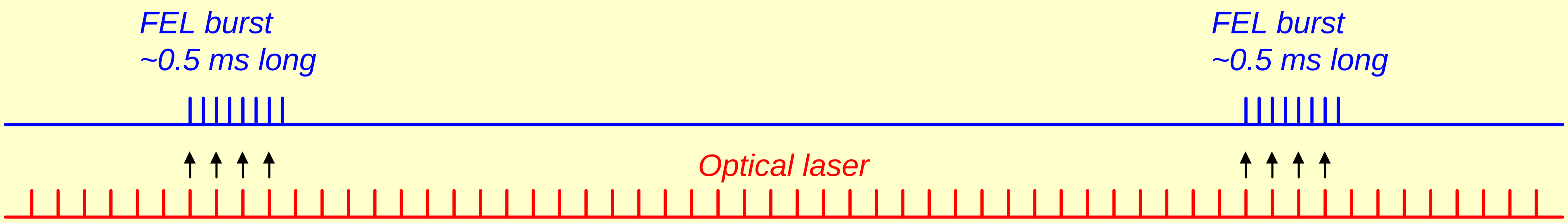
Overview on the available laser parameters

operational mode	single pulse laser f = 10 Hz		CW with high rep. rate (f ³ 250 kHz)		Special Burst-mode laser (present Pump-Probe laser at FLASH)	
laser type	Ti:Sa	OPCPA	TiSa	OPCPA	Ti:Sa	OPCPA (presently at FLASH)
energy per micropulse	**5 J, up to 10 J**	**several J**	**20 mJ**	**?**	**unknown**	**0.5 mJ**
energy per train (600 ms long)	**single pulse**	**single pulse**	**0.003 J**	**?**	**unknown, 0.1 ...1 J estimated.**	**~ 1 J (presently at FLASH: 0.1 J)**
pulse duration	**£ 25 fs**	**> 15 fs**	**25...160 fs**	**> 20 fs (?)**	**~ 25 fs**	**100 fs**
wavelength [nm]	**800 nm**	**600...1500**		**600 ... 2000**	**800 nm**	**800 nm (600 ... 2000)**
availability	**commercial**	**home-made, under development**	**commercial: f < 200 kHz**	**home-made, under development**	**home-made, under development**	**home-made, working at FLASH**
comments		Outperformed by Ti:Sa for $\tau > 20$ fs, E < 10 J	**very few pulses (< 0.5%) coincide with pulses from the FEL**		**Development neccessary**	

High rep-rate Ti:Sa lasers and OPCPA systems

- Reported systems:
  - 20 μJ, τ < 50 fs, f = 250 kHz (P = 5 W) (KML labs)
  - 250 μJ, τ < 200 fs, f = 50 kHz (P = 12.4 W) (Cyber lasers Inc. Japan)
  - 200 μJ, τ < 25 fs, f = 50 kHz (P = 10 W) (ALPHA 1000 by Thales)
  - 0.3 μJ, τ < 160 fs, f = 800 kHz (P = 0.3 W) (CNRS, Univ Paris-Sud)

- **Major problem** with high-rep.-rate lasers applied at the FEL:



- Duty cycle of the FEL < 0.5 %
  -> **Less than 0.5 % of the pulses** from the optical laser would **coincide with the FEL pulses**
  -> laser power effectively used at 5 W average power: $P_{effective}$ < 25 mW
  -> Lasers operating in burst-mode would be much more suitable for FLASH and the XFEL

- In addition: experience shows that the FEL is usually operated with reduced pulse duration (duty cycle < 0.1%)

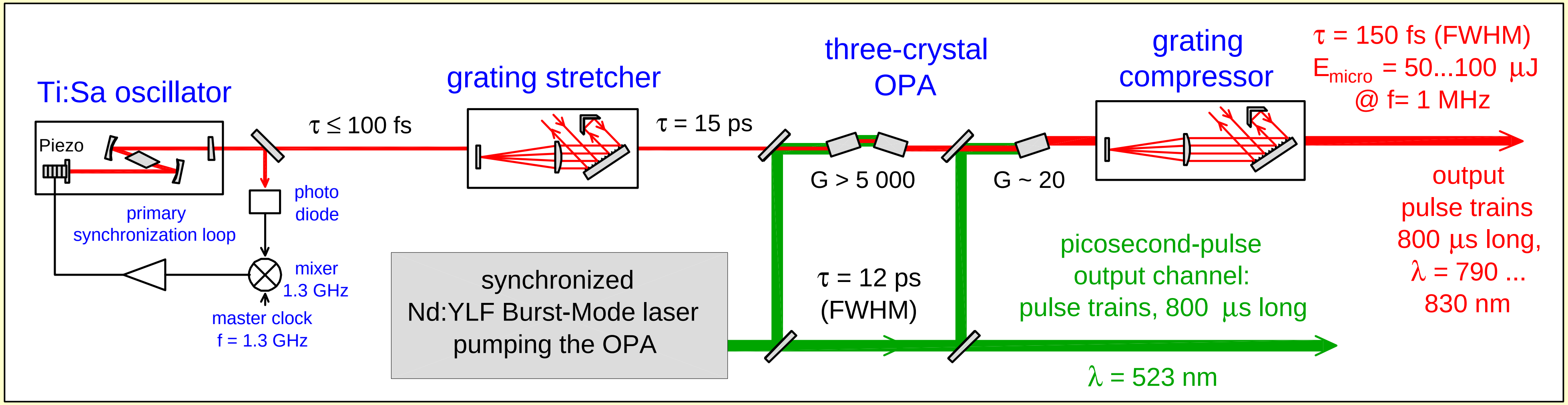
Burst-mode lasers and OPCPA systems

- Burst-mode lasers short-pulse lasers are a very special requirement of DESY (due to the time structure given by the TESLA-type linac)
  -> small market, no commercial systems available.

- Burst-mode Ti:Sa lasers
  - Not commercially available
  - Very few projects exists to develop these systems.
    On the other hand: Urgent need of these systems for both FLASH and the XFEL
    - Pump-probe lasers for various experiments
    - Drive laser for seeding of the XFEL with High Harmonics
  - **Development of burst-mode Ti:Sa lasers for FLASH/XFEL would be highly desirable**

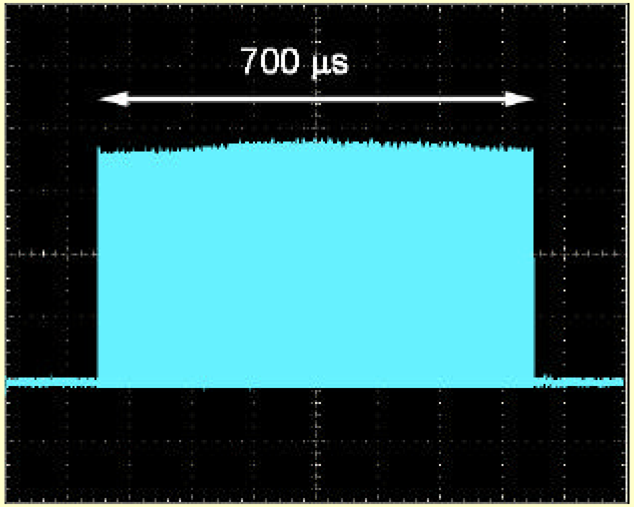
- Burst-mode OPCPA
  - Not commercially available
  - First burst-mode OPCPA system developed at the MBI in 2001…2005,
    in operation at FLASH since 2004
  - Further improvements realistic
    - Pulse duration can be reduced to 25 fs (in special version to 15 fs)
    - Pulse energy could be increased by ~ one order of magnitude
    - Improvement of the pump laser: Diode pumped system now feasible

OPCPA system developed at the MBI in 2001…2005 (now operated at FLASH by H. Redlin)



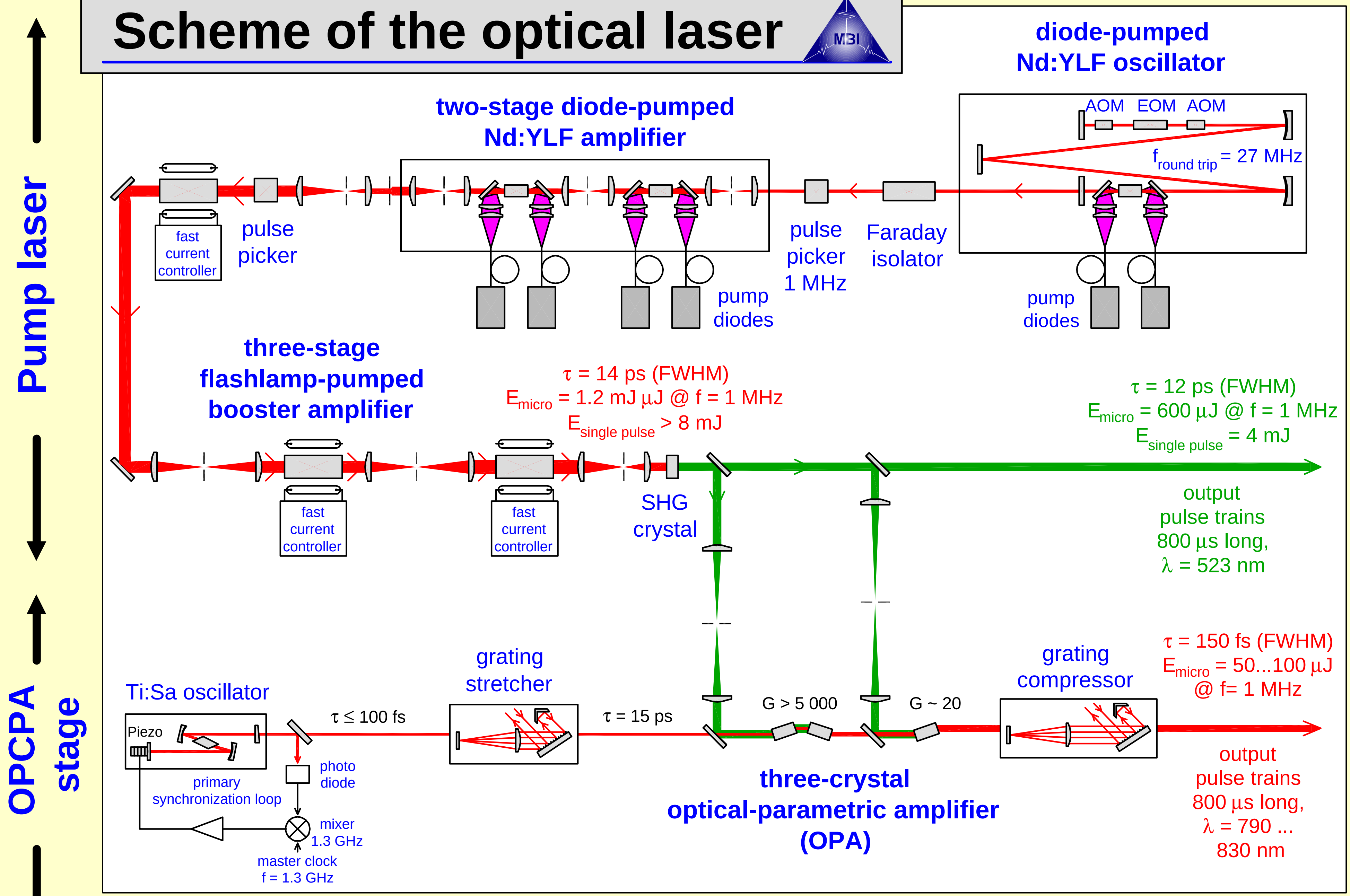
OPCPA: Optical Parametric Chirped-Pulse Amplification

- Generates femtosecond pulses
  $\tau \leq 150$ fs FWHM
- pulse energy available at present :
  E_{micro} = 100 µJ (before compressor)
  E_{micro} = 50 µJ (behind compressor)
- Available wavelength:
  - λ = 790…830 nm
  - on request: λ = 395…415 nm

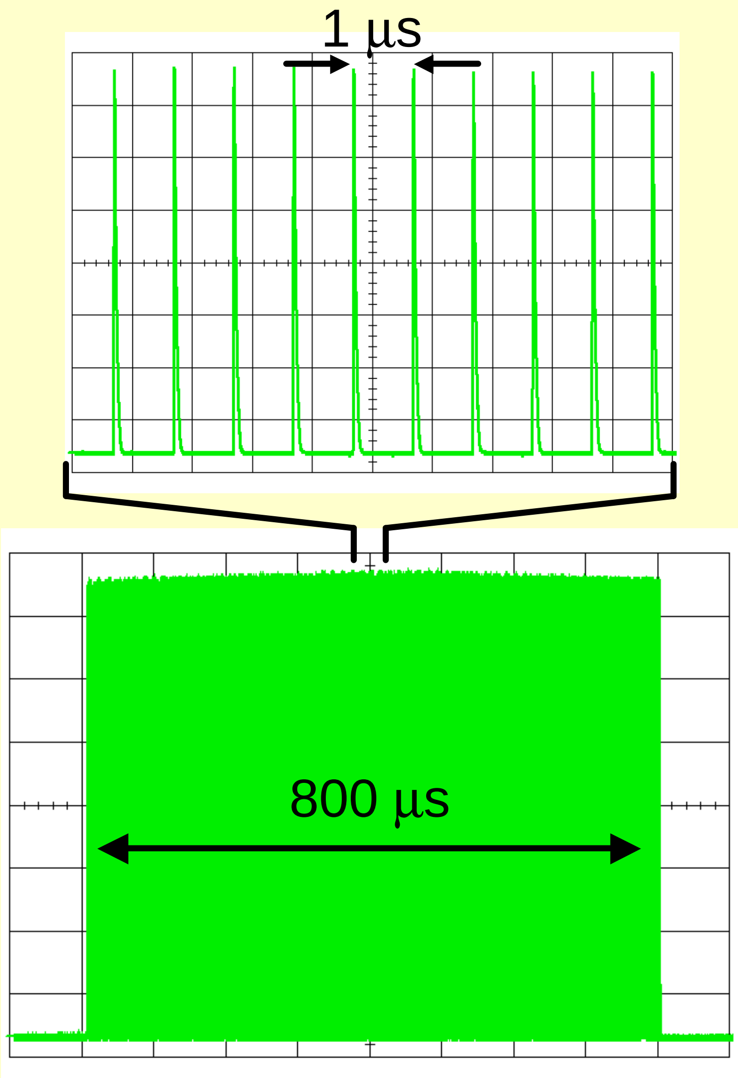


output pulse train which contains 700 micropulses

Scheme of the optical laser



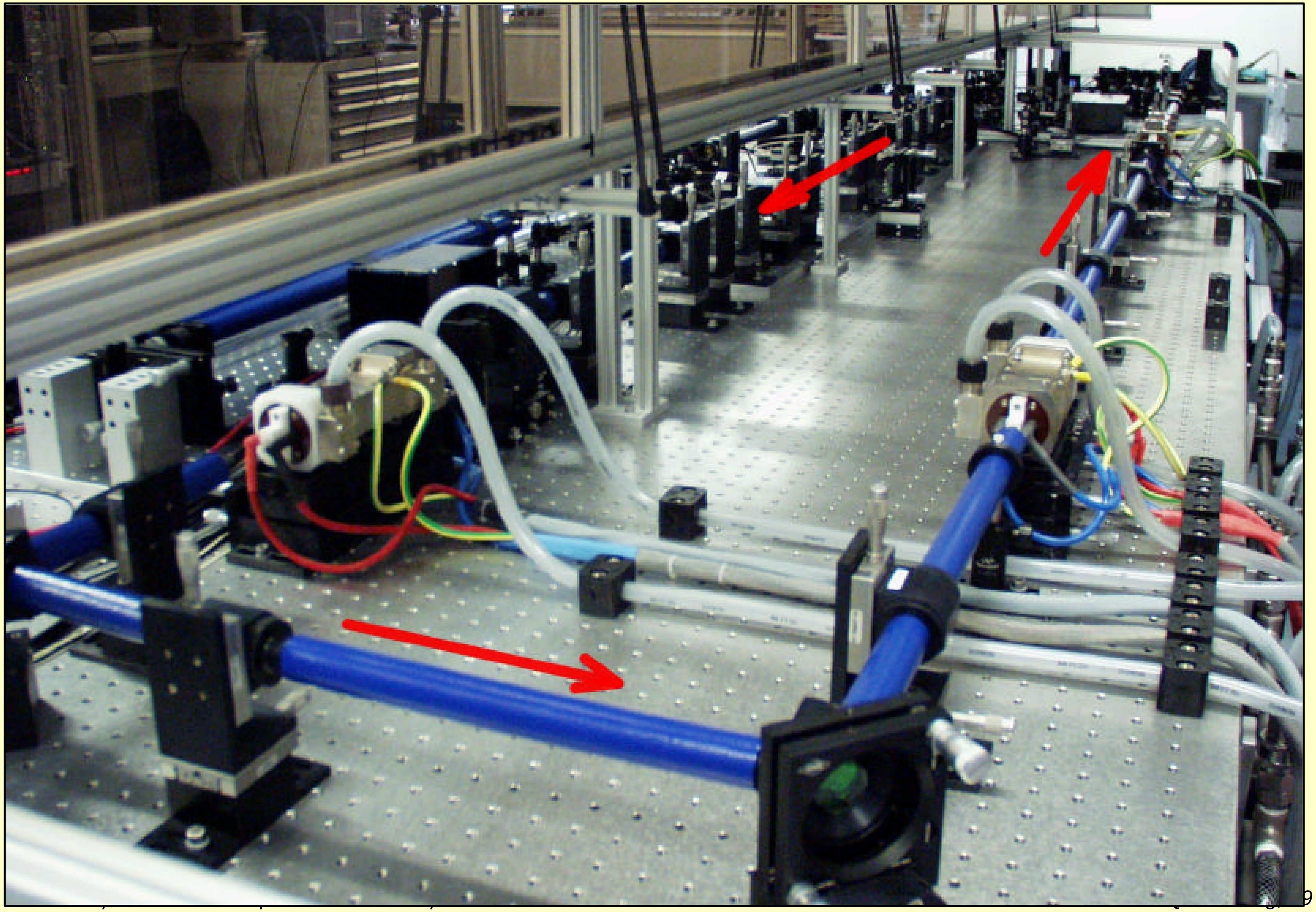
The Nd:YLF pump laser and its output



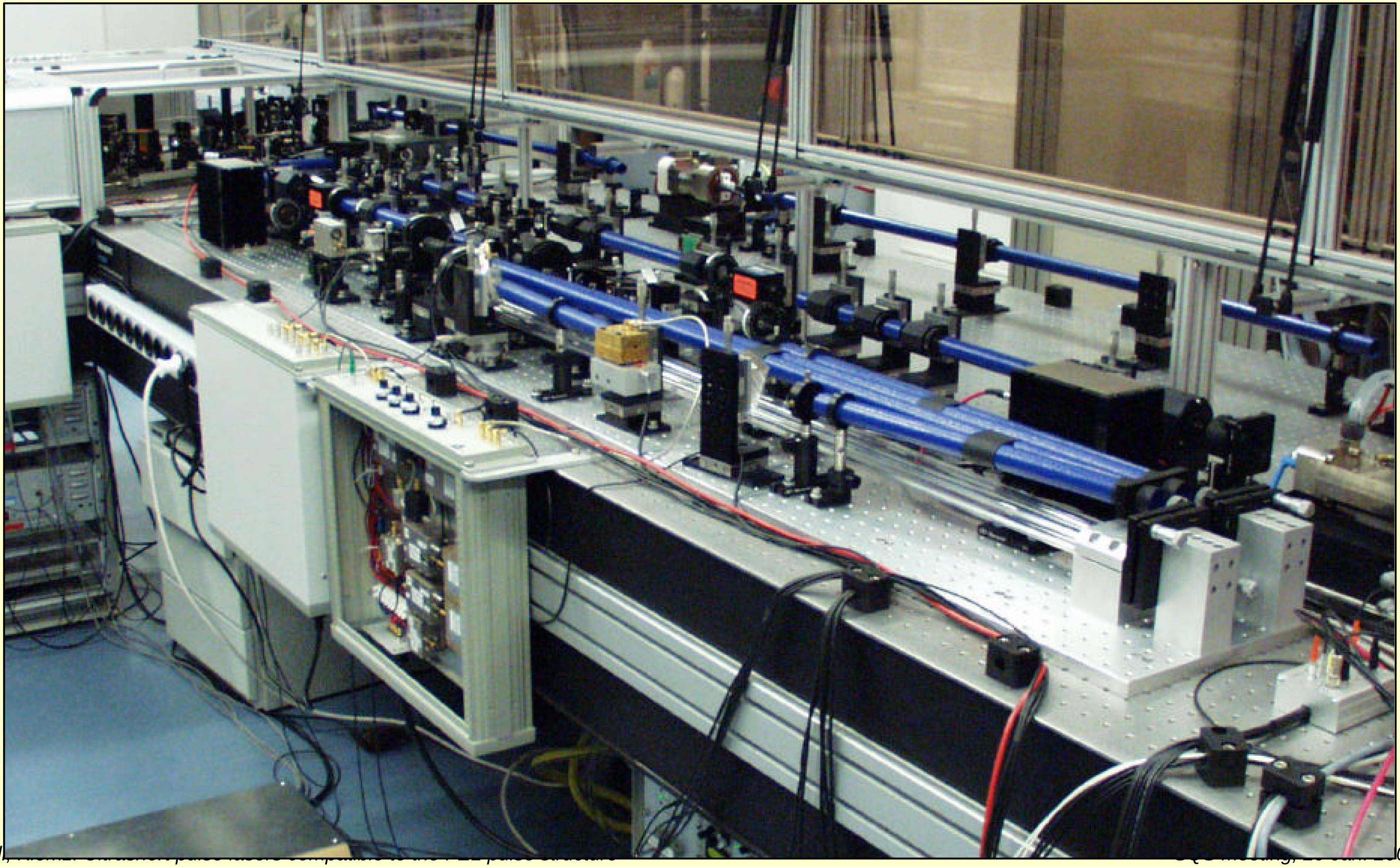
output train of the Nd:YLF laser

- Generates trains of picosecond pulses (τ = 10 …15 ps FWHM)
- Synchronization accuracy (phase noise): σ < 0.5 ps
- Very reliable synchronization
- Rectangular envelope of the pulse trains
  -> energy of the micropulses is stable within 1%
- Large flexibility in:
  - Duration of the pulse train
  - Repetition rate within the pulse train
  - Number of micropulses per train
- Wavelengths available to the user
  - λ = 1047 nm,
  - λ = 523 nm
  - on special request: λ = 349 and 262 nm
- Pulses can be lengthened
  - Potential application: “alignment” laser

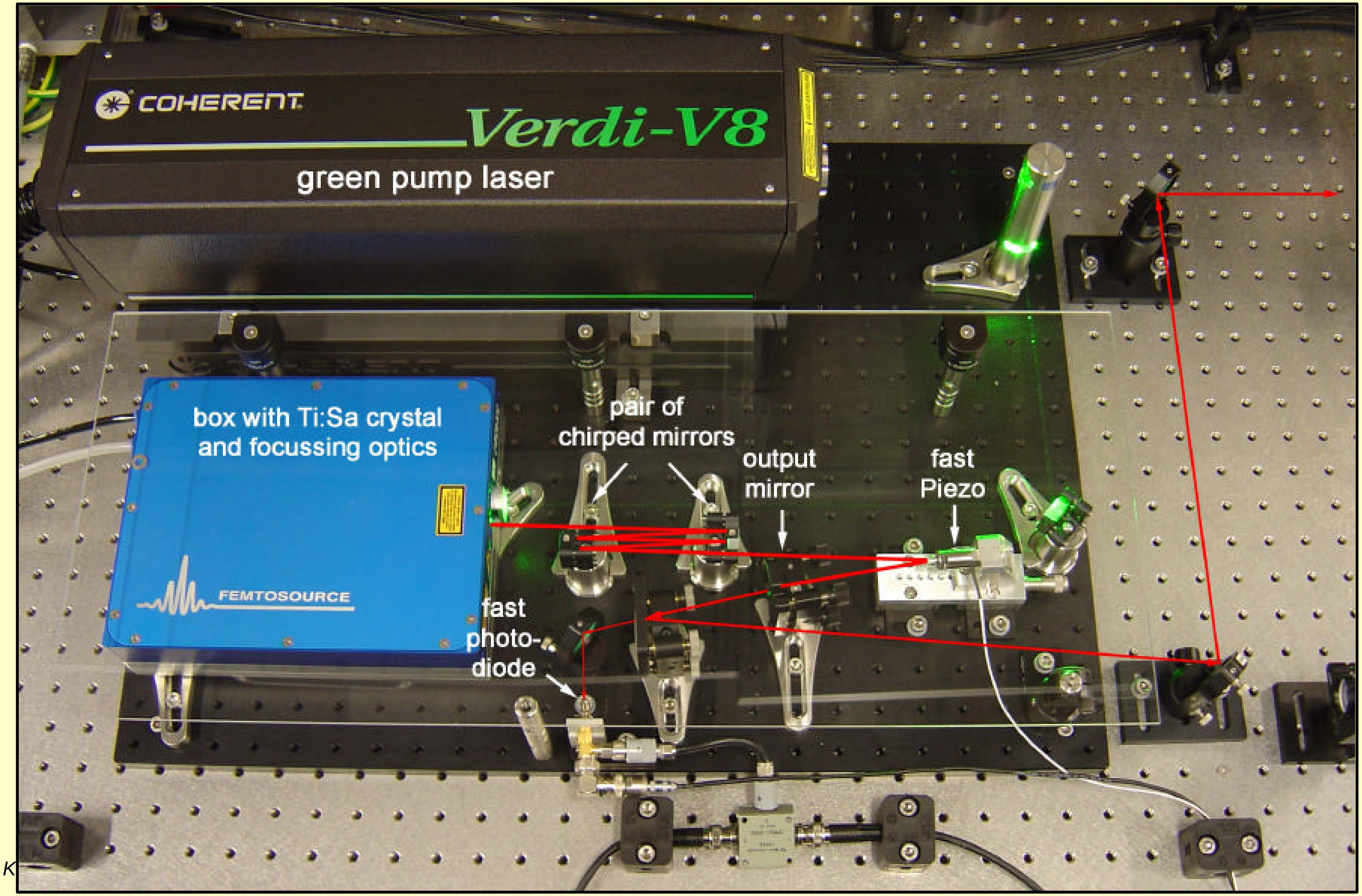
The three-stage booster amplifier



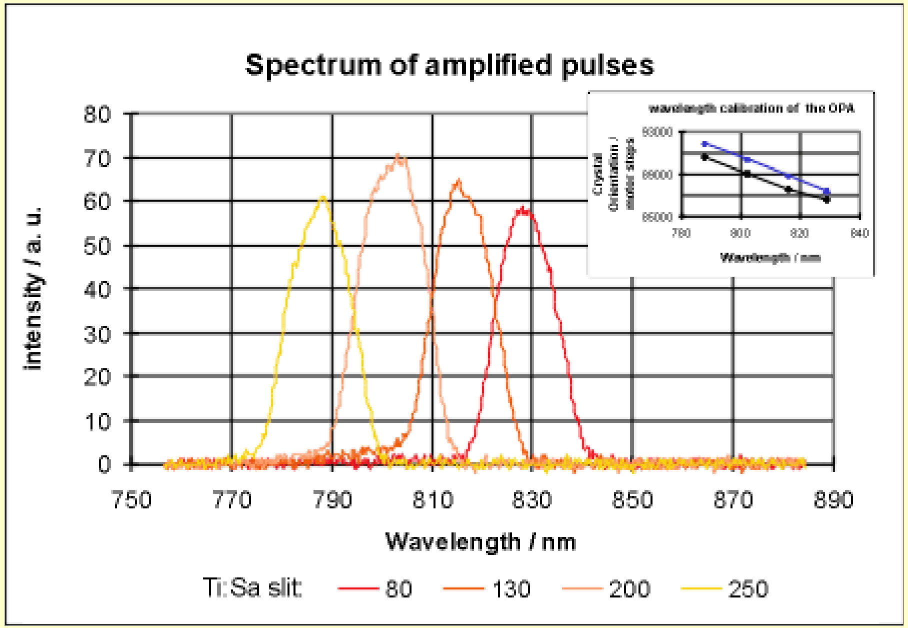
Diode-pumped oscillator and two-stage preamplifier of the pump laser



Ti:Sa oscillator of the synchronization test system



Tuning the wavelength of the OPCPA output



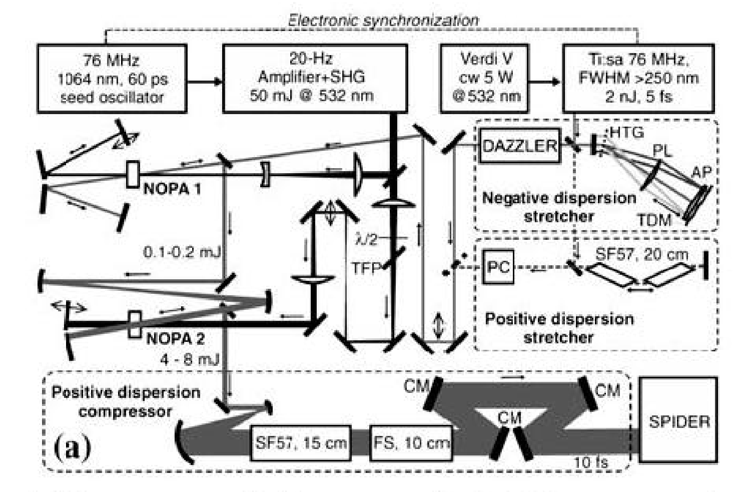
- Wavelength of the output pulses is determined by:
  - wavelength of the pulses from Ti:Sa oscillator (position of a slit in the resonator)
  - tilt of the OPA crystals (phase matching angle)
- Present wavelength range:
  - λ = 790…830 nm
  - on special request: λ = 395…415 nm
- Challenge of future work:
  fully remote-controlled scan of the wavelength

Possible upgrades of the present Burst-mode OPCPA at FLASH

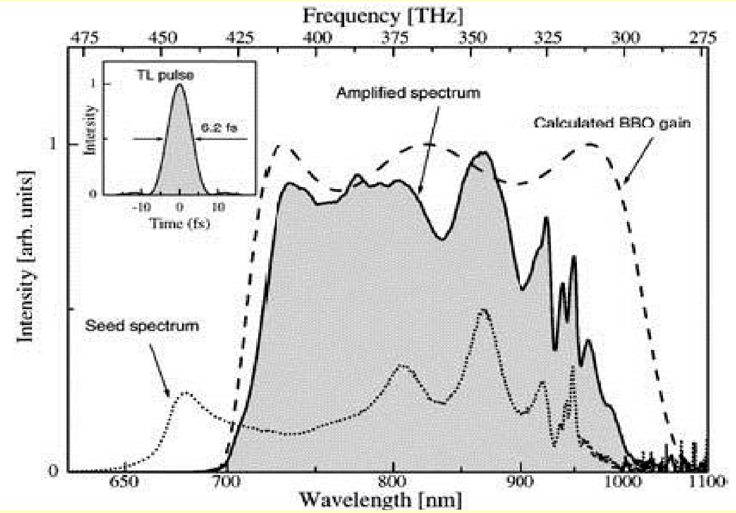
- Improved pump laser:
  - replace flashlamps by diode pump system
    - increased repetition rate
    - improved stability
  - Higher pump power
    - Increase of the output pulse energy E_{micro} = 0,5…1 mJ feasible (at f = 1 MHz)

- Enhanced tunability in wavelength (e.g by using a tunable oscillator, OPO)

- Reduction of the pulse duration to ~25 fs (optional down to <15 fs)
  - Improved dispersion management,BBO can support a very broad gain spectrum in an NOPA (**N**on-collinear **O**ptical-**P**arametric **A**mplifier) (see e.g. Krauss et al. Opt. Lett 30 (2005), pp. 547)



20 Hz OPCPA system developed at the MPQ



Experience with the OPCPA system at FLASH

- OPCPA systems **can be operated in Burst-mode** with a time structure identical to the one of FLASH and XFEL

- Extended versions of the photocathode lasers are suitable for the required burst-mode pump lasers
  - Nd:YLF lasers (in operation at FLASH)
  - Yb:YAG lasers (under development)

- OPCPA turns out to be a **rather complex** technique
  - Expensive picosecond pump laser required
  - Pump lasers have to be synchronized to FLASH
  - More difficult to operate than Ti:Sa lasers
    - No turn-key system,
    - specialists are needed to operate the OPCPA system
  - OPCPA systems have rather **limited flexibility** and extendibility

  -> constant effort to extend/replace the OPCPA by Ti:Sa lasers (single pulse)

  But: The Ti:Sa systems do not run in burst mode at present

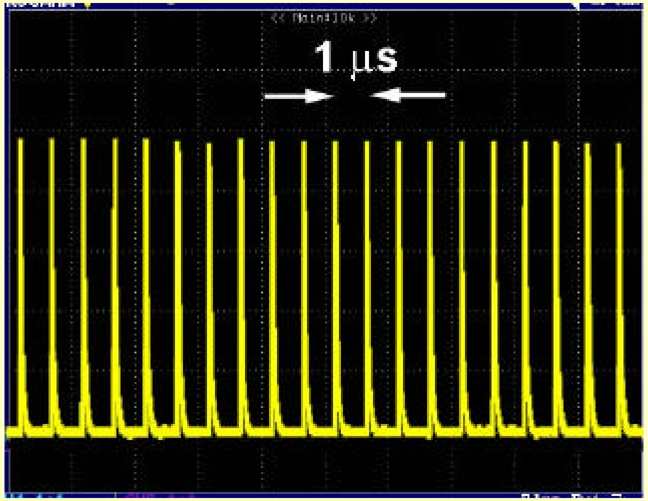
-> Feasibility of an alternative Ti:Sa systems running in burst-mode should be checked

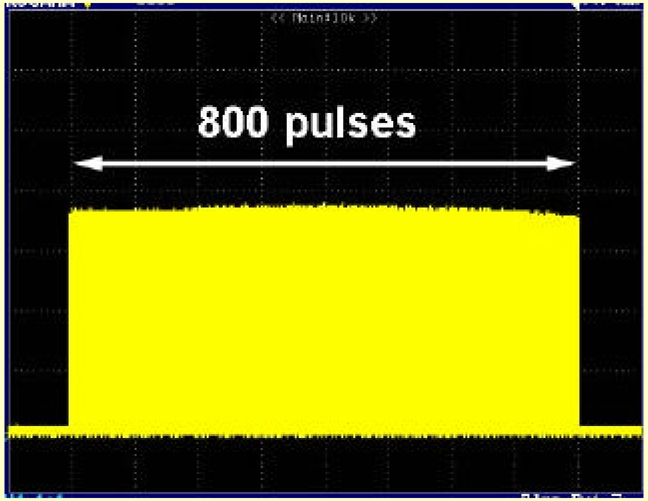
Are Ti:Sa lasers capable of generating <u>bursts</u> of ultrashort pulses?

- Has anybody successfully built a Ti:Sa laser with at pulse structure compatible to FLASH or the XFEL?
  - Special pump laser required (not commercially available)
    - Fortunately, much smaller and more simple than the pump laser for an OPCPA system
    - No synchronization required
    - Can run with multiple TEM modes.
  - Thermal lensing during in the Ti:Sa crystal may cause stability of the pulse train
    - May be compensated by dynamically deformable mirror

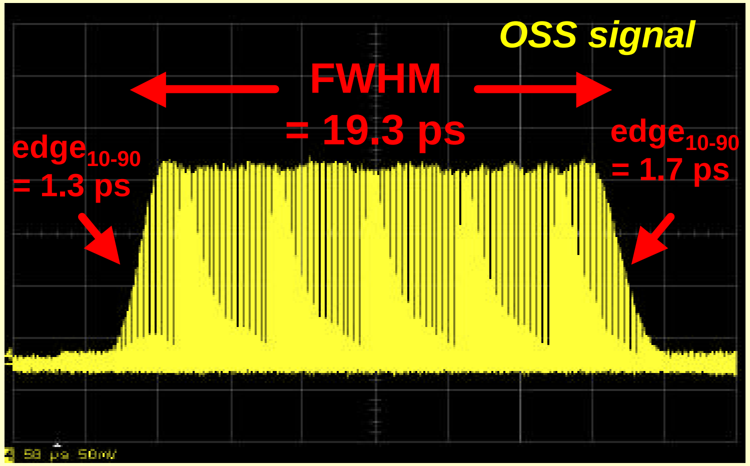
- Which part of the technology of the photoinjector drive lasers is suitable to develop a burst-mode Ti:Sa system?

UV output pulses of the present photoinjector drive laser at DESY Zeuthen



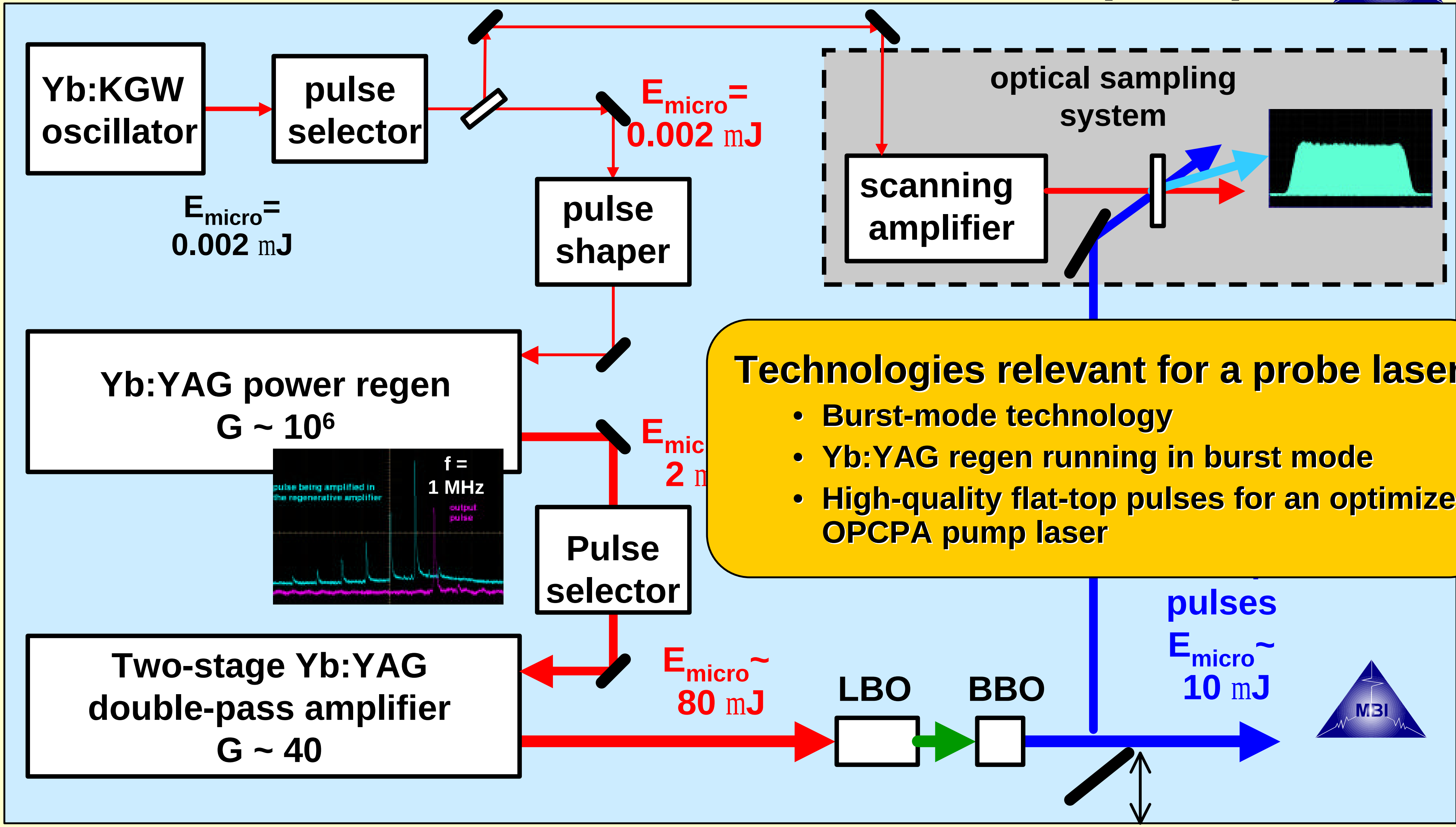


Pulse trains containing up to 800 micropulses



Shape of the micropulses measured with an optical sampling system

Status of the photoinjector drive laser for XFEL: Present laser installed at DESY Zeuthen (PITZ)

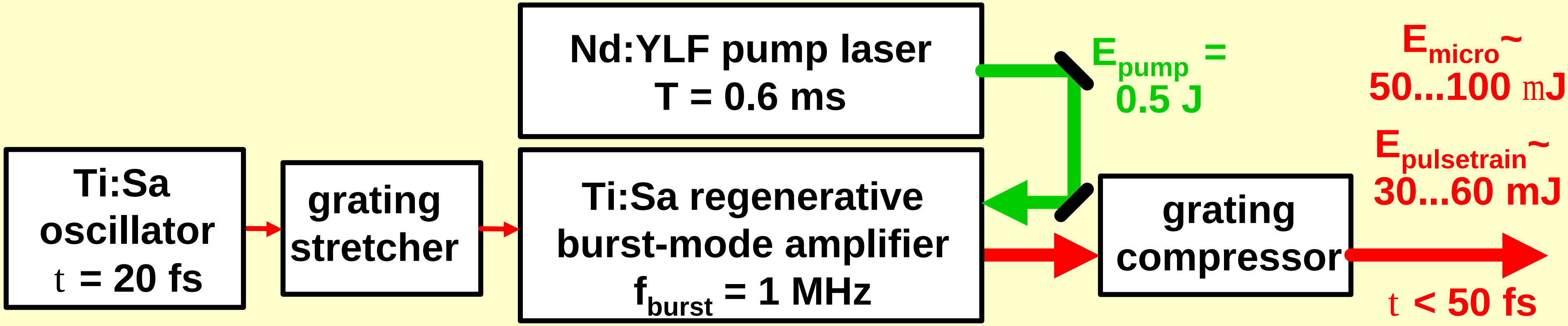


Technologies relevant for a probe laser

- Burst-mode technology
- Yb:YAG regen running in burst mode
- High-quality flat-top pulses for an optimized OPCPA pump laser

Proof-of-principle experiment for a burst-mode Ti:Sa laser (proposal)

- Burst-mode Ti:Sa systems: important technology for both FLASH and XFEL



- Proposed system can be set up based on existing technologies
  - Pump laser: experimental version exists at the MBI (present: E = 0.5 J during 0.6 ms)
  - High-frequency regenerative amplifier technology:
    developed at the MBI for the PITZ photocathode laser, transferred to DESY Zeuthen in spring 2008
  - Dynamic correction of the thermal lens: being developed for the XFEL photocathode laser

- Present limits
  - Man power, money
  - Decision to do it is needed!

Overview on the available laser parameters

operational mode	single pulse laser f = 10 Hz		CW with high rep. rate (f ³ 250 kHz)		Special Burst-mode laser (present Pump-Probe laser at FLASH)	
laser type	Ti:Sa	OPCPA	TiSa	OPCPA	Ti:Sa	OPCPA (presently at FLASH)
energy per micropulse	**5 J, up to 10 J**	**several J**	**20 mJ**	**?**	**unknown**	**0.5 mJ**
energy per train (600 ms long)	**single pulse**	**single pulse**	**0.003 J**	**?**	**unknown, 0.1 ...1 J estimated.**	**~ 1 J (presently at FLASH: 0.1 J)**
pulse duration	**£ 25 fs**	**> 15 fs**	**25...160 fs**	**> 20 fs (?)**	**~ 25 fs**	**100 fs**
wavelength [nm]	**800 nm**	**600...1500**		**600 ... 2000**	**800 nm**	**800 nm (600 ... 2000)**
availability	**commercial**	**home-made, under development**	**commercial: f < 200 kHz**	**home-made, under development**	**home-made, under development**	**home-made, working at FLASH**
comments		Outperformed by Ti:Sa for τ > 20 fs, E < 10 J	**very few pulses (< 0.5%) coincide with pulses from the FEL**		**Development neccessary**	

Most likely scenario for XFEL: Installation of two different laser types

- 1. Single-pulse Ti:Sa laser with 10 Hz repetition rate (commercial)
  - 20…25 ps pulse duration
  - Initially: moderate pulse energy 50…200 mJ
  - Different final amplifiers (E= 0.1 …5 J) in dependence on requirement of the experiment (financing by the particular experiment?)
  - Additional CPA or NOPA stages mainly for tuning the wavelength
  - Single-pulse OPCPA by MPQ: parameters to be shown (can it run in burst mode?)

- 2. Systems running in burst-mode (home-made)
  - Options:
    - Ti:Sa laser system with wavelength conversion (not yet available)
    - Short-pulse OPCPA laser with <50fs pulse duration (not yet available), pumped by a Nd:YLF or Yb:YAG burst-mode laser

- **Proof-of-principle experiment of a Ti:Sa laser that runs in burst mode is highly desired**

Summary

- Most optical lasers are not compatible to the FEL due to the different time structure (FEL pulse trains)
  - Application of high-rep rate CW-pumped lasers will be extremely inefficient due to the small duty cycle of the FEL
  - More suitable for FLASH and XFEL: lasers running in burst mode

- Option #1: **OPCPA system running in burst-mode**
  - Pulse duration down to ~ 15 fs and micropulse energy up to 0.5mJ feasible (at 1 MHz)
  - Complex system, not commercially available

- Option #2: **Ti:Sa laser running in burst mode (to be developed)**
  - Pulse duration down to ~ 25 fs and micropulse energy up to 0.5 mJ seam to be feasible
  - Best reliability + high flexibility
    - can be extended by commercial single-pulse amplifiers
    - Extension of the wavelength by frequency conversion and NOPAS
  - not commercially available, proof-of-principle experiment can be done at the MBI

- Option #3: **Single-pulse Ti:Sa laser running at 10 Hz**
  - Commercially available with up to ~ 5J pulse energy and $\tau > 20$ fs