High Repetition Rate mJ-level Few-Cycle Pulse Laser Amplifier for XUV-FEL seeding .

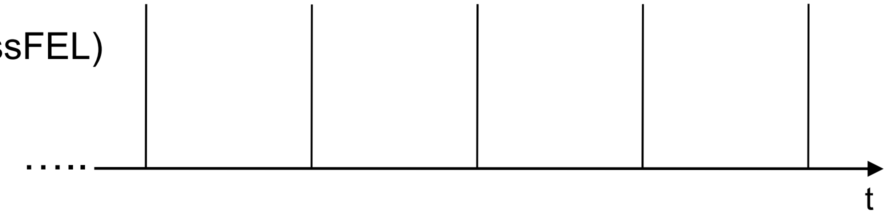
- Laser amplifier development: applications at high repetition rate FELs
- The FLASH-II FEL seeding project
- Requirements for an XUV seed source and for the driver laser amplifier
- High repetition rate amplifier system for XUV seed generation
  enabling technologies: Optical Parametric Chirped Pulse Amplification
  Ultrashort-pulse OPCPA pump amplifier systems

F. Tavella - Helmholtz Institut Jena

"4th" Generation Light Sources – repetition rates.

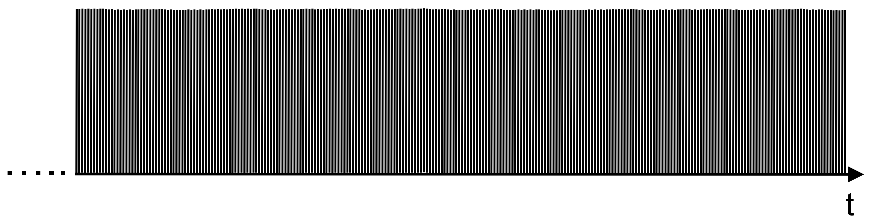
single-pass FEL
(LCLS, Spring8 XFEL, Fermi@Elettra, SparcX, SwissFEL)

tens to hundreds of pulses/second



ERL

high repetition rate (quasi-cw)
up to GHz repetition rate



FLASH (800μs burst at 10 Hz)

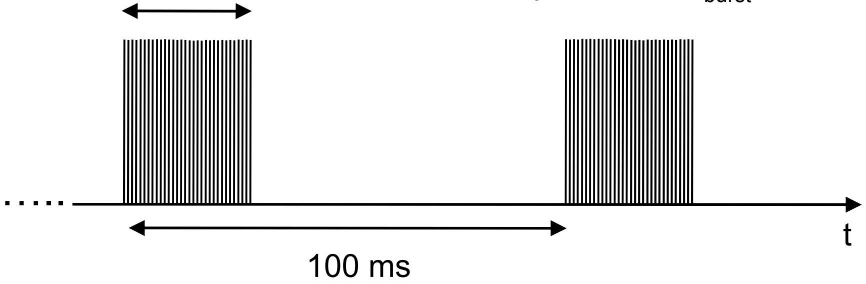
- 8000 pulses/s at f_{burst} = 1MHz

Euro-XFEL(600μs burst at 10 Hz)

- 27000 pulses/s at f_{burst} = 4.5 MHz

single-pass burst-mode FEL
(FLASH, European XFEL)

(cryogenically-cooled LINAC modules)
thousands of pulses/second



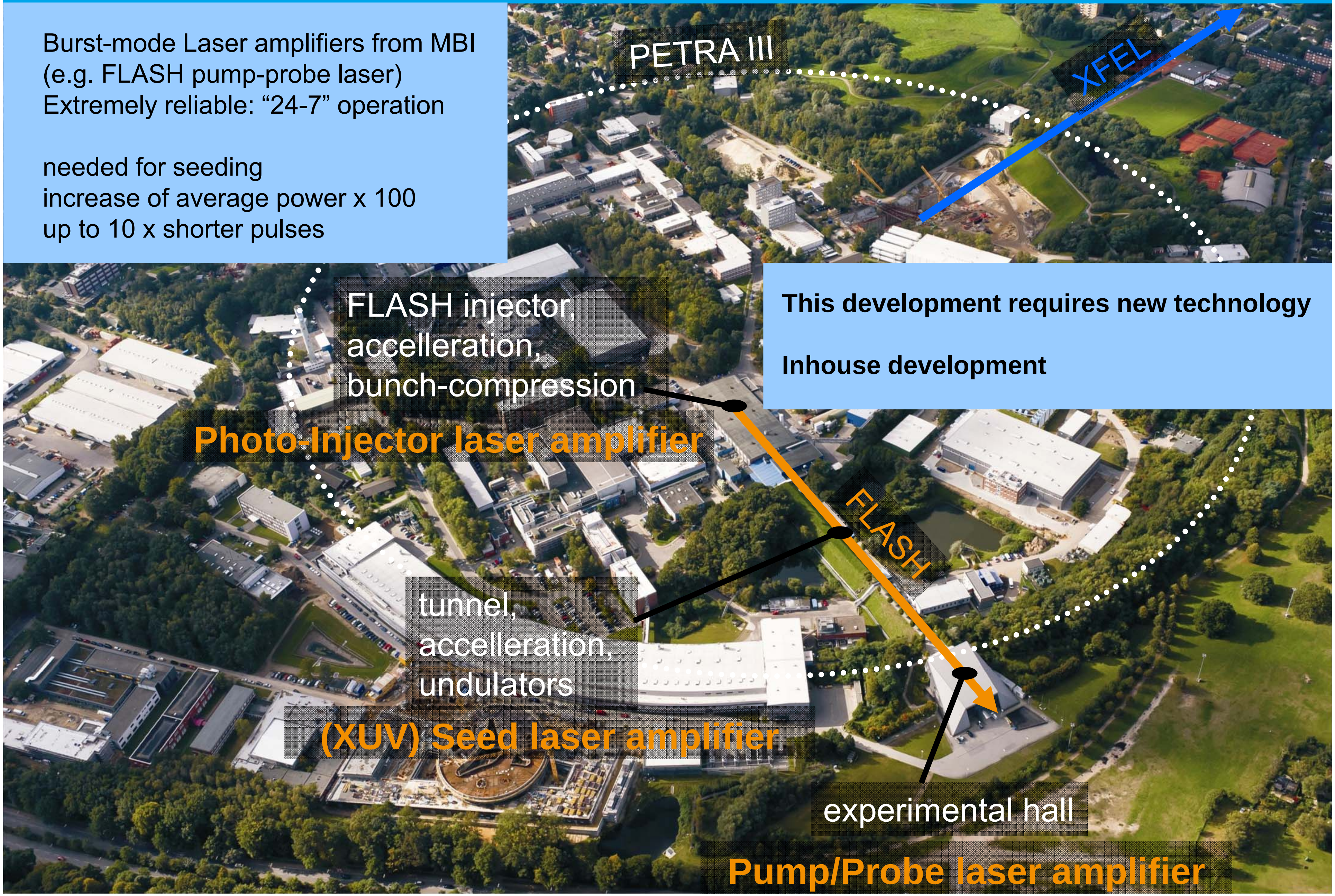
FLASH at DESY – Laser Amplifier Applications.

Burst-mode Laser amplifiers from MBI
(e.g. FLASH pump-probe laser)
Extremely reliable: “24-7” operation

needed for seeding
increase of average power x 100
up to 10 x shorter pulses

This development requires new technology

Inhouse development



Laser amplifier development for applications at FEL light sources.

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Seeding.

SASE radiation properties for a large class of experiments is insufficient:

- More timing stability for pump probe is needed (<10 fs)
- Single mode laser is required (no uncorrelated SASE pulse modes/structure)

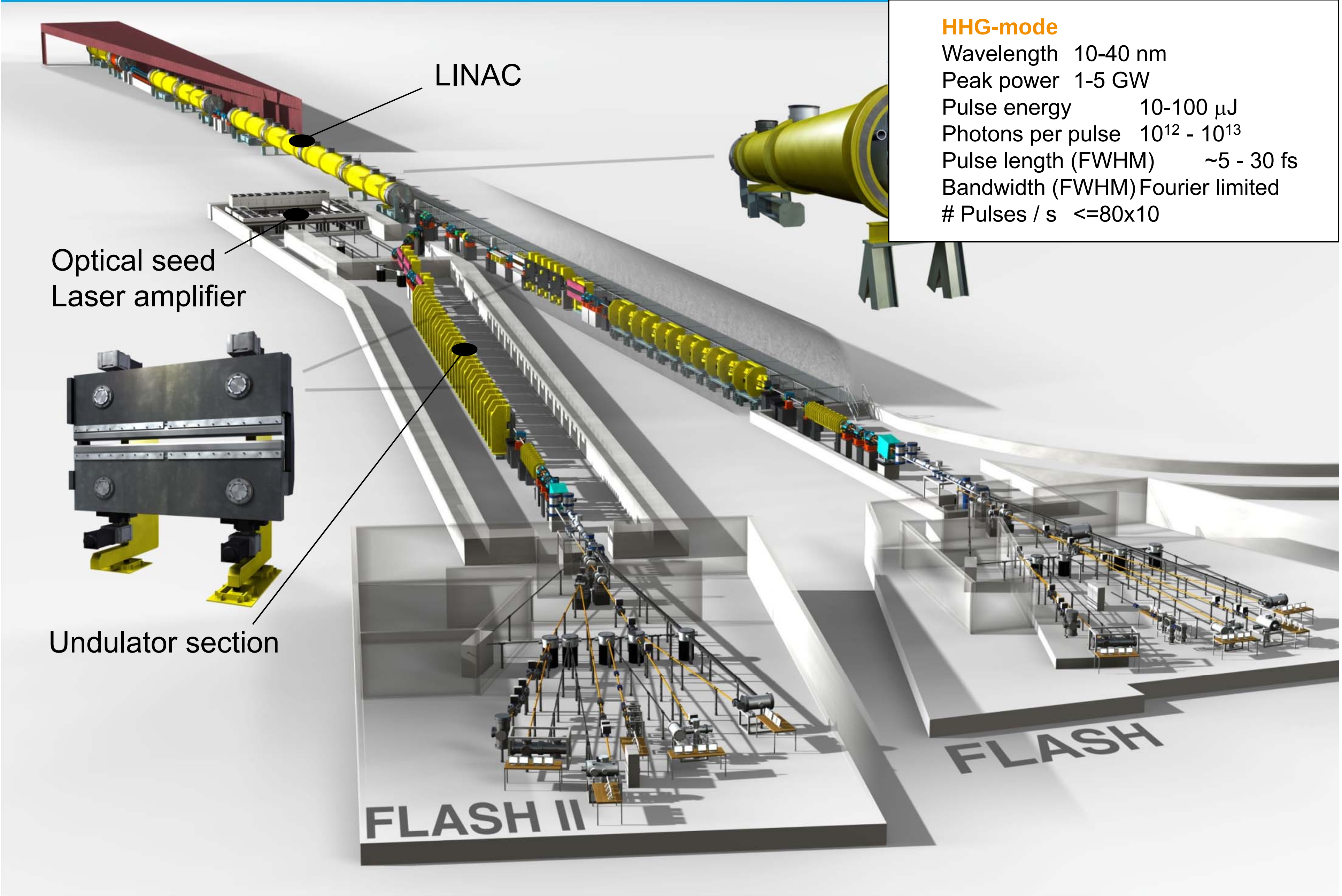
Solution: **seeding with very well defined spectral and temporal pulse properties**

G. Lambert et al, Nature Physics ***4****, 296-300, (2008).*

Electrons interact with an external seed source (laser-driven XUV pulses)

- Full transverse and longitudinal coherence
- Offer improved spectral and temporal pulse properties by seeding schemes
- Pump-probe experiments with small temporal jitter possible
- Ultimately: phase control for FEL pulses

FLASH II – Undulator Section.



HHG-mode

Wavelength	10-40 nm
Peak power	1-5 GW
Pulse energy	10-100 μJ
Photons per pulse	10^{12} - 10^{13}
Pulse length (FWHM)	~5 - 30 fs
Bandwidth (FWHM)	Fourier limited
# Pulses / s	<=80x10

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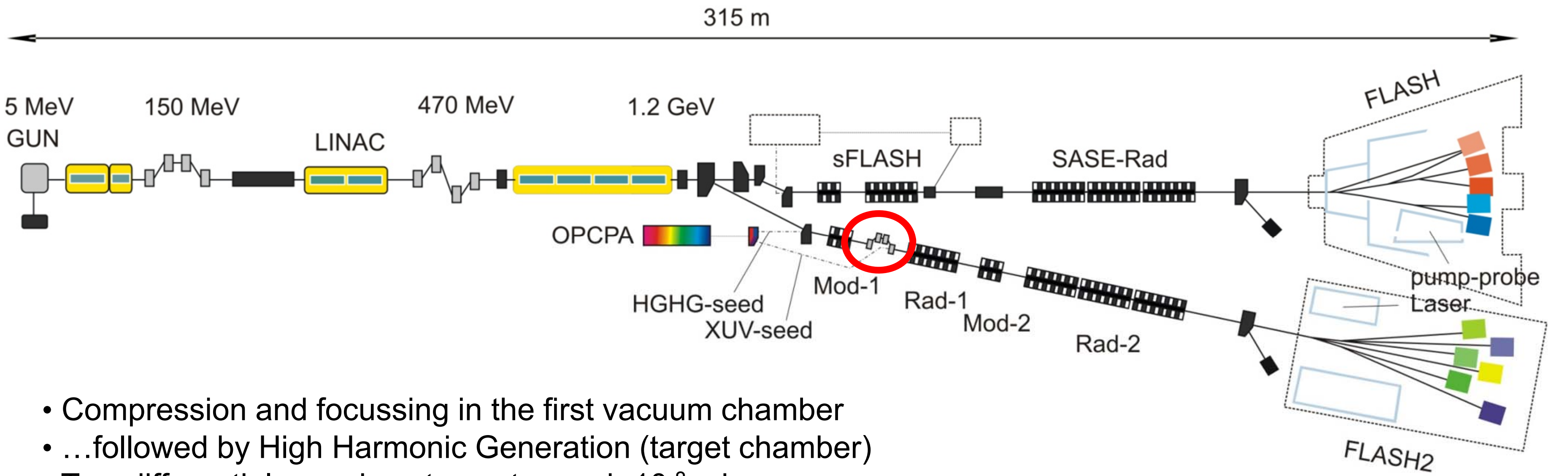
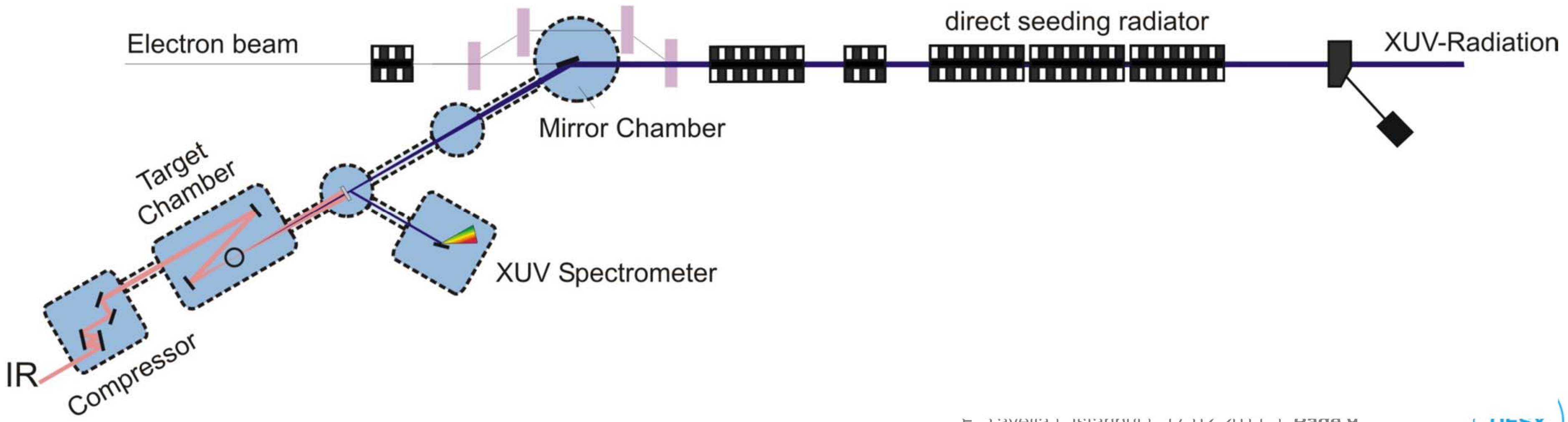
HHG incoupling.



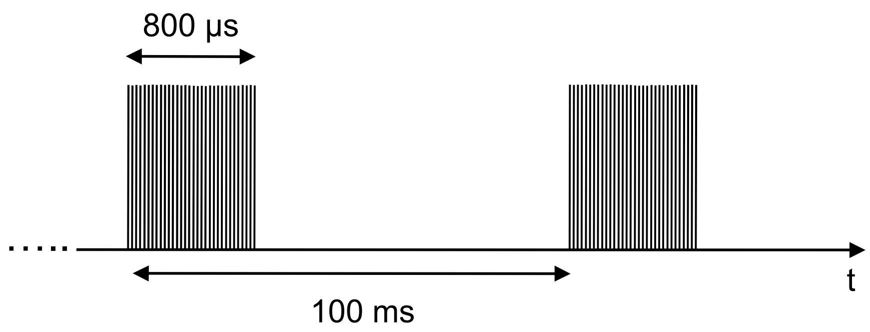
- Compression and focussing in the first vacuum chamber
- …followed by High Harmonic Generation (target chamber)
- Two differential pumping stages to reach 10^{-8} mbar
- XUV diagnostics (spectrum, power, spatial+temporal overlap,…)



DESY

Requirements for laser amplifier system and the XUV source.

Prototype (for FEL seeding)
10Hz Bursts of 800 µs length
100 kHz (1 MHz) intra-burst rep-rate
>1 mJ energy per intra-burst pulse
~7 fs pulsewidth, $\lambda_c \approx 750$ nm
synchronization to the machine <10 fs



XUV seed : few nJ/harmonic

Harmonic conversion efficiencies of >>10^{-6}

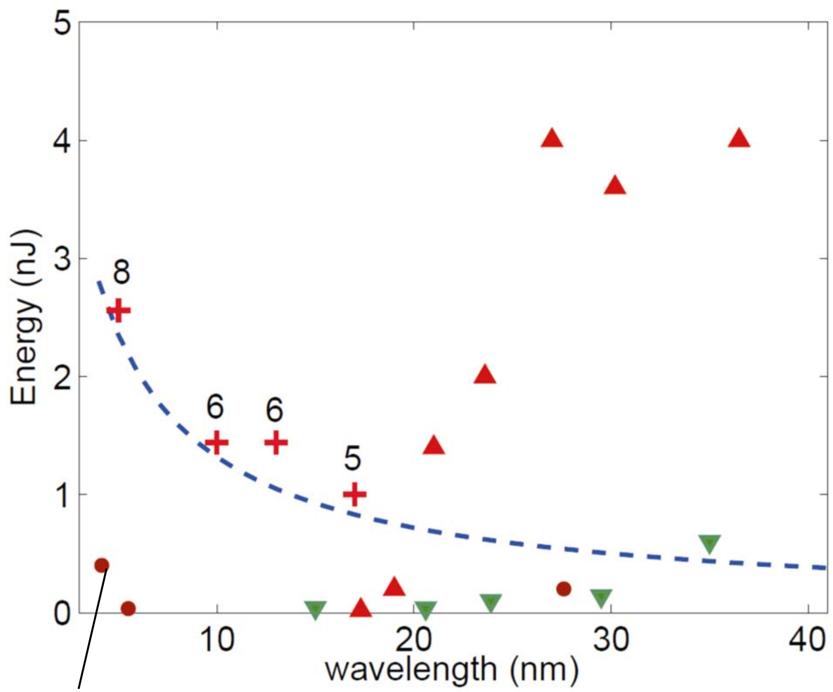
Seed power
to overcome the background noise
presuming a good transverse coupling
seed~100xnoise **(>5-30 pJ)**

spatial and temporal overlap
(Input seed transverse mode size and overlap ...)
What is an acceptable jitter?

Learn from s-FLASH project

Bandwidth requirements
couple well to FEL gain curve

High repetition rate
to be able to fully exploit the seeding



M. Zepf et al., Phys. Rev. Lett ***99****, 143901, (2007)*

Quasi-Phase-Matching (QPM) with multi-jet arrays.

harmonic conversion efficiency:

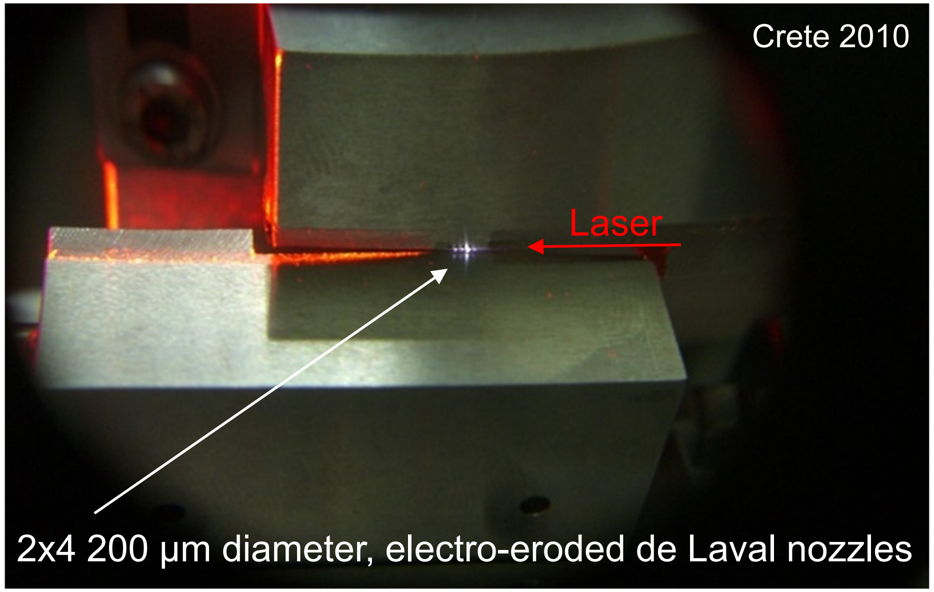
-Quasi-phase-matched HHG with multi-jet arrays (neutral gas and ions) Only free standing jet geometry is possible due to the high average power

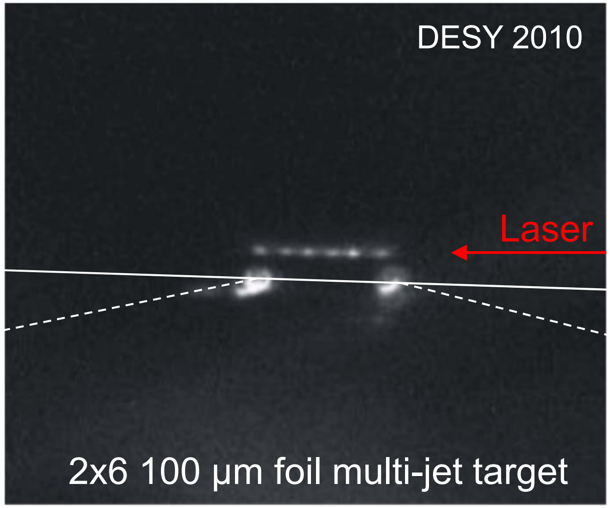
-Different driver laser wavelength (i.e. SH-400nm lower cut-off but higher yield)
-Mixing ω-2ω fields (i.e. 400nm 800nm)
-Mixing of different gases

tunability:

-Flexible pulse duration of the driver laser
-shifting the central wavelength in the OPCPA (at longer wavelength)
-even and odd harmonics through mixing ω-2ω fields
-harmonics generated with sub-10 fs pulses (seeding at shorter wavelength)

Collaboration: QUB Belfast (M. Zepf group) - TEI Crete (M. Tatarakis, N. Papadogiannis) – DESY/HI-Jena (F. Tavella)





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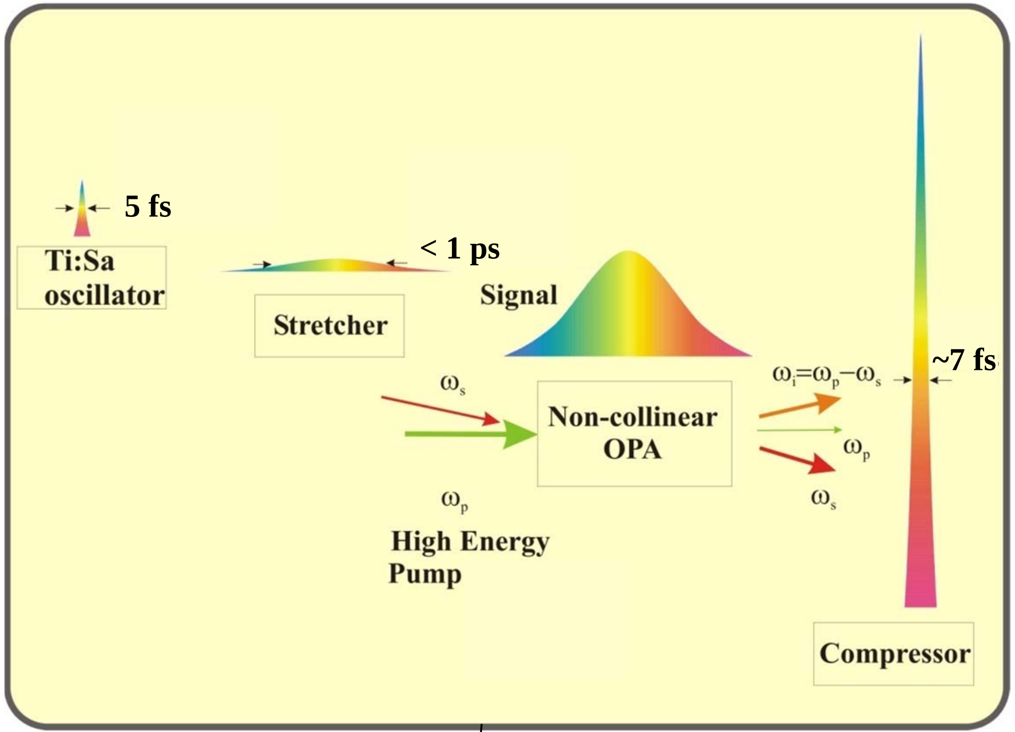
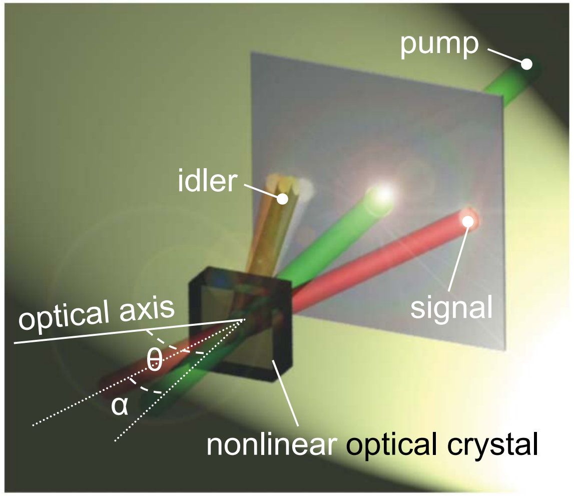
OPCPA technique.

*Dubietis et al., Opt. Commun., **88**, 437 (1992).*
*I. N. Ross et al., Opt. Commun., **144**, 125 (1997).*





$$\Delta \mathbf{k} = \mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i$$

$$\omega_s = \omega_p - \omega_i$$

non-collinear type-1 phase-matching

Chirped Pulse Amplification (CPA) + Optical Parametric Amplification (OPA)

high single-pass gain, broad phase-matching bandwidth, negligible thermal load, high conversion efficiency, compact and scalable

Numerical simulation of two stage OPCPA.

OPCPA stages

- pump @515 nm
- seed-pump pulse sub-ps
- BBO crystal (>2mm)
- non-collinear type-1 phase-matching

stage 1

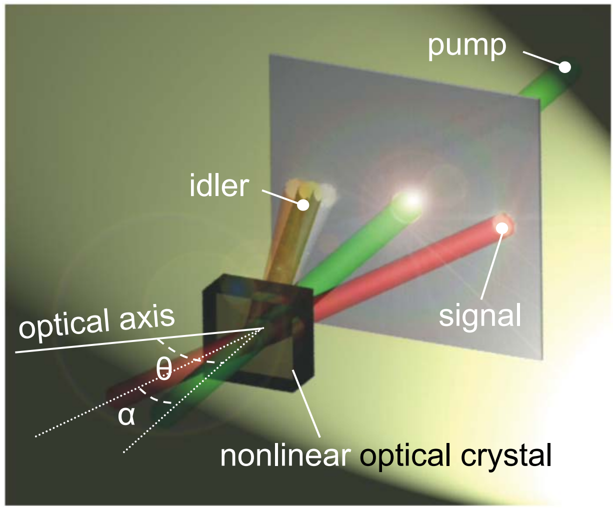
I_p= 46 GW/cm^2
1 mJ pump (t=800fs,r=1.5mm),
1 nJ seed (t=500fs,r=1.5mm)

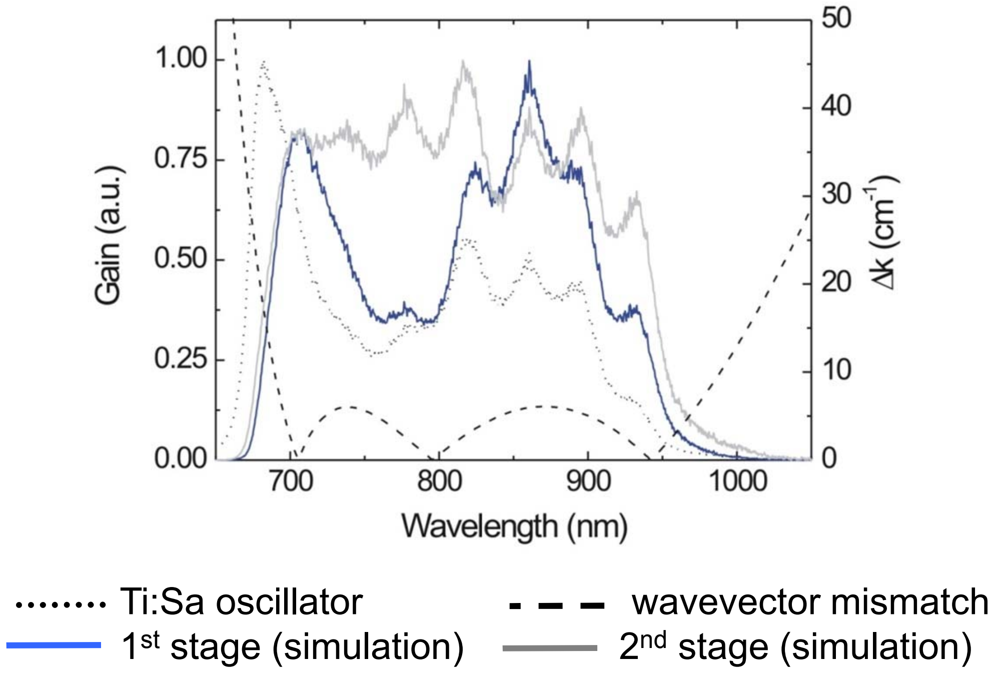
G > 1000 → exp. output ~5 μJ

stage 2

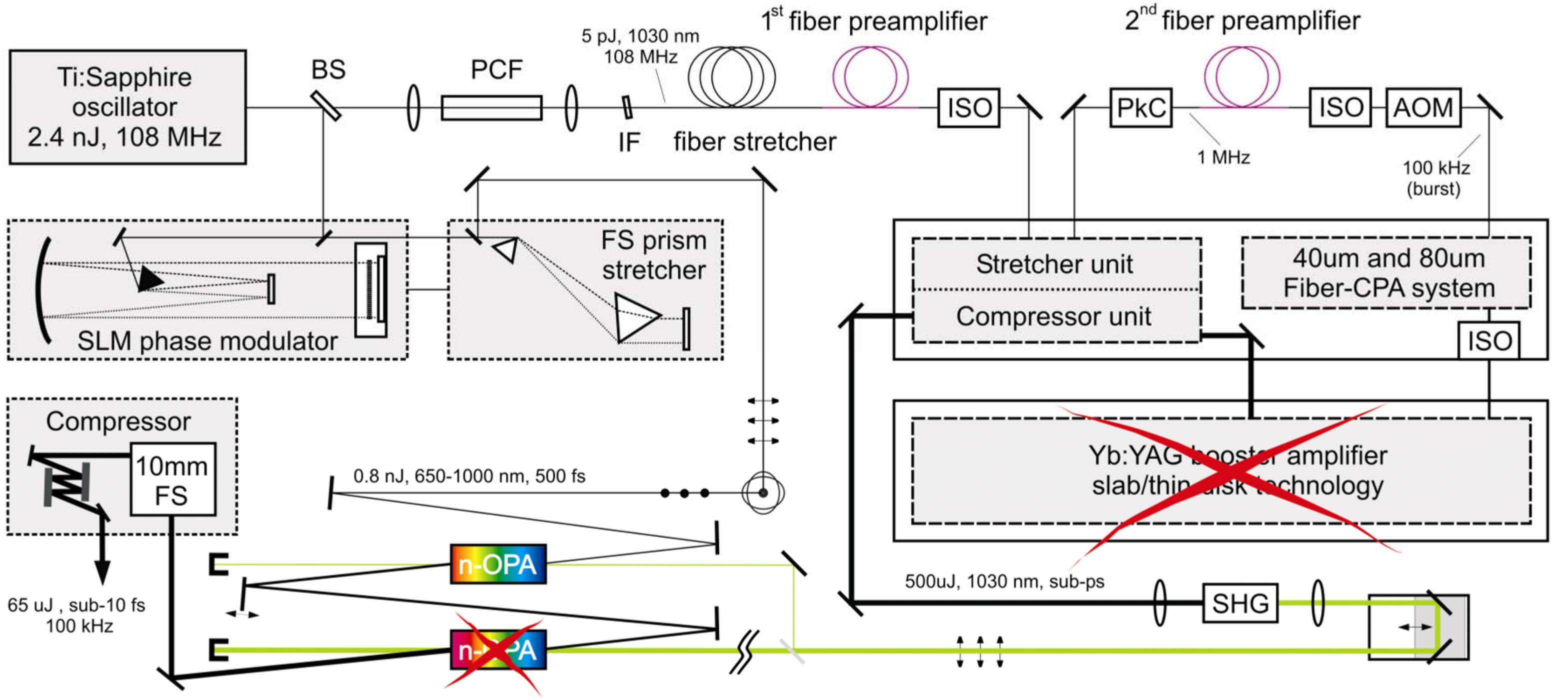
I_p=13 GW/cm^2
10 mJ pump (t=800fs,r=8.5mm),
5 μJ seed (t=500fs,r=8.5mm)

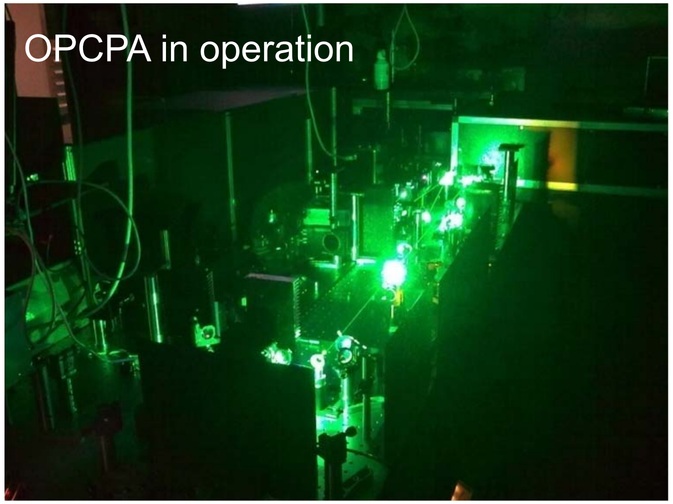
G ~ 400 → exp. output 1.2 mJ
(double-pass OPA for ~2mJ)

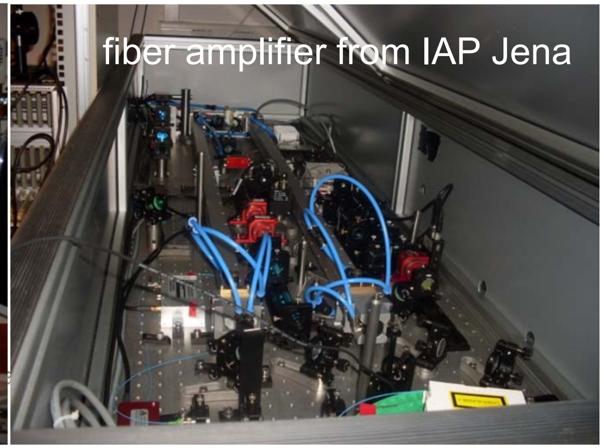




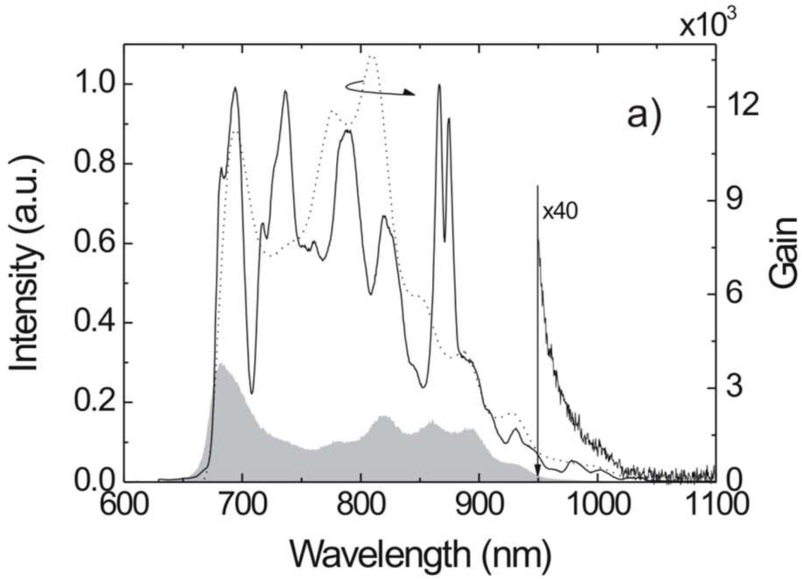
Laser amplifier system.

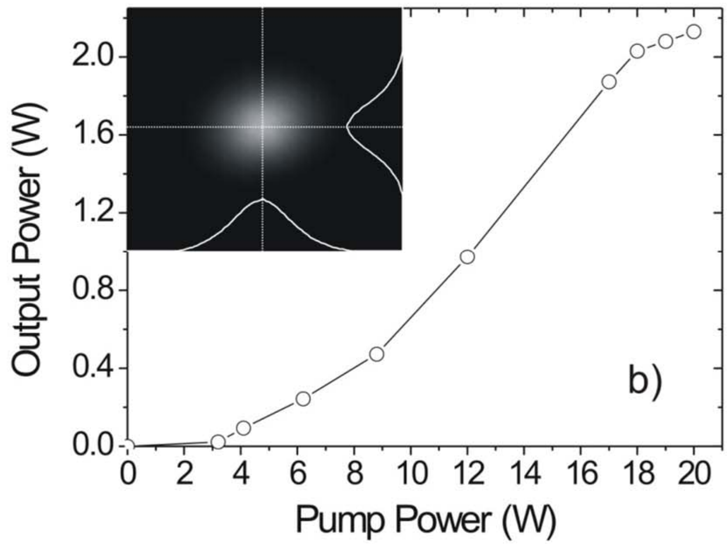


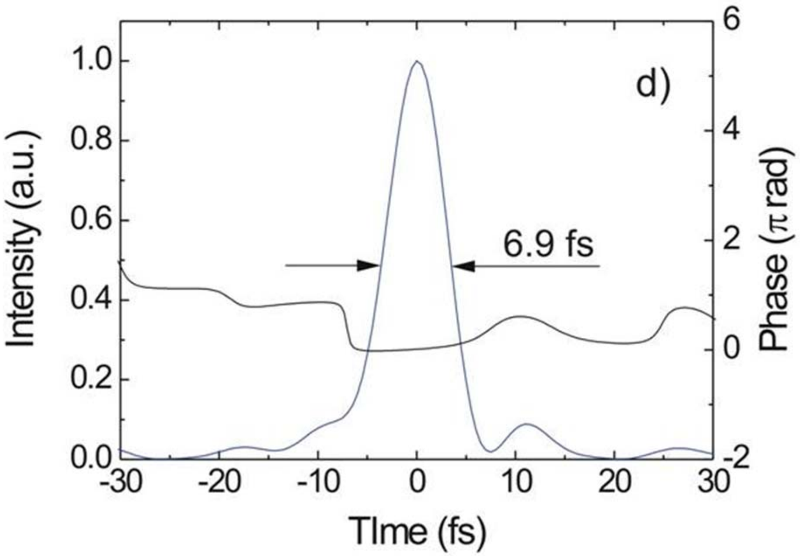




noncollinear-OPA: amplified pulse/beam properties.







RECORD – high average power sub-10 fs amplifier

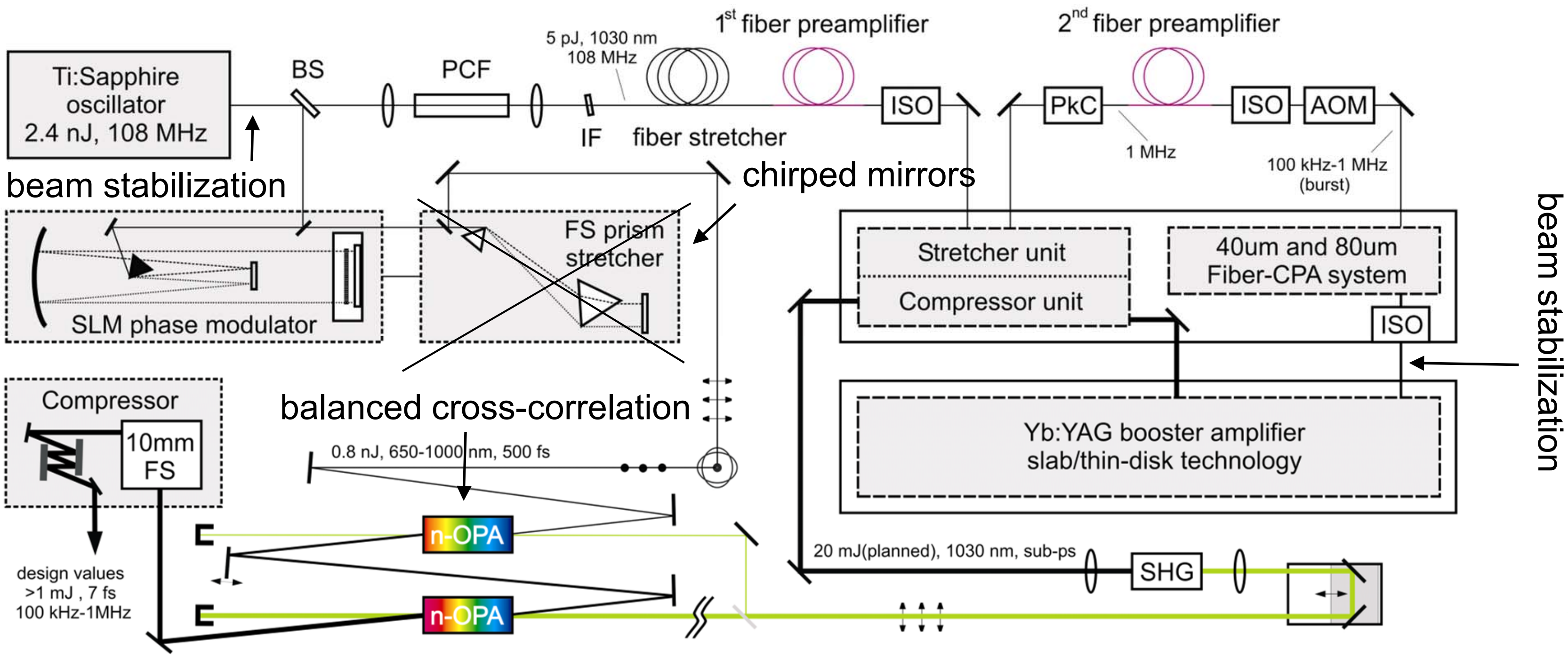
broadband amplification [670-1000]nm

repetition rate: 100 kHz max.
amplified pulse energy several tens of µJ

compressed pulse duration of sub-10 fs (shortest 6.9 fs)

*F. Tavella et al., Opt. Express **5**, 4689-4694, (2010)*
*F. Röser et al. Opt. Lett. **32**, 3495-3497, (2010)*

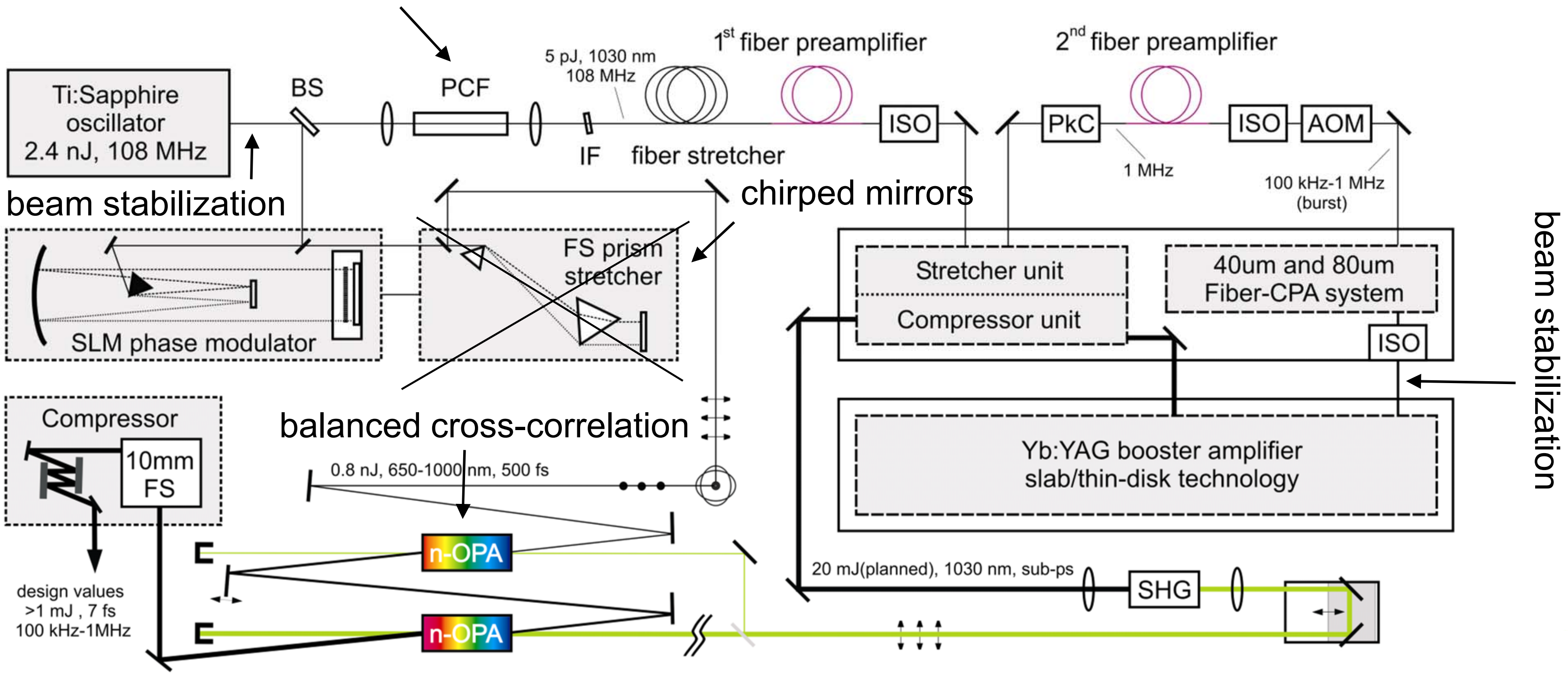
Improvement on the system for stable operation.



Improvement on the system for stable operation.

front-end options

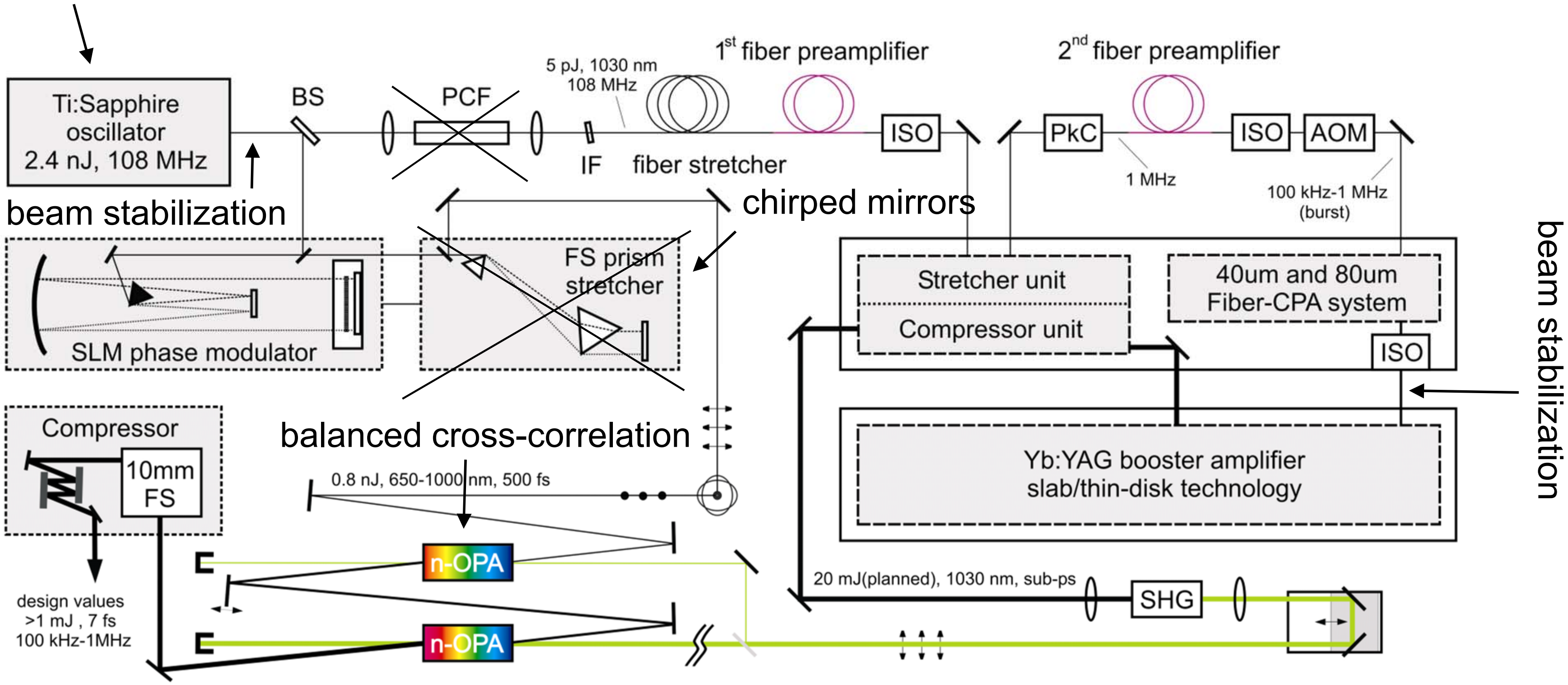
• solitonic self-frequency shifting in PCF
with improved PCF incoupling



Improvement on the system for stable operation.

front-end options

- direct pump amplifier seeding (new oscillator)



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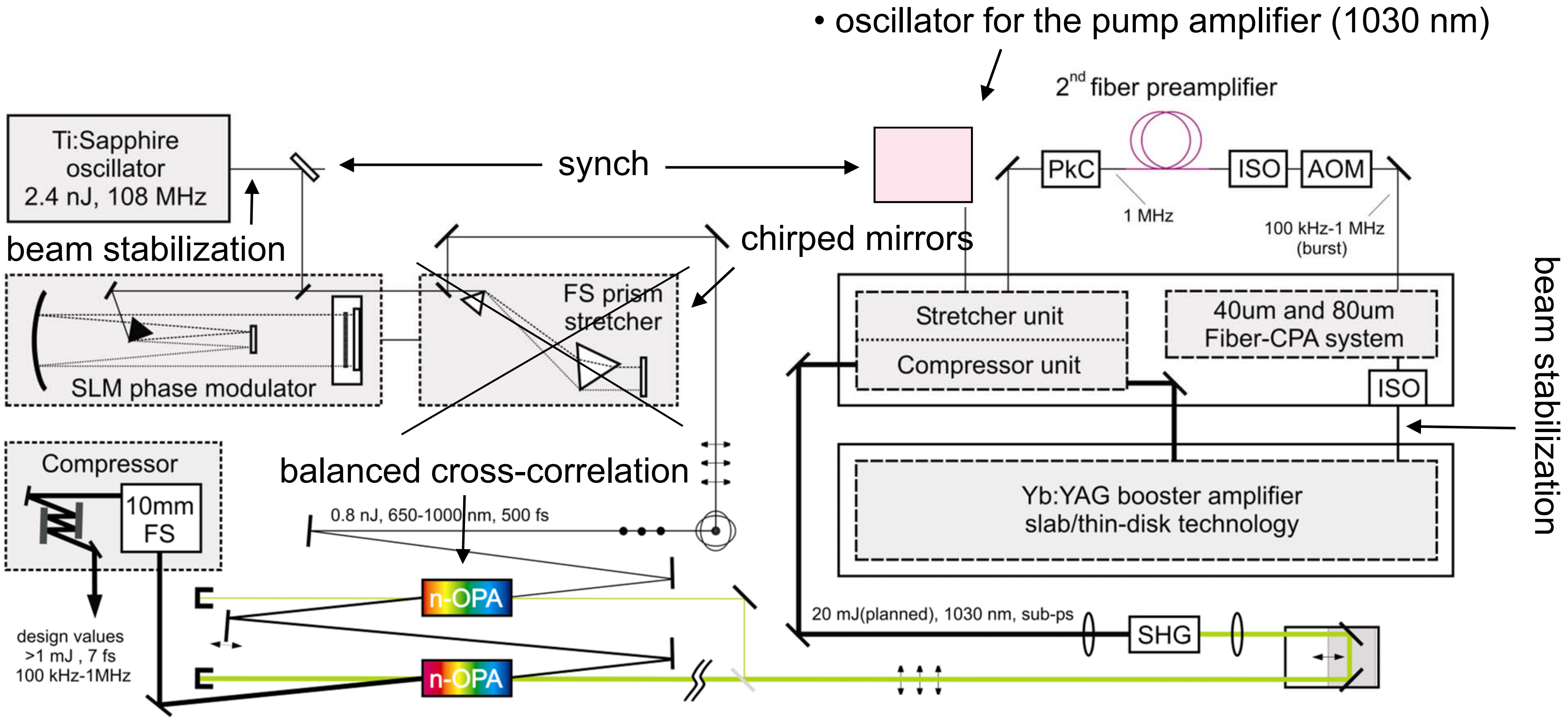

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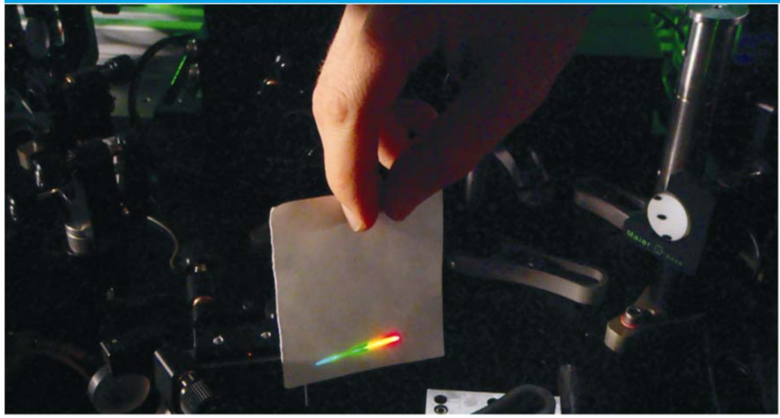
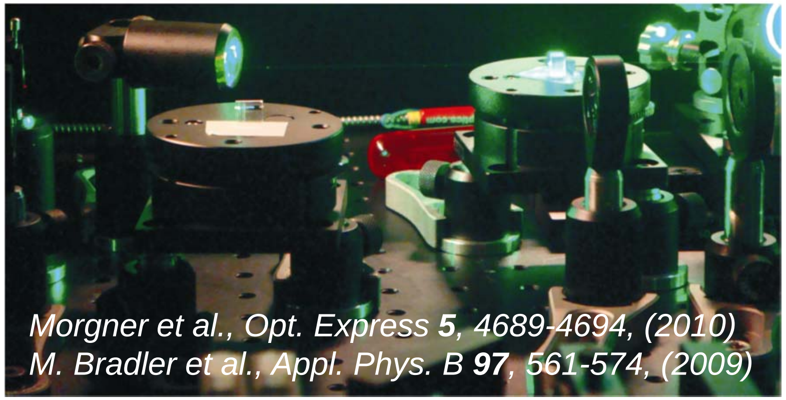


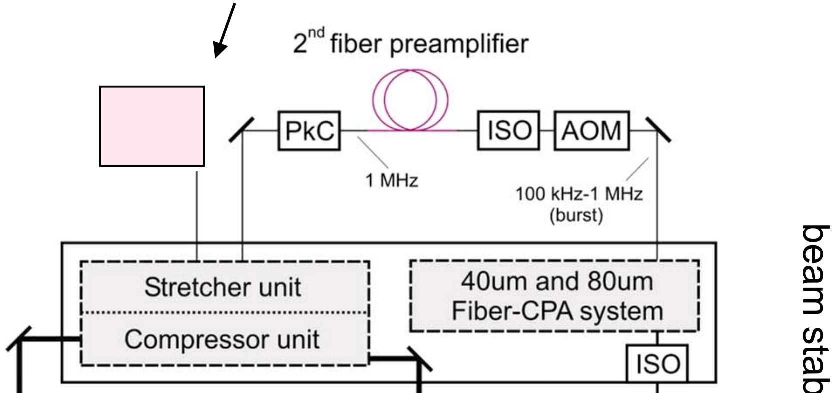


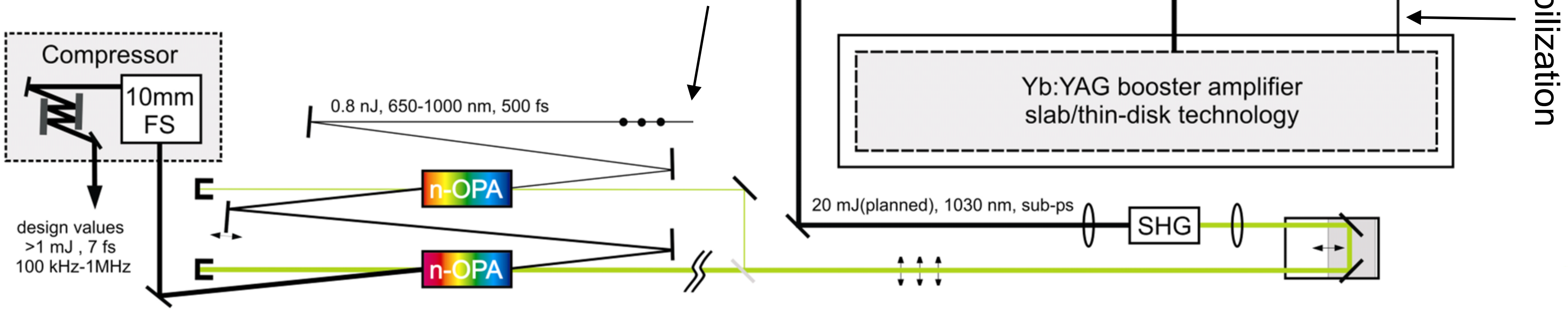
*Morgner et al., Opt. Express **5**, 4689-4694, (2010)*
*M. Bradler et al., Appl. Phys. B **97**, 561-574, (2009)*

- test of white light seeded OPA,
  (850 fs, 10 µJ to generate filament,…24 fs, 20 µJ)
  (in collaboration with IAP Jena)

- oscillator for the pump amplifier (1030 nm)

Continuum generated in a YAG crystal





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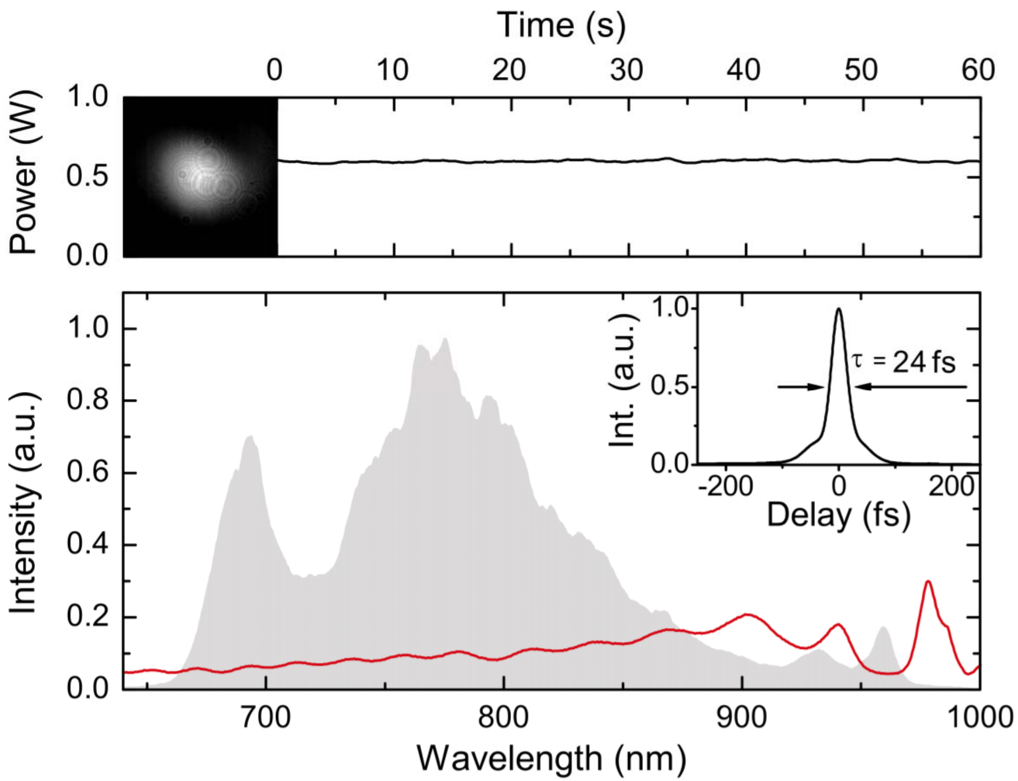
front-end options



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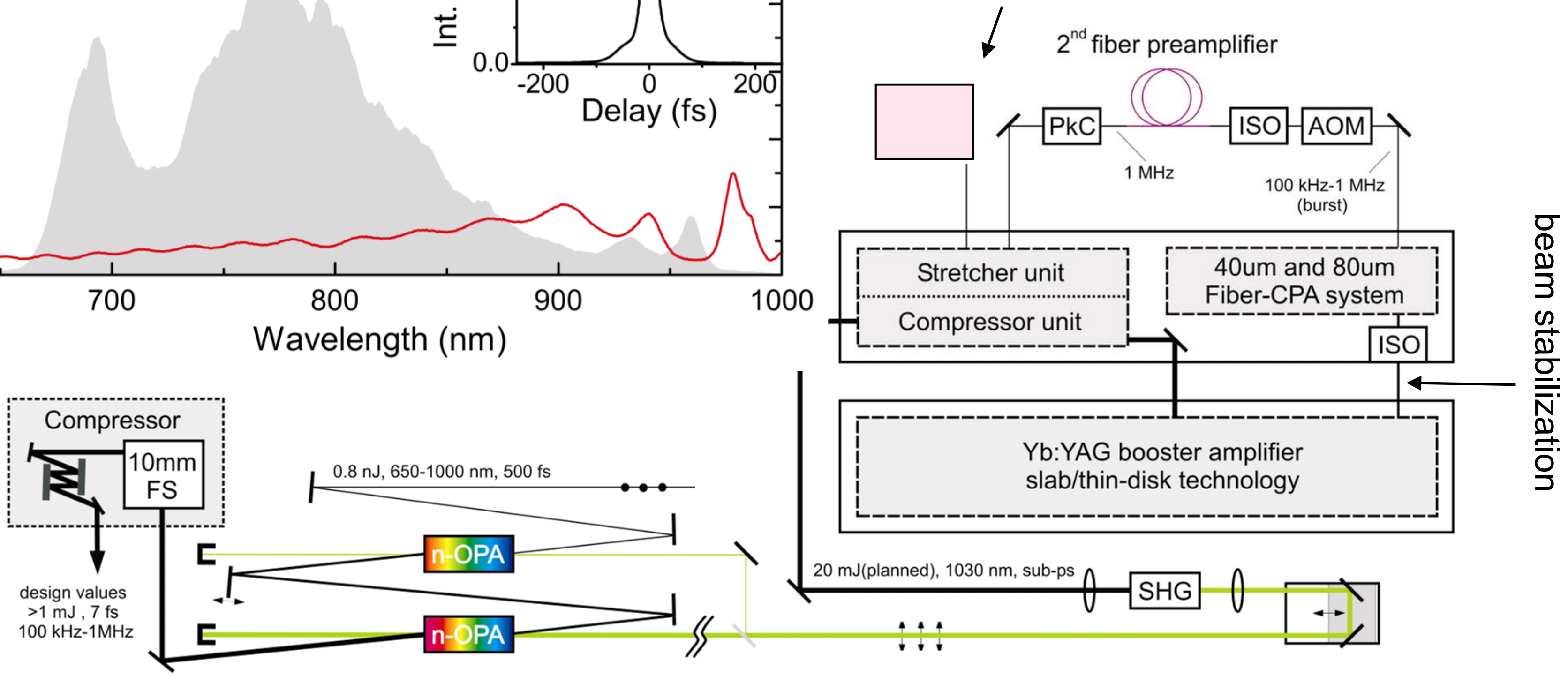


Requirements for laser amplifier systems.

Laser amplifier for FEL seeding

10Hz Bursts of 800 μs length

100 kHz (1 MHz) intra-burst rep-rate

>1 mJ energy per intra-burst pulse

~7 fs pulsewidth, $\lambda_c \approx 750$ nm

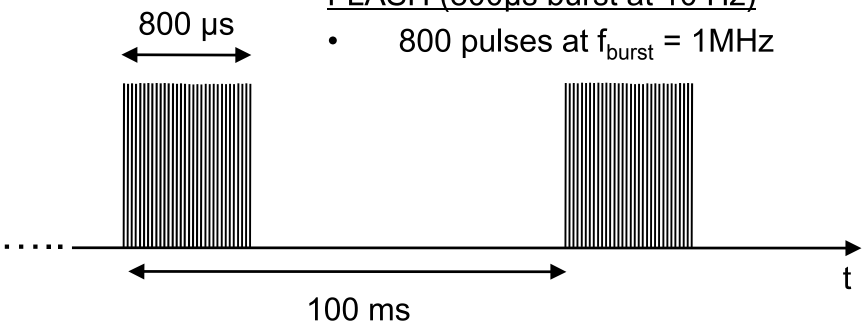
synchronization to the machine <10 fs

100 kHz prototype: continuous or burst @ 100 kHz

1 MHz final version: only burst-mode operation

FLASH (800μs burst at 10 Hz)

- 800 pulses at f_{burst} = 1MHz



…ist pump amplifier

10Hz Bursts of 800 μs length

100 kHz (1 MHz) intra-burst rep-rate

~20 mJ energy per intra-burst pulse

<1 ps pulsewidth, λ_c = 1030 nm

Average burst power 20 kW

PUMP
(OPCPA pumped at 515 nm...
SH of an Yb:YAG Laser amplifier)

HIGH AVERAGE POWER:
up to 20 kW intra-burst average power for the 1MHz amplifier

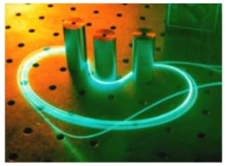
Scalability of the pump amplifier design (DESY-XFEL).

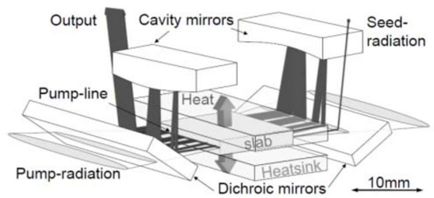
High average power amplification schemes for 1030nm, (sub-)ps pulses:

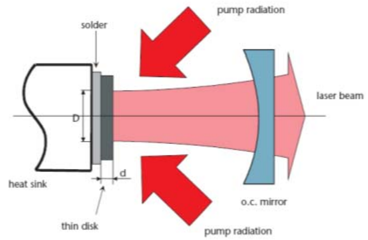
*A. Giesen, et al, IEEE J.Sel.Top Quantum Elect. **13**, 598, (2007).*

P. Rußbüldt et al., Opt. Letters, Accepted, Doc. ID: 131645 (2010)

*T. Eidam, et al, Opt. Lett. **35**, 94-96, (2010).*







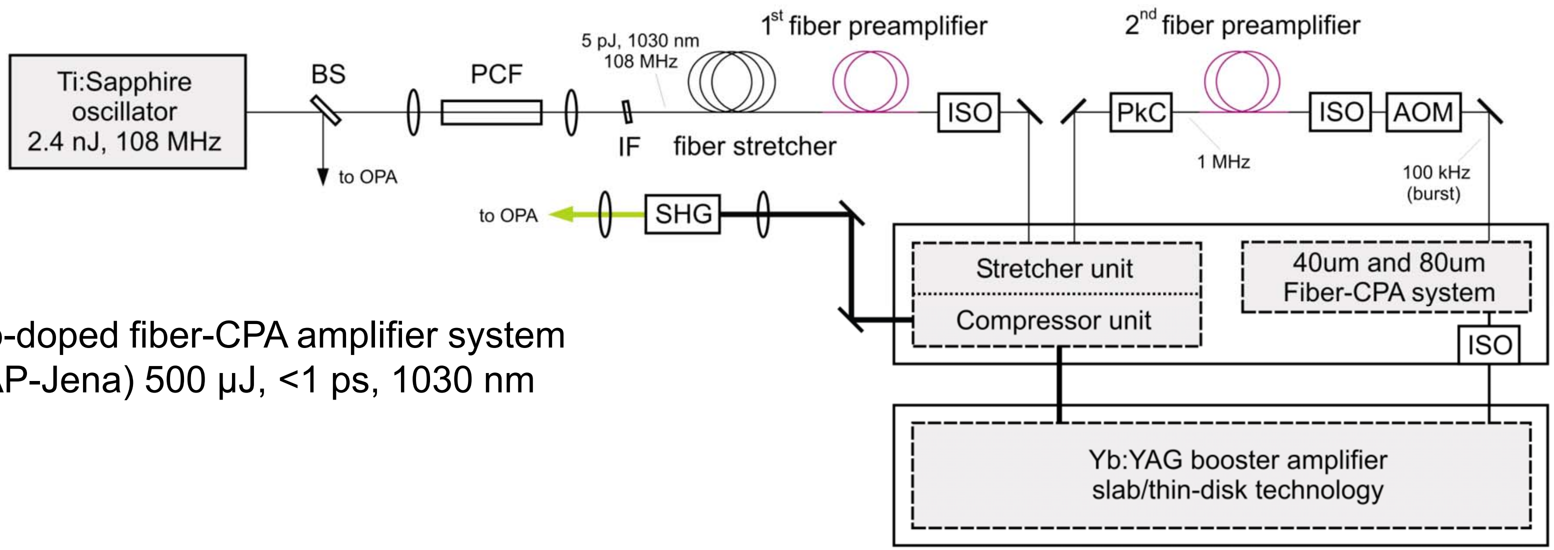
	Fiber 1W-2kW	Innoslab <2kW	Thindisk regenerative <100W	Thindisk multipass >>100W
Average power	++	++	++	++
Amplification factor	++	+	+	- -
Average power scaling	++	+	-	++
Pulse energy	- -	+	+	++
Nonlinearity	- -	+	+	++
Dispersion	- -	+	-	++
Complexity	0	0	-	-
Robustness	+	++	-	+

P. Russbueldt et al., Opt. Express 15, 12234, (2009)

Avenue for multi-kW burst-mode amplifier systems

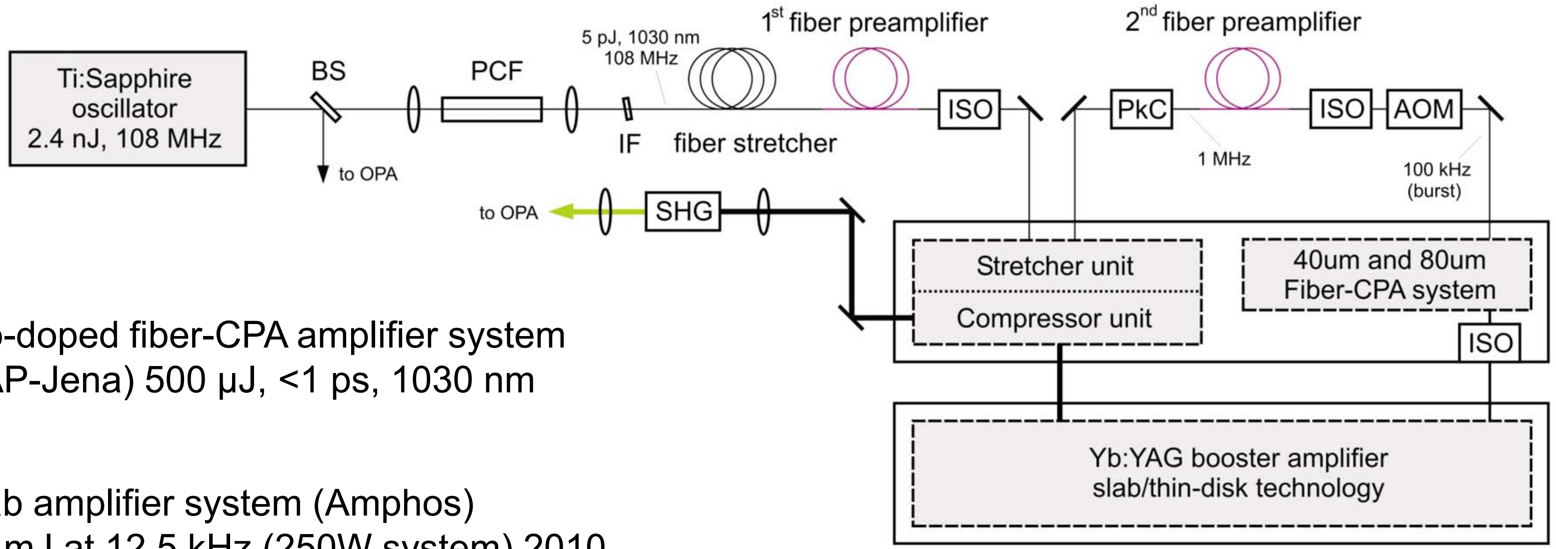
…no thermal limitation due to the low duty cycle of the burst (~1%)

Pump amplifier development - fiber front-end.



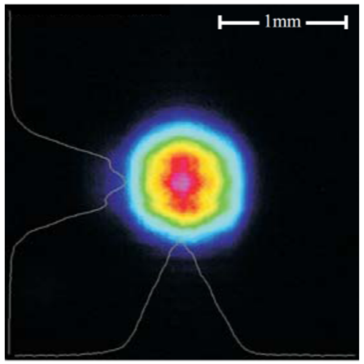
- Yb-doped fiber-CPA amplifier system (IAP-Jena) 500 µJ, <1 ps, 1030 nm

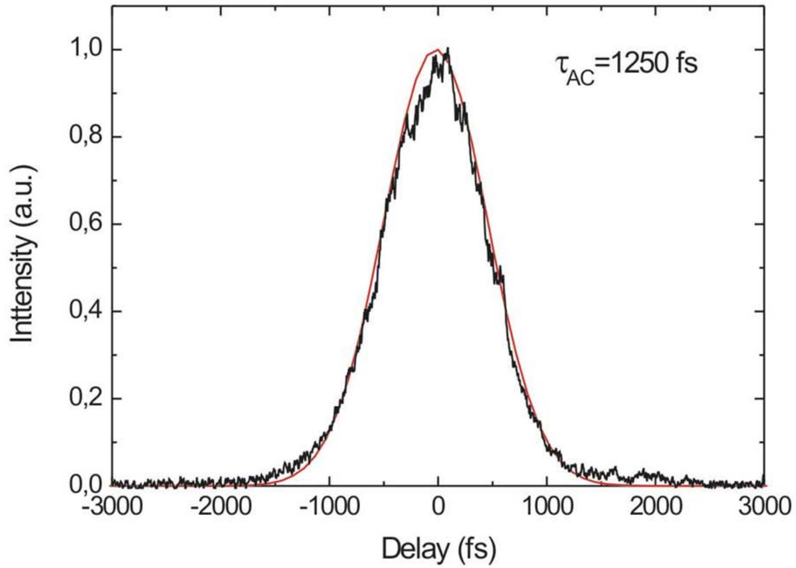
Pump amplifier development - slab amplifier test.



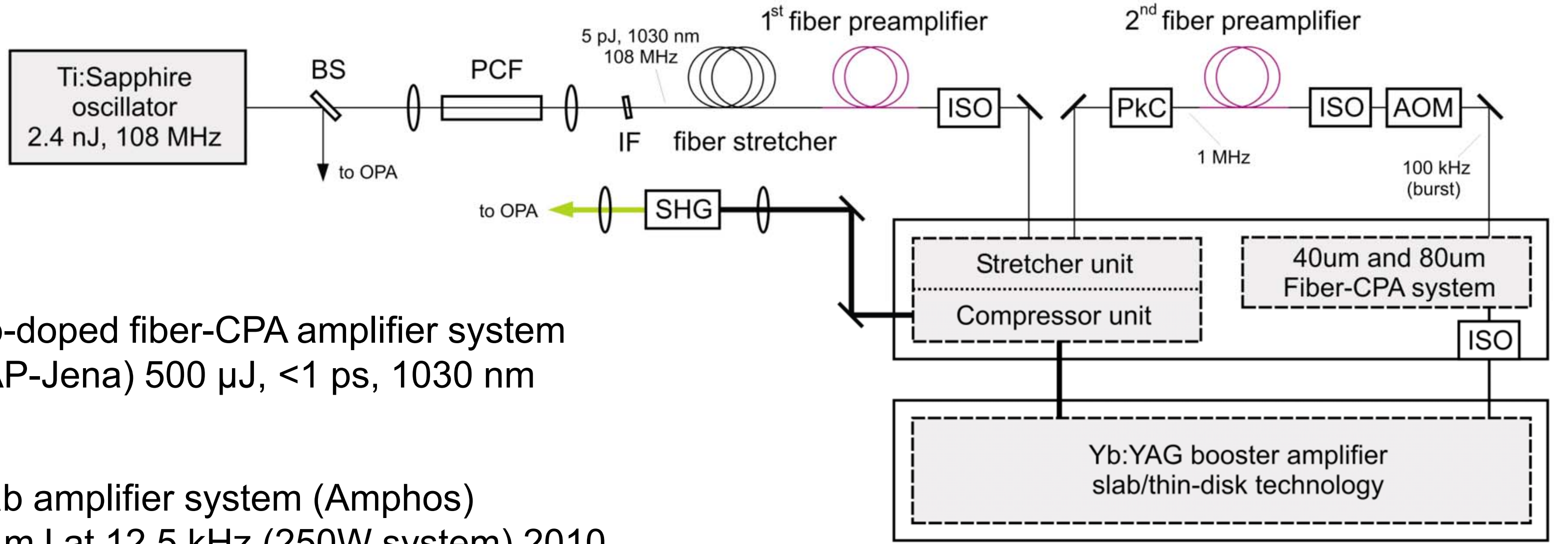
- Yb-doped fiber-CPA amplifier system (IAP-Jena) 500 µJ, <1 ps, 1030 nm

- slab amplifier system (Amphos)
  20 mJ at 12.5 kHz (250W system) 2010
  2.5 mJ at 100 kHz, $M^2 < 1.5$,
  $\Delta\lambda$=2.7 nm at FWHM
  compression to ~900 fs at 100 kHz
  planned: >1.5(2) kW system





Pump amplifier development - booster amplifier.



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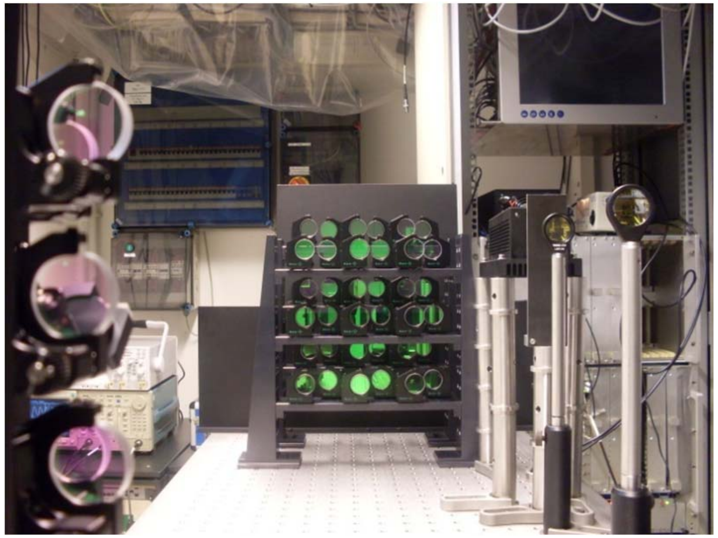
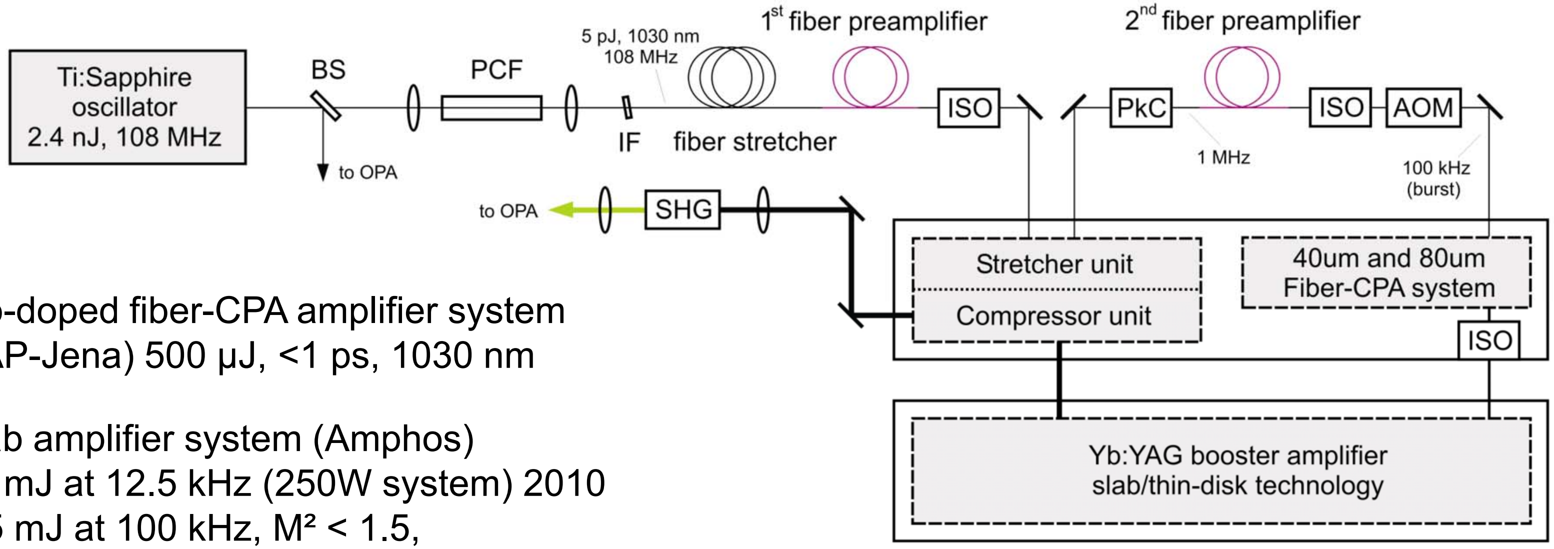
- 10 kW (diode pump power) thin-disk amplifier head multipass geometry to be tested (gain?)



Pump amplifier development - booster amplifier.



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  compression to ~900 fs at 100 kHz

  available: >1.5(2) kW system

- 10 kW (diode pump power) thin-disk amplifier head
  multipass geometry to be tested (gain?)

Key technology for OPA pump source
20 mJ per single pulse @1 MHz in FEL burst-mode

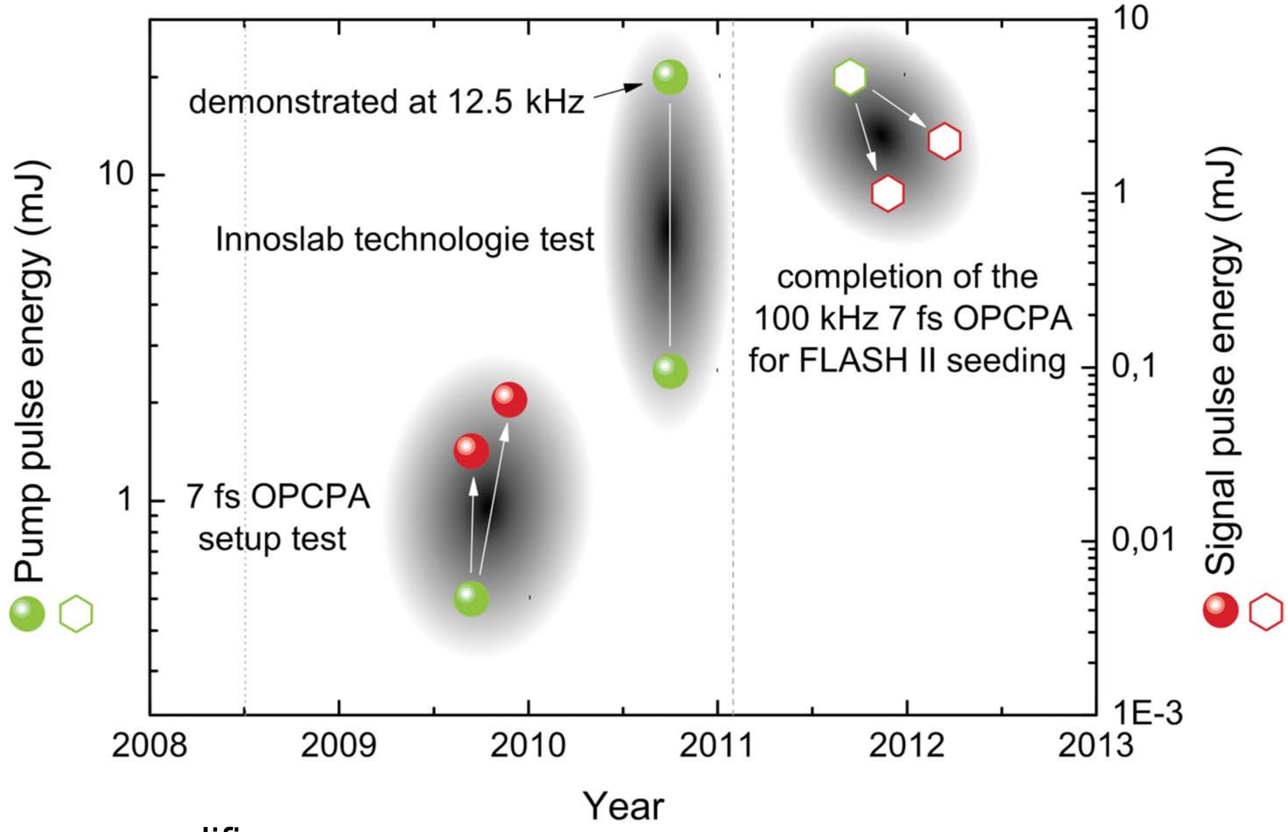
thin-disk pump amplifier head development

development in progress

slab amplifier system (>1.5kW)… Amphos Aachen

possibility to reach higher intra-burst average power (no thermal limitations)
study for a **20 kW** burst-mode amplifier (DESY-XFEL-Amphos)

mJ-level few-cycle pulse OPCPA development for FEL seeding at DESY.



- kW-level pump amplifier
- mJ-level few-cycle pulse OPCPA
- burst-mode: 20kW intra-burst average power

- development and characterization of a highly efficient QPM-HHG source
- commissioning of the amplifier for FLASH-II seeding in 2014

Seeding FLASH II.

development of high repeptition rate, mJ-level, sub-10 fs laser amplifiers
-enabling technologies-

Collaboration partners:

- Helmholtz Institut Jena
- Institut of Applied Physics Jena (IAP)
  group of A.Tünnermann
- Institut of Lasertechnik Aachen (ILT)
  H. Hoffmann group
  ILT-spinoff Amphos
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development of a laser-driven XUV source with high conversion efficiency (QPM-schemes)

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