Towards an ytterbium based frequency synthesizer

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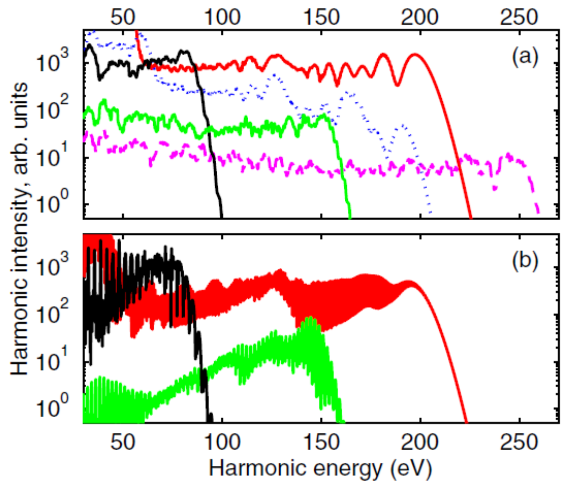
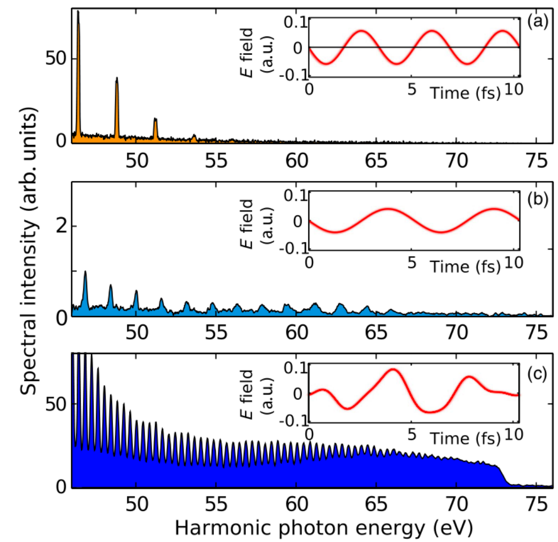
DPG Frühjahrstagung

3rd March 2015

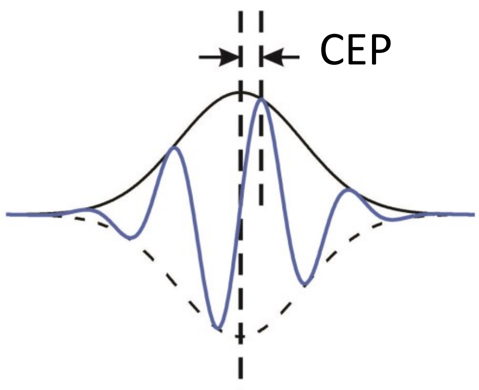
Motivation: Some applications

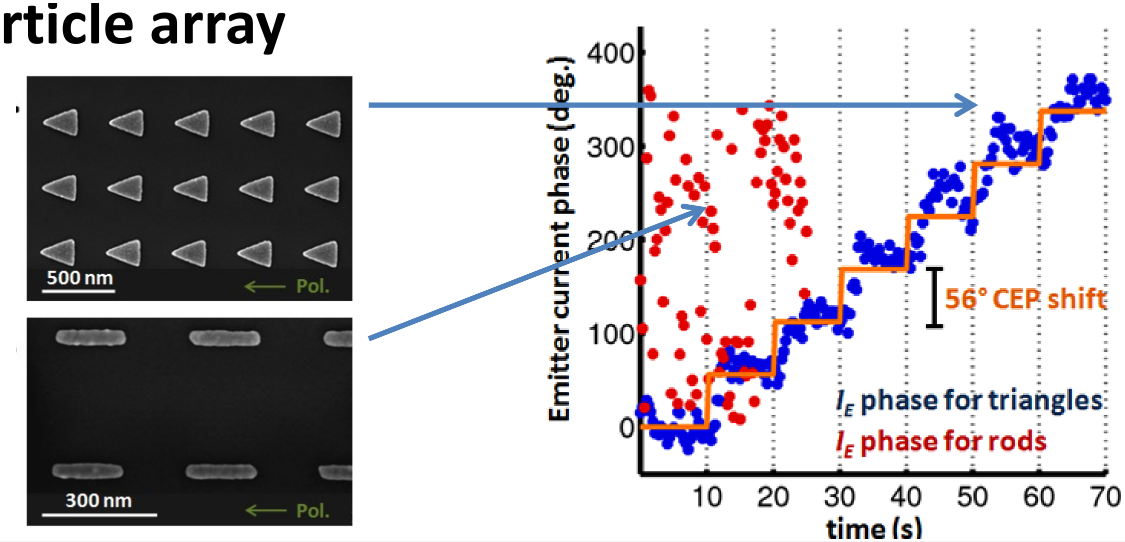
- **Control of electron trajectory: HHG**





- **Plasmonic Nano-particle array**

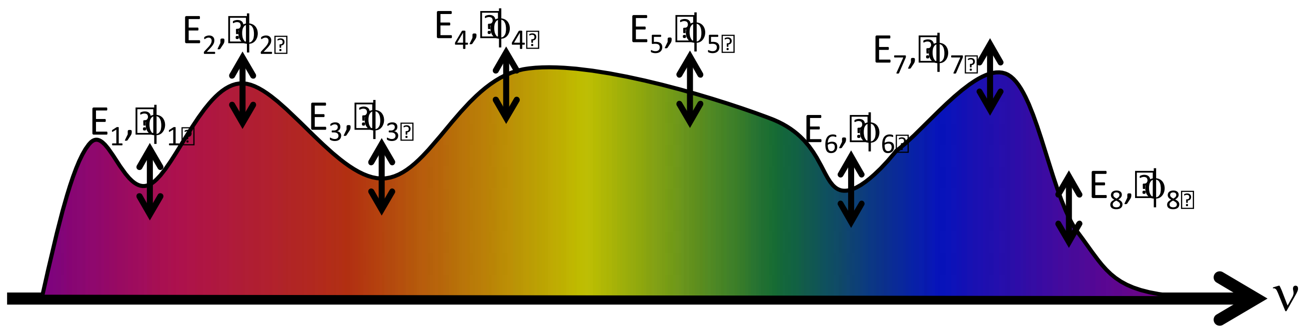




Chipperfield *et al.*, PRL **102**, 063003 (2009)
Hässler *et al.*, PRX **4**, 021028 (2014)
Putnam *et al.*, UP2014, talk 08.Tue.B.3

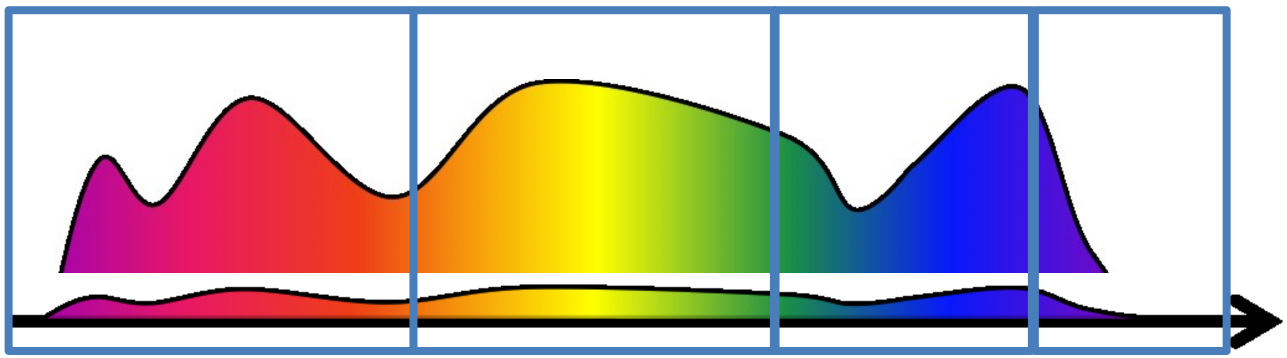
Requirements

- **Broad spectral coverage: Visible to the IR**
- **High energy: ~mJ level**
- **CEP stability**
- **„Beam line“: high stability and high reproducibility**



How to realize it ?

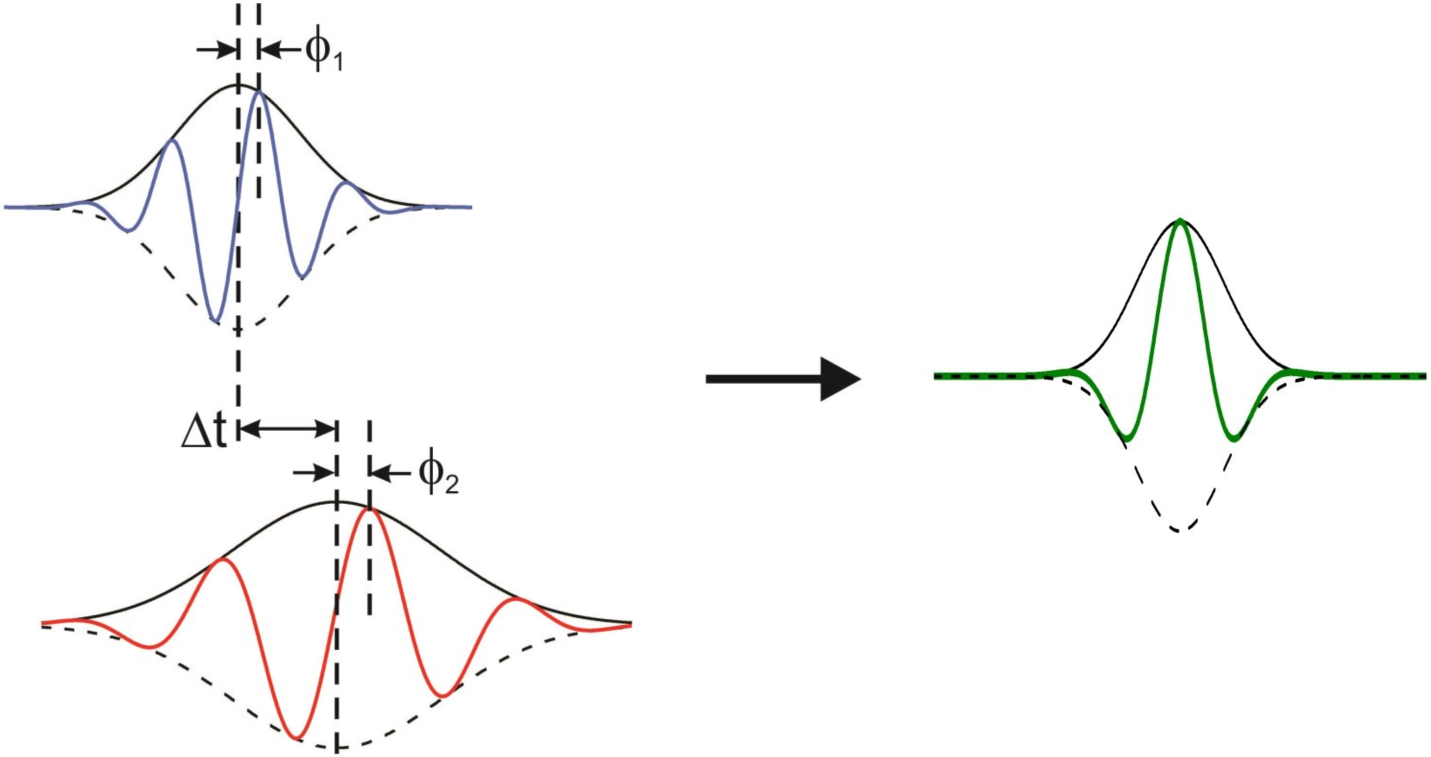
Broad spectrum → Amplification → Compression



OPA = optical parametric amplification

Key ingredients of coherent sub-cycle waveform synthesis

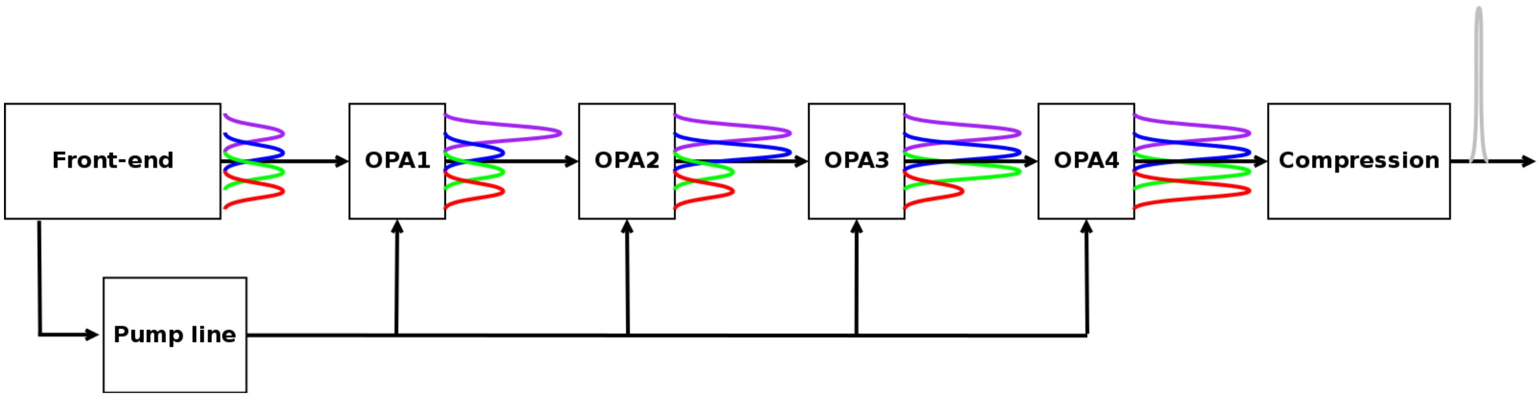
- ❑ **High-energy multi-color pulses (ultrabroad spectrum for each pulse)**
- ❑ **Extremely precise dispersion control over the whole bandwidth**



- ❑ **Relative timing should be locked to sub-cycle precision**
- ❑ **Each pulse should be CEP stable at the synthesis point**

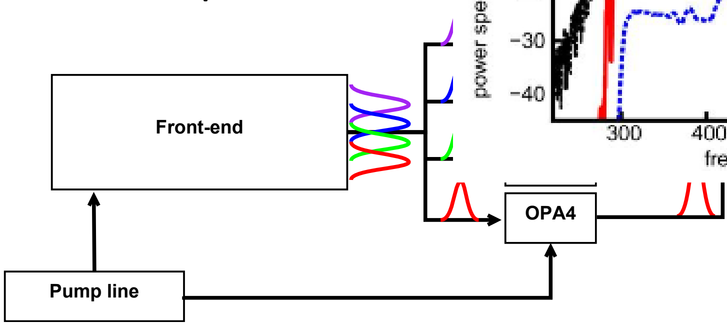
How to realize it ?   Frequency synthesizer

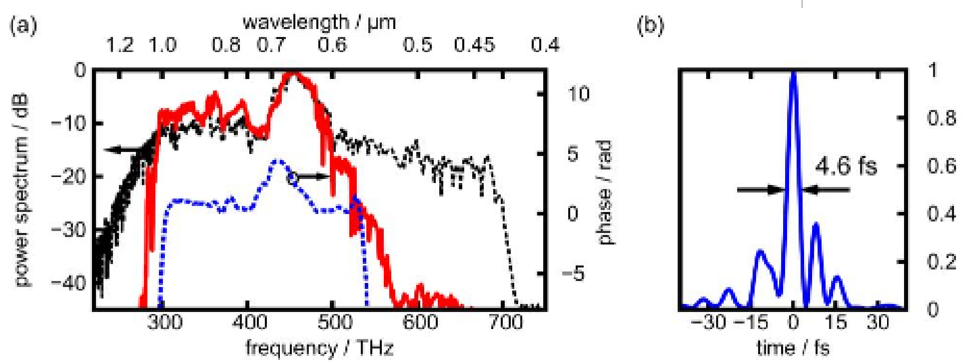
Serial synthesis

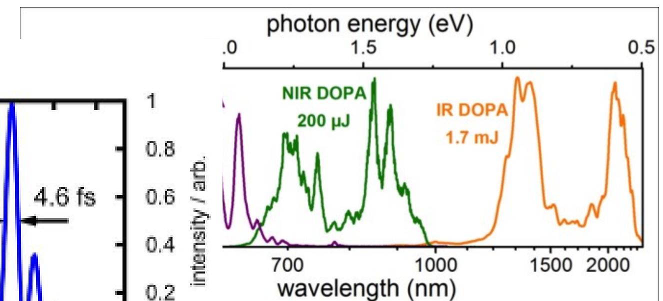


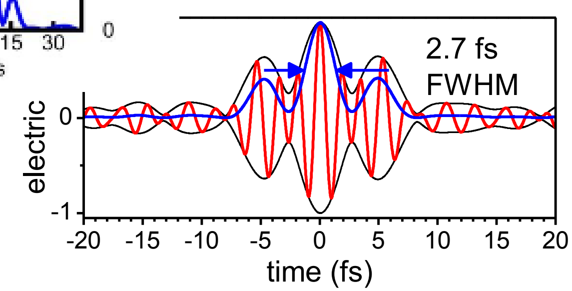
Parallel synthesis

µJ level





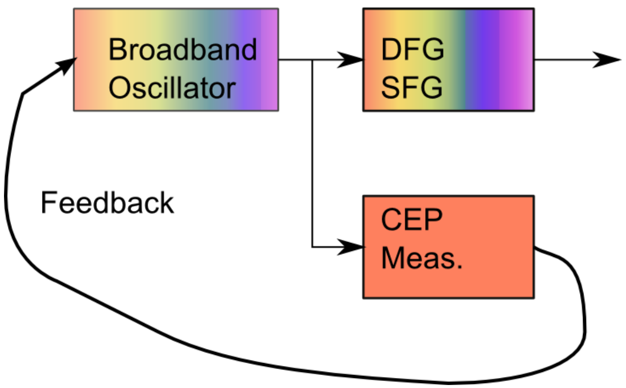




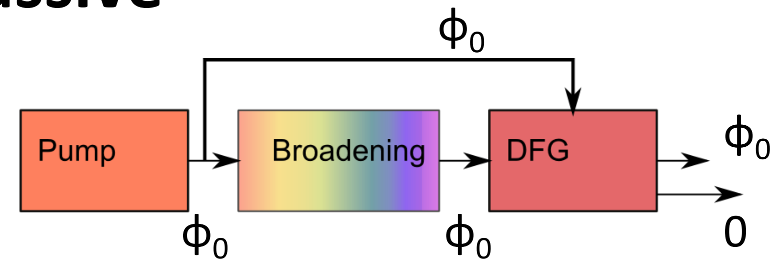
Harth *et al.*, OE **20** (3), 3076 (2012)
Huang *et al.*, Nat. Phot. **5**, 475 (2011)
Manzoni *et al.*, LPR 201400181 (2015)

And for the CEP stability ?

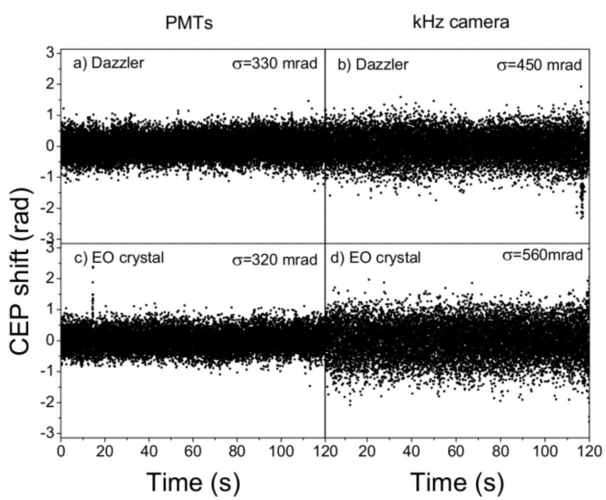
- **Active**



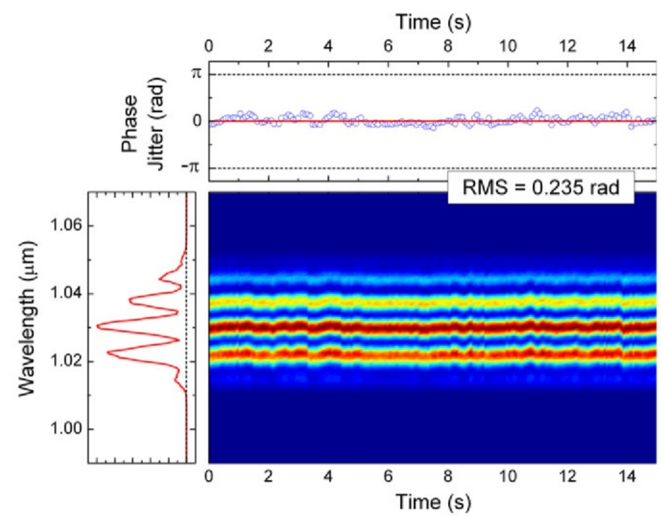
- **Passive**



- **Achieved:**
  - $\Delta\phi_{rms}$ = 0.320rad

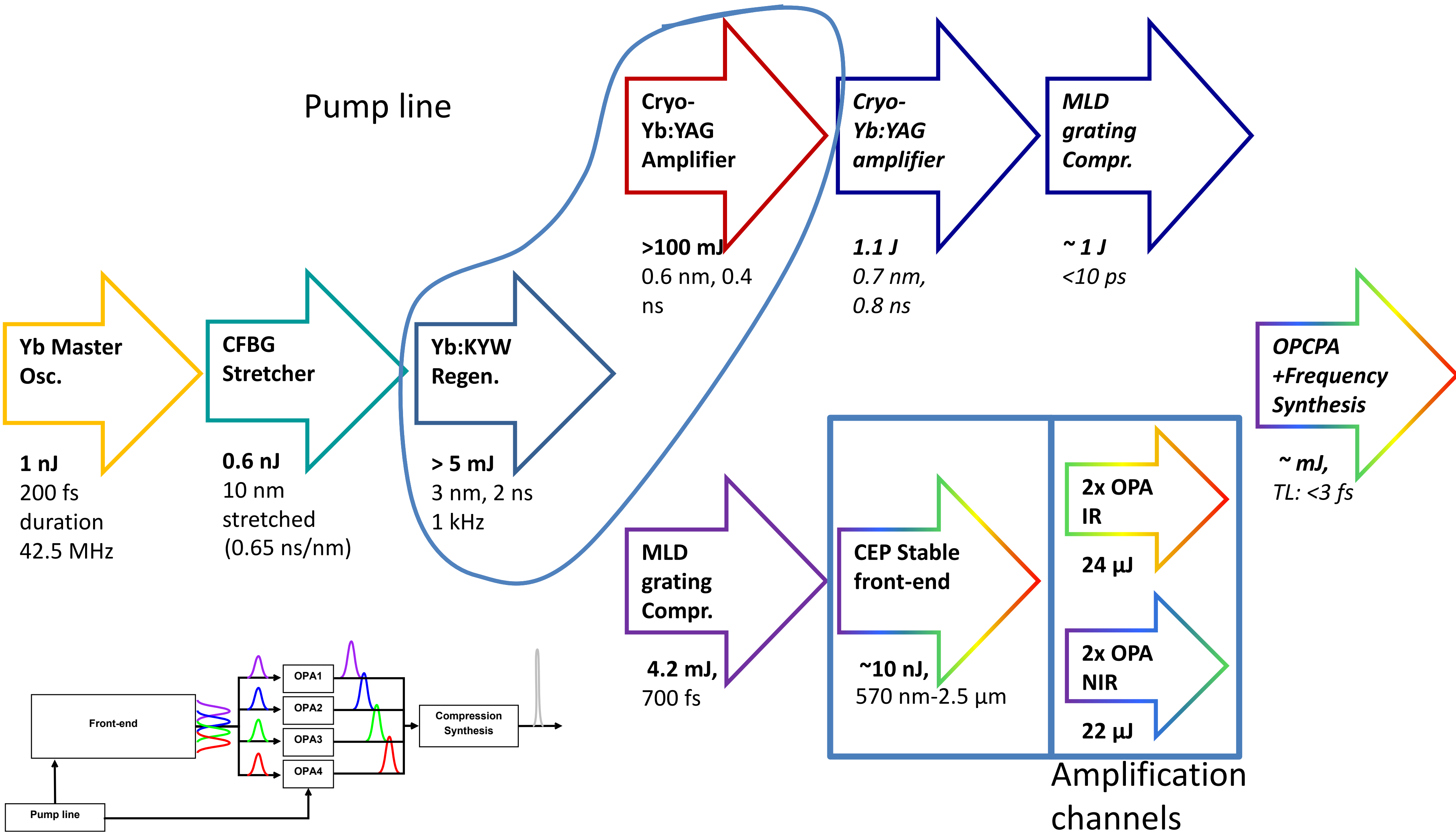


- **Achieved:**
  - $\Delta\phi_{rms}$ = 0.235rad



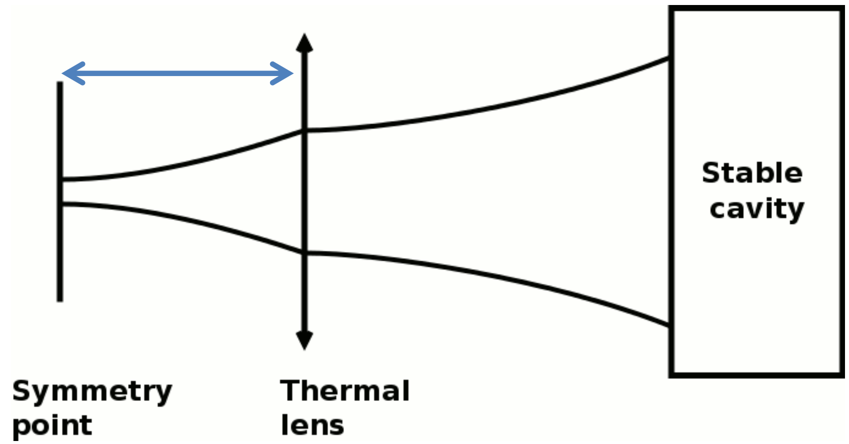
Feng *et al.*, OE **21** (21), 25248 (2013)
Brida *et al.*, JO **12**, 013001 (2010)

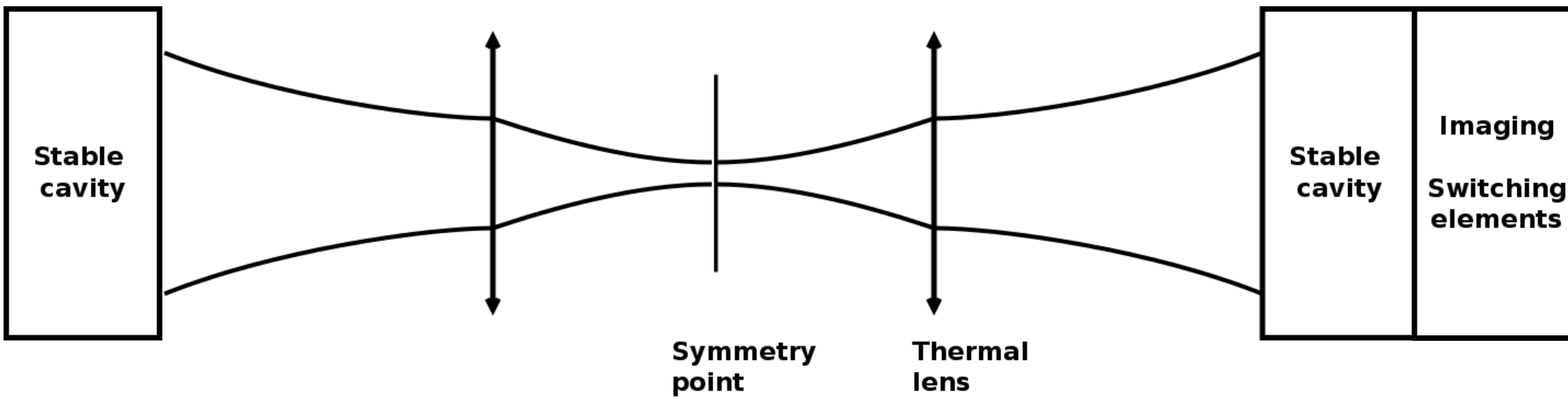
System overview



Regenerative amplifier design

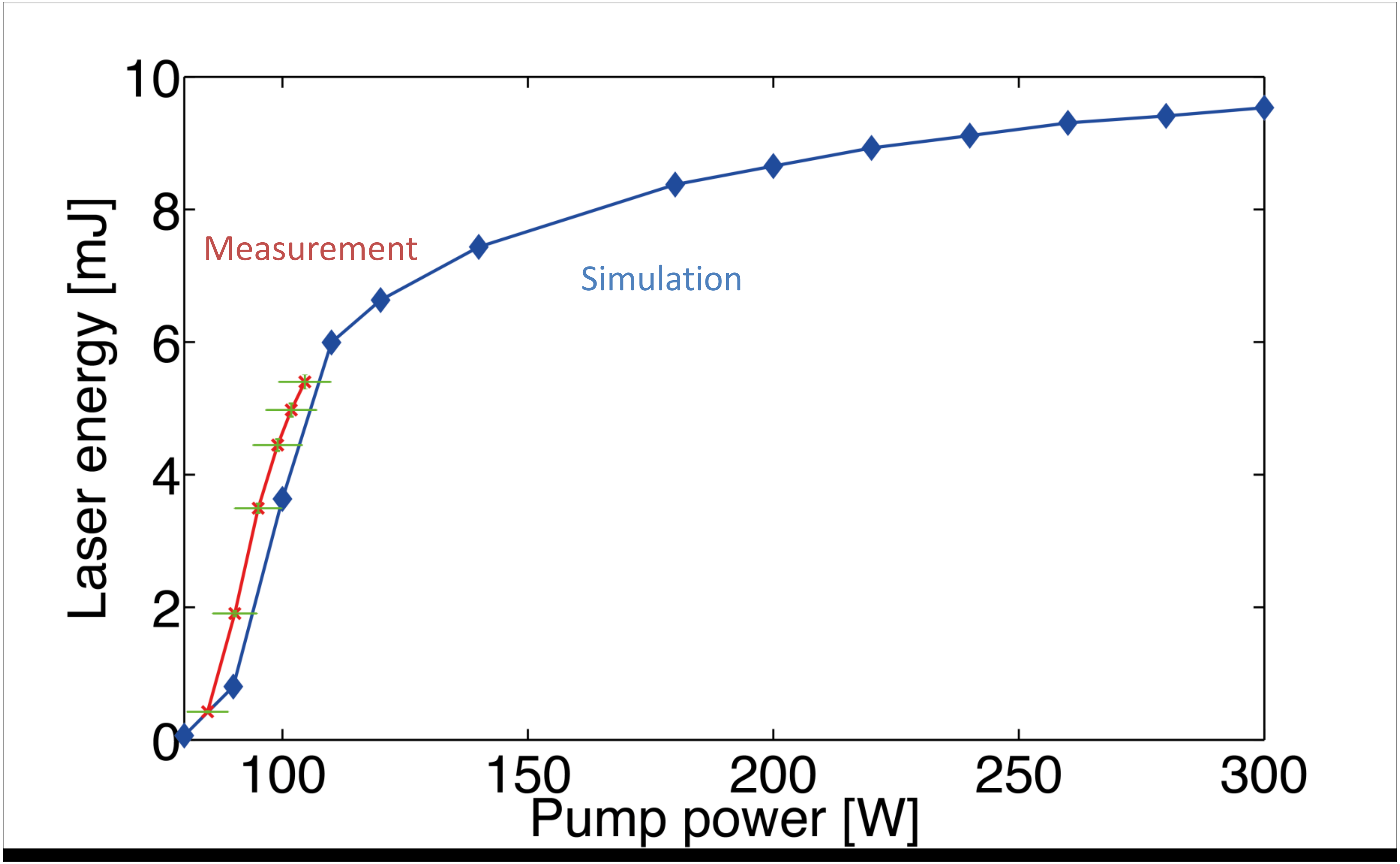
High pump power
→ Thermal load
→ Thermal lensing
→ Pointing





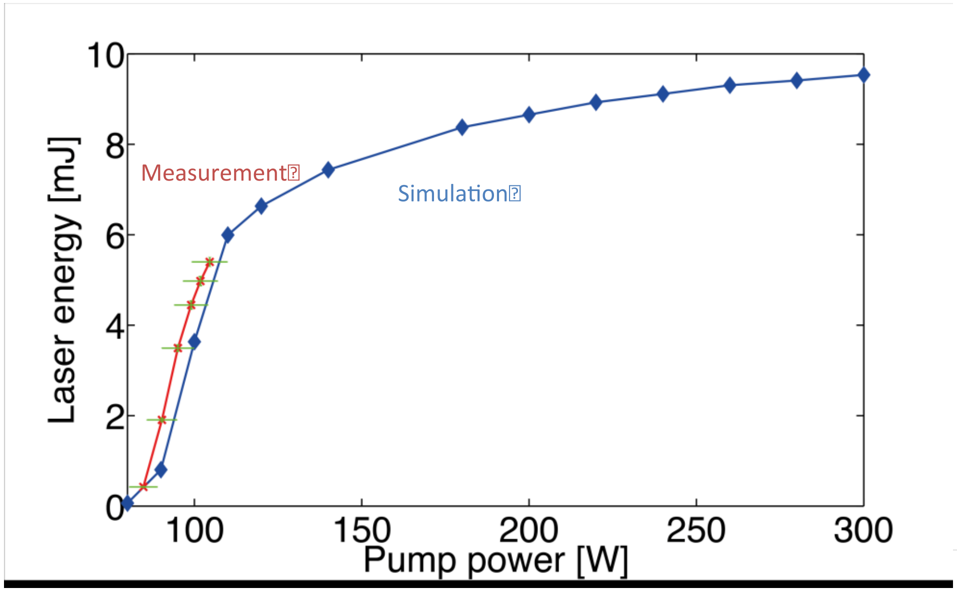
Magni, JOSA A **4** (10), 1962 (1987)

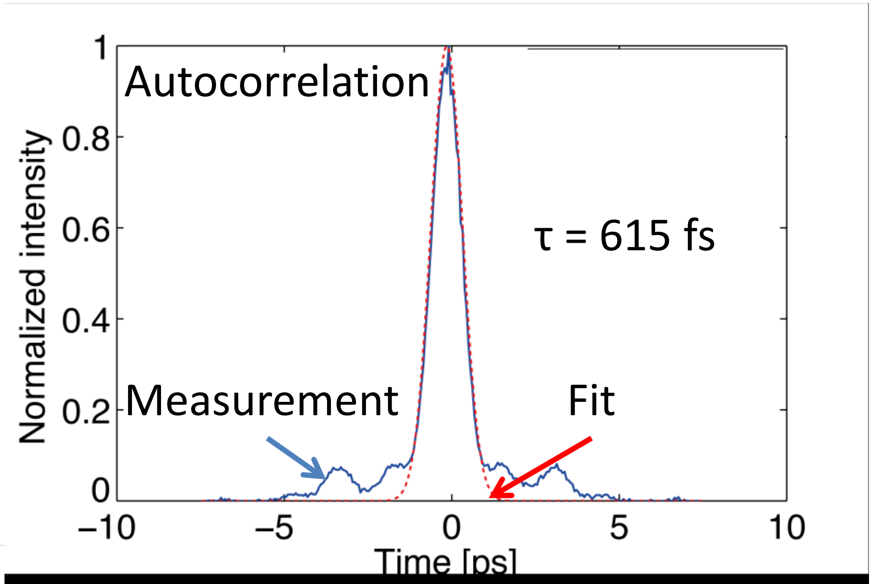
Yb:KYW Regenerative amplifier

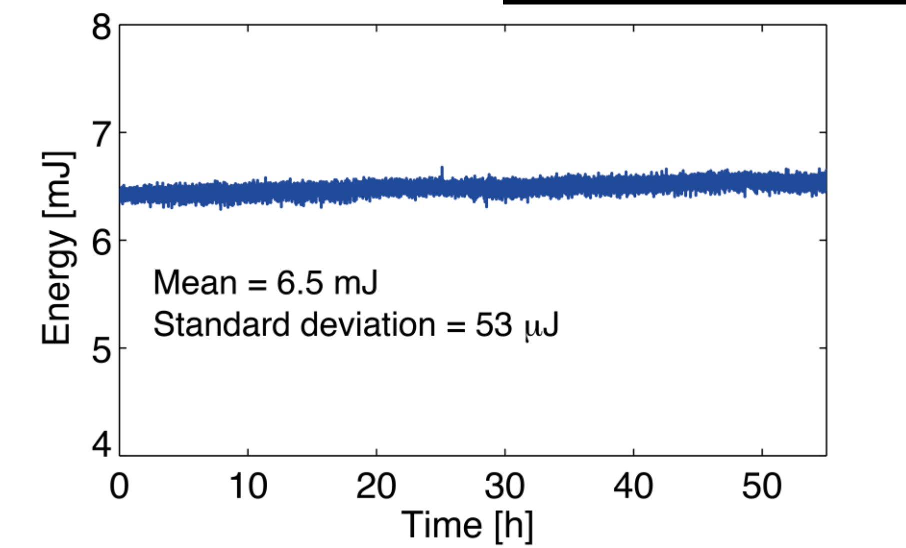


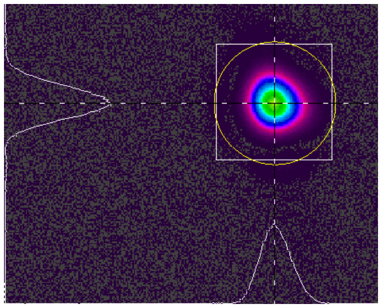
Calendron *et al.*, OE **22** (20), 24752 (2015)

Yb:KYW Regenerative amplifier



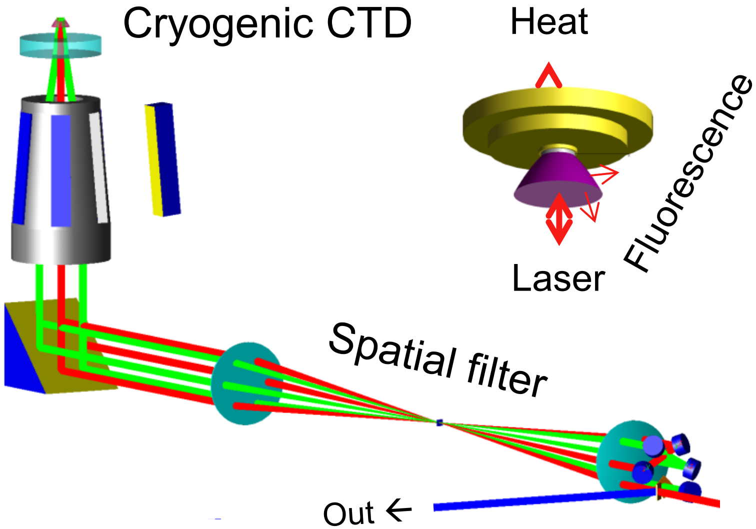


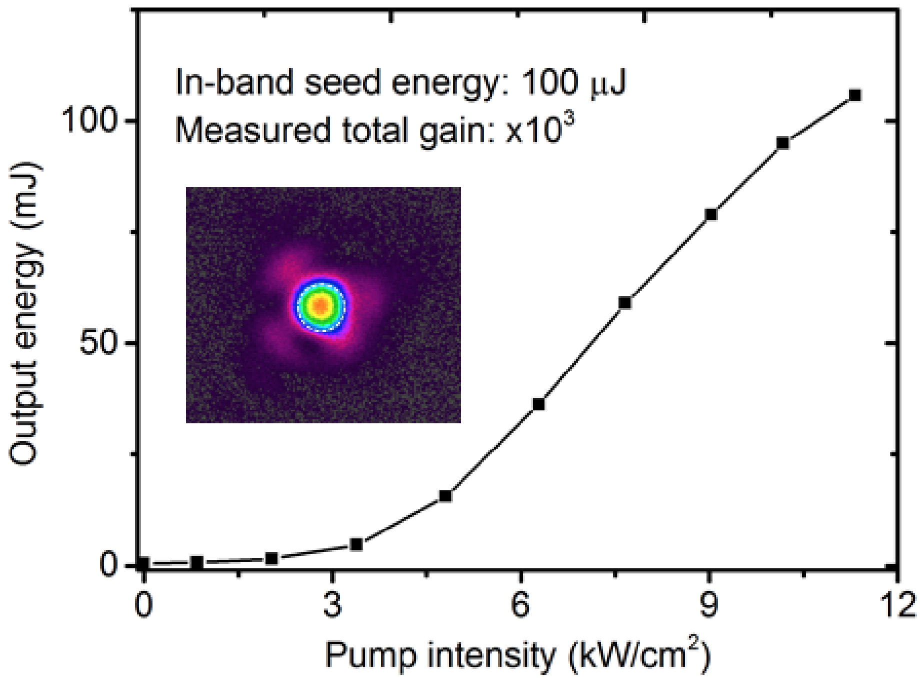




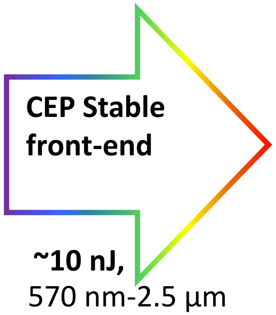
Calendron *et al.*, OE **22** (20), 24752 (2015)

Cryogenic Yb:YAG amplifier

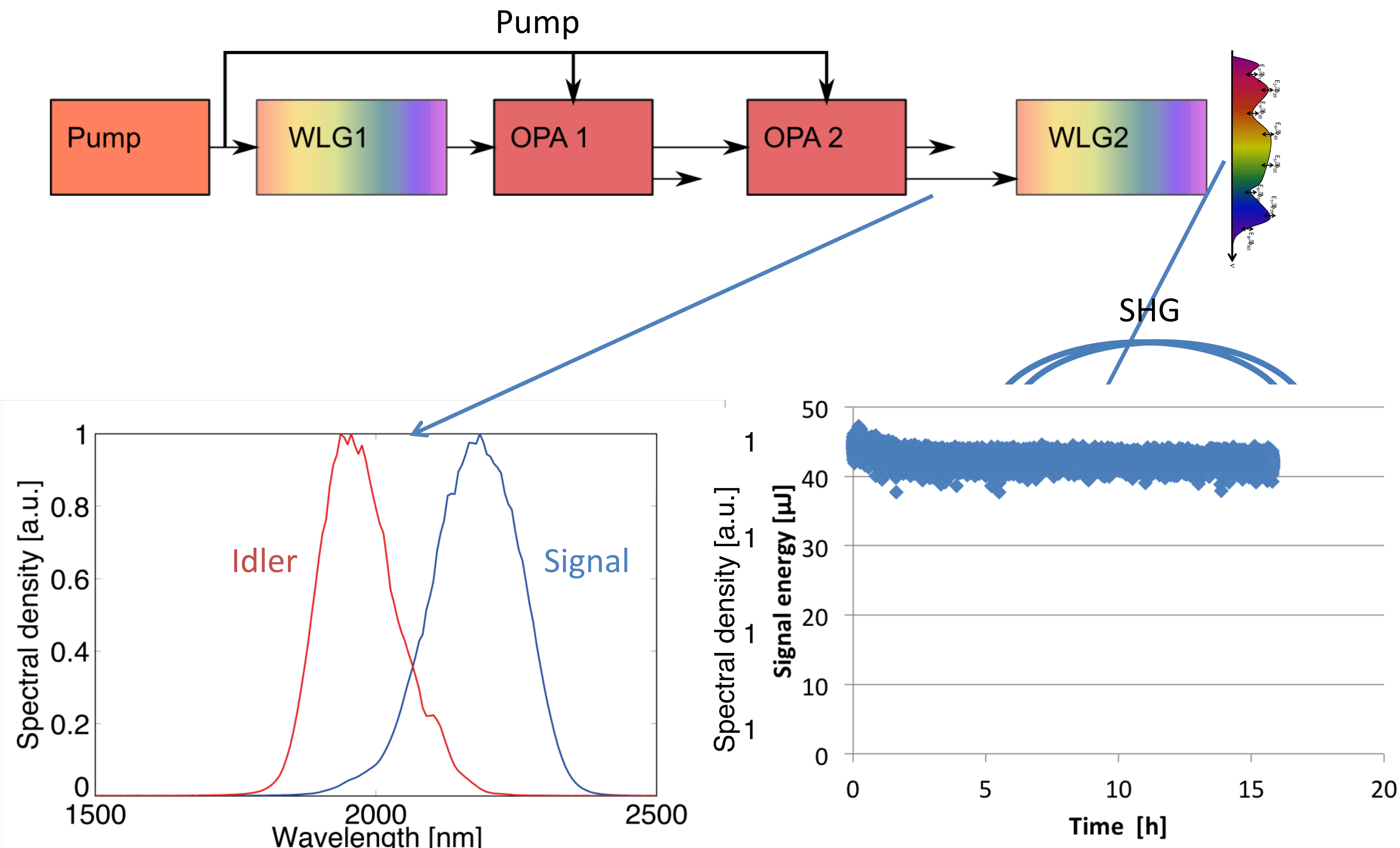




System overview

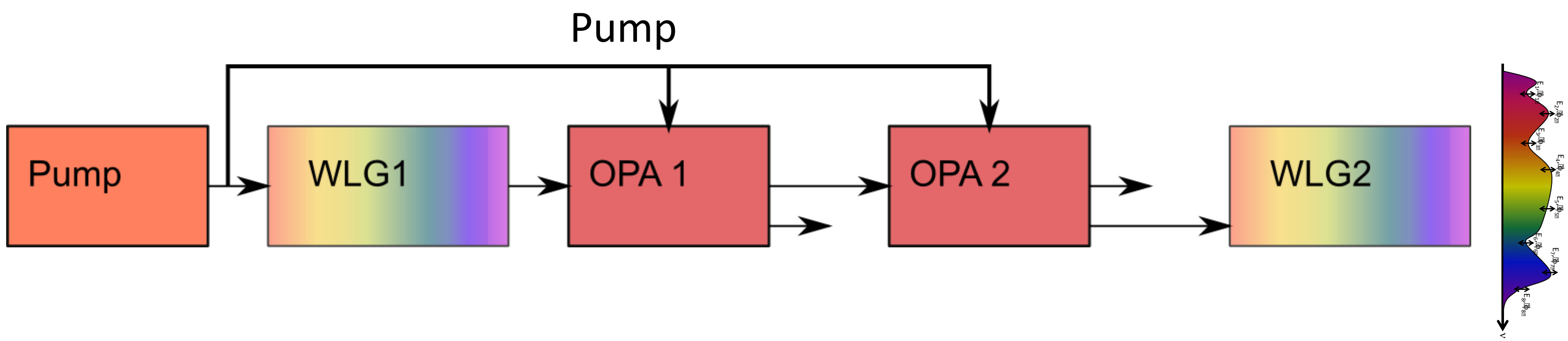


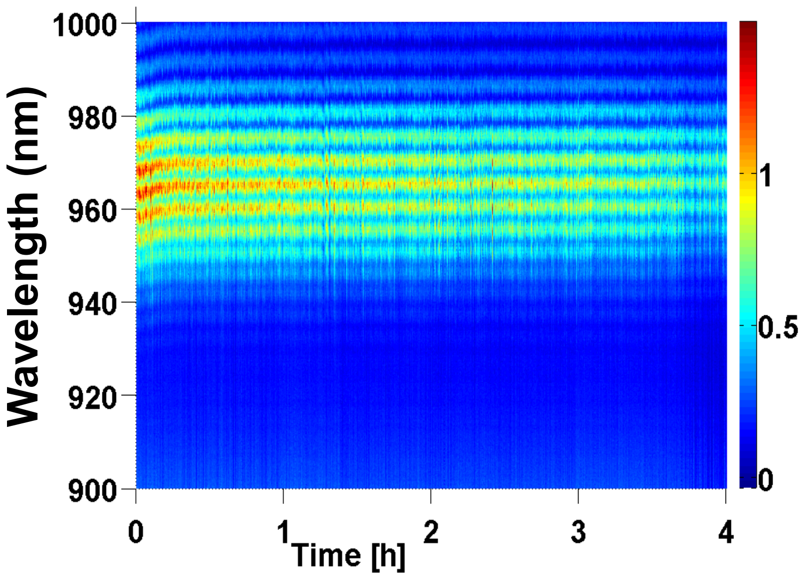
CEP stability

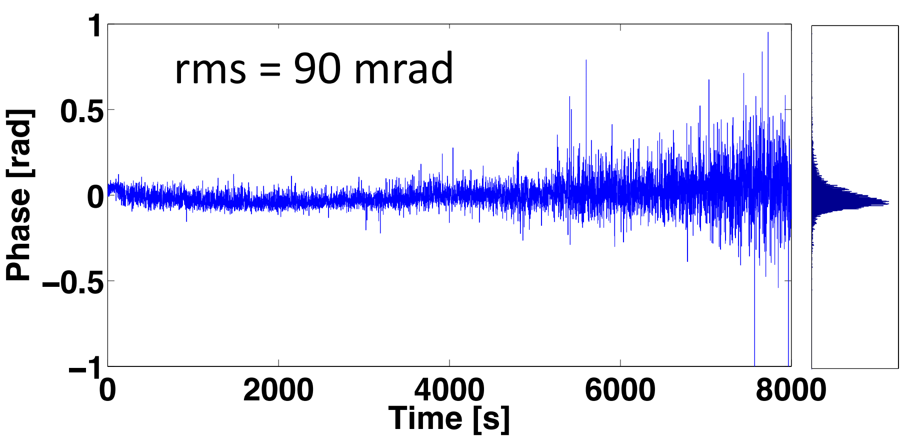


Cankaya *et al.*, UP2014, poster 07.Mon.P1.58

CEP stability







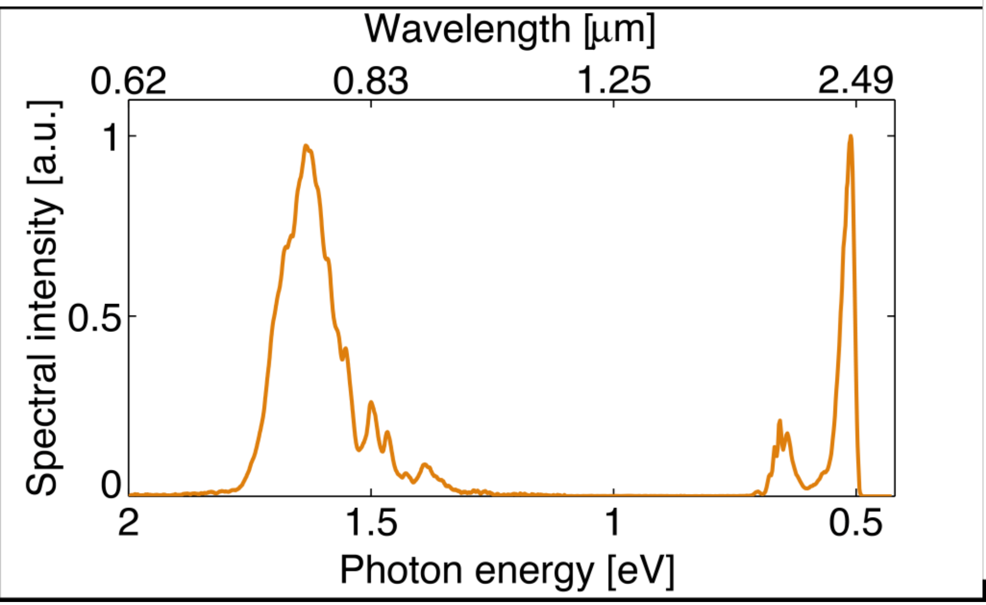
System overview

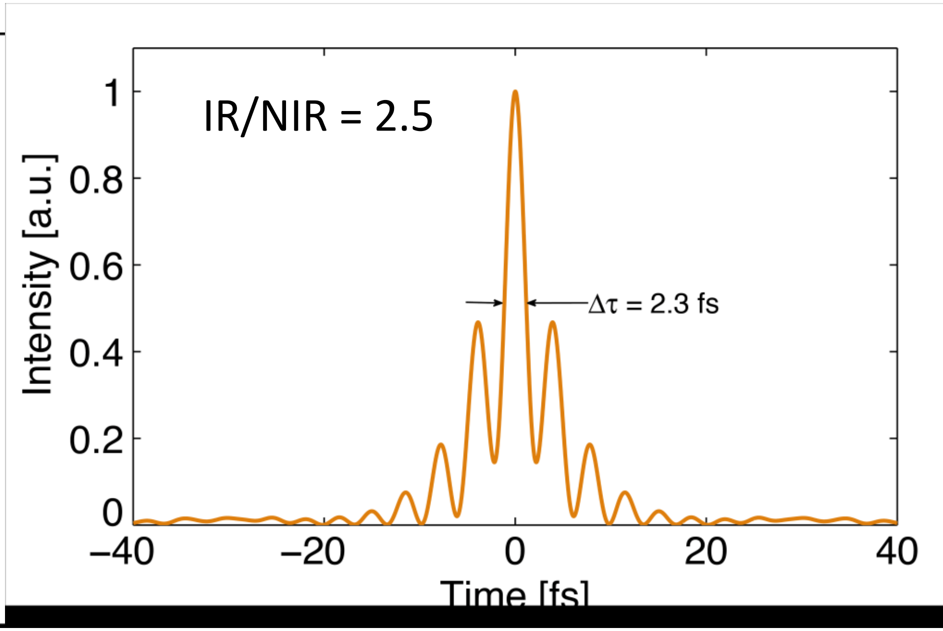
2x OPA
IR
24 µJ

2x OPA
NIR
22 µJ

Amplification

- **DOPA: IR (2 μm) – 2 stages: 24 μJ**
- **NOPA: NIR (800 nm) – 2 stages: 22 μJ**

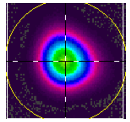


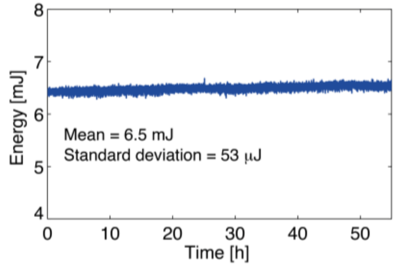


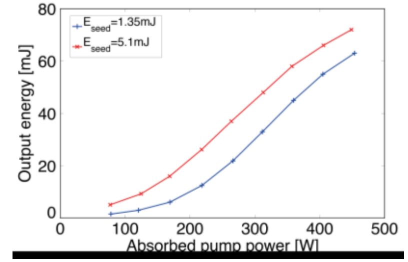
Calendron *et al.*, submitted CLEO Europe 2015

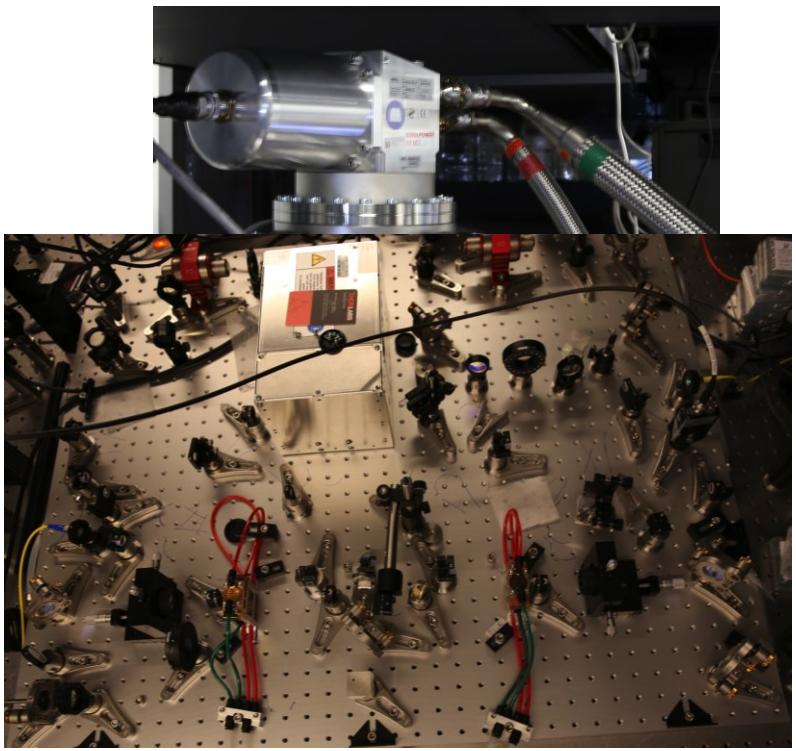
Summary: towards a stable frequency synthesizer

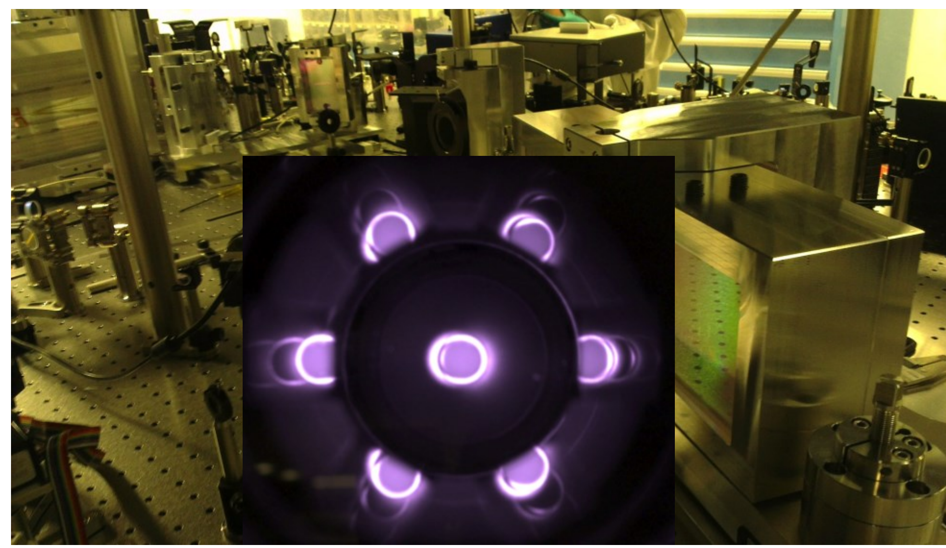
Pump line











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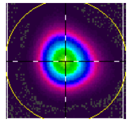
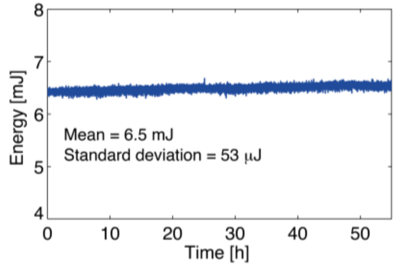
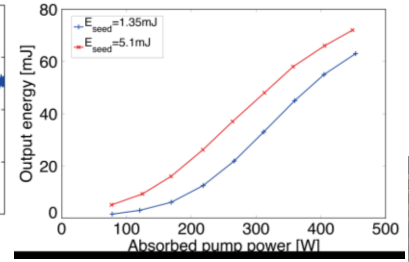
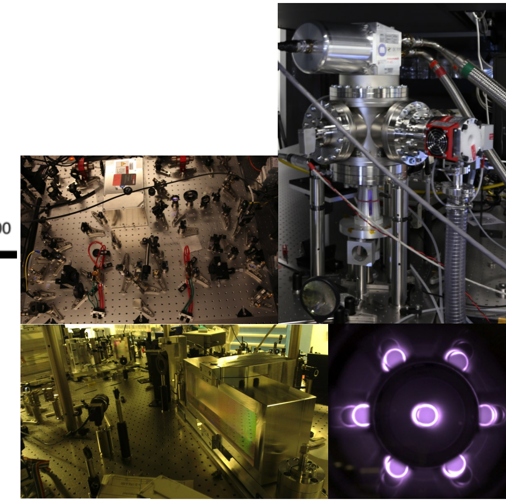
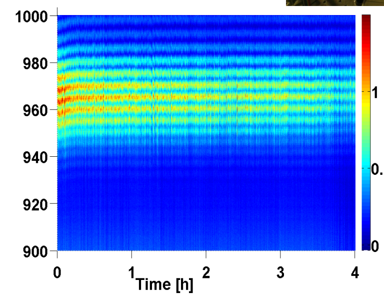


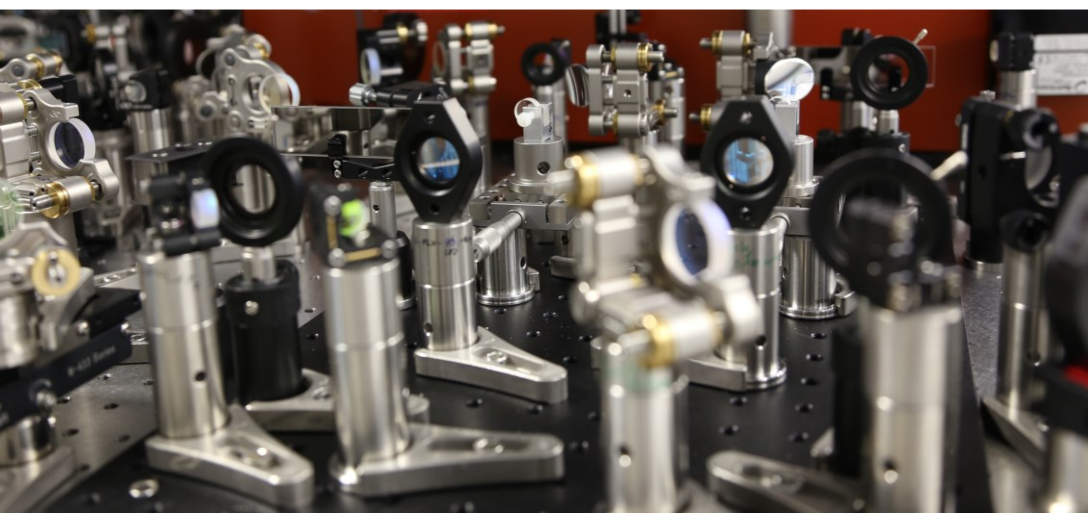






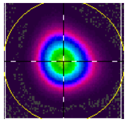
Broadband, CEP stable front-end

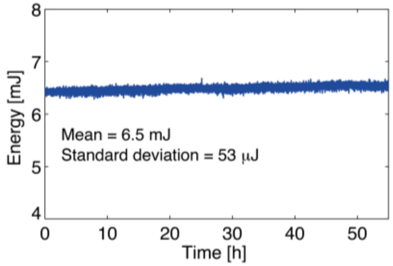


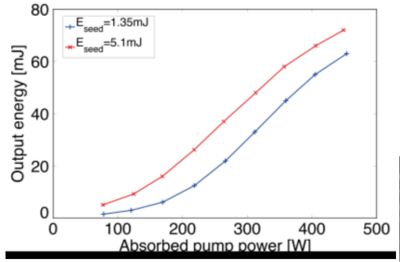


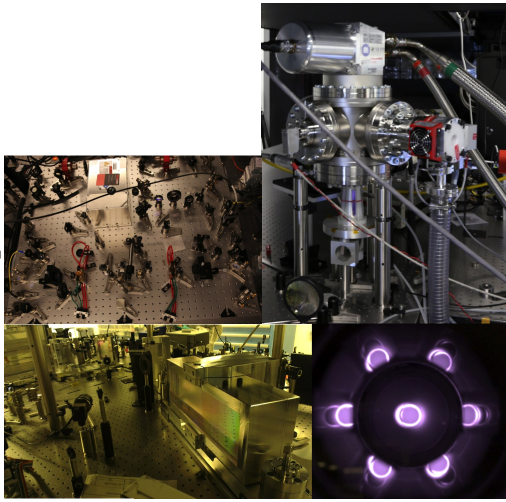
Summary: towards a stable frequency synthesizer

Pump line

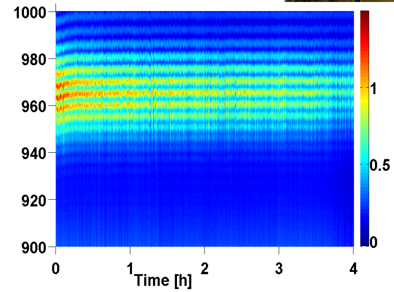


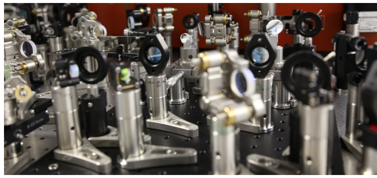




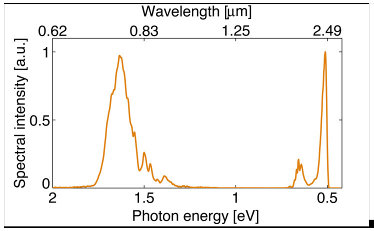


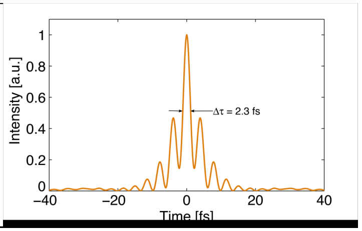
Broadband, CEP stable front-end





First 2 amplification stages

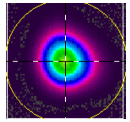


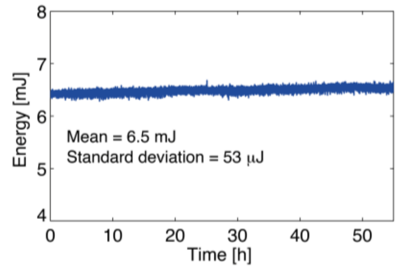


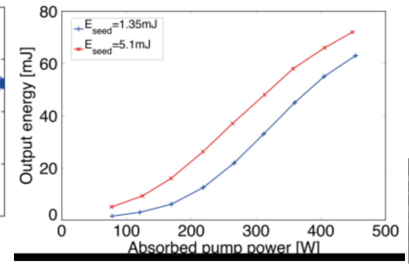
DESY CFEL SCIENCE UH

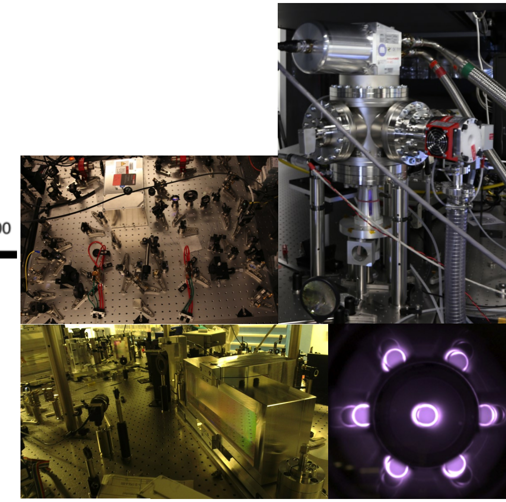
Summary: towards a stable frequency synthesizer

Pump line

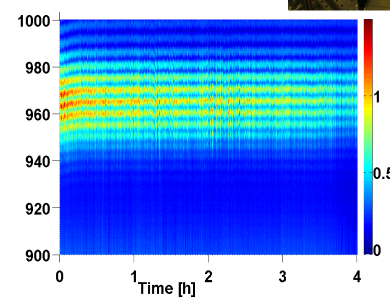


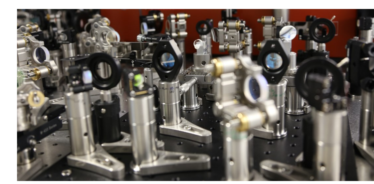




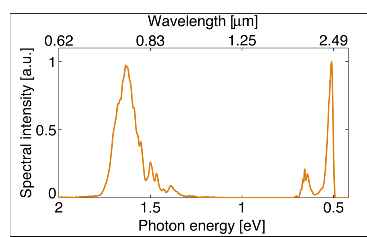


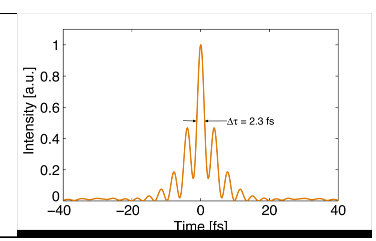
Broadband, CEP stable front-end





First 2 amplification stages





Next steps

- **Compression of the cryogenically cooled Yb:YAG amplifier**
- **Amplification to higher energies of the different channels**
- **Synthesis and compression of the amplified channels**

Thank you for your attention

European Research Council

Established by the European Commission

Back-up slides

- **Regenerative amplifier**
  - Yb:KYW
  - Yb:CALGO
  - Yb:Lu_2O_3
- **Cryogenically cooled amplifier**
- **Laser materials**
- **Thermal lensing**
- **Front-end**
- **White-light study (Meas., Cherenkov, Disp. YAG/Sap, ??)**
- **OPCPA**
- **Compression broadband pulses**
- **Stretcher / Compressor pump line**

Thanks to...

- Prof. Franz X. Kärtner
- Huseyin Cankaya
- Max Lederer
- Giovanni Cirmi
- Damian N. Schimpf
- Jeff Moses
- CFEL Engineering Teams

- Funding

European Research Council
Established by the European Commission

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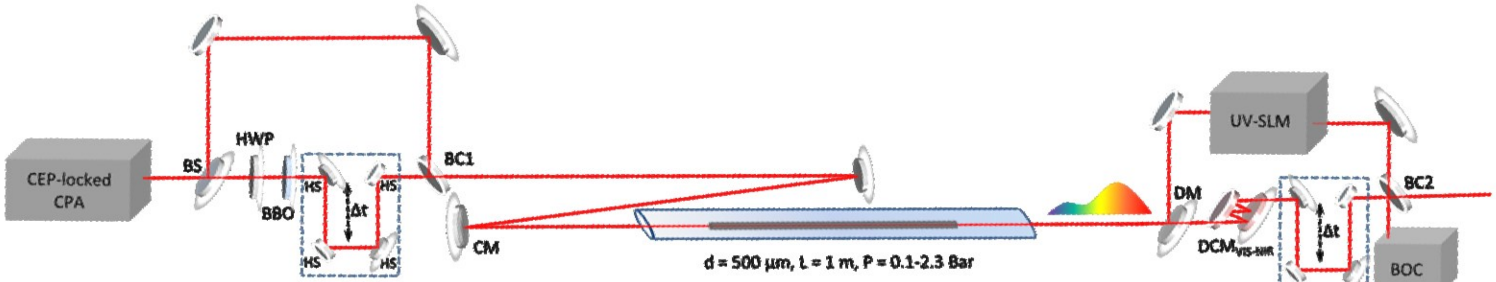
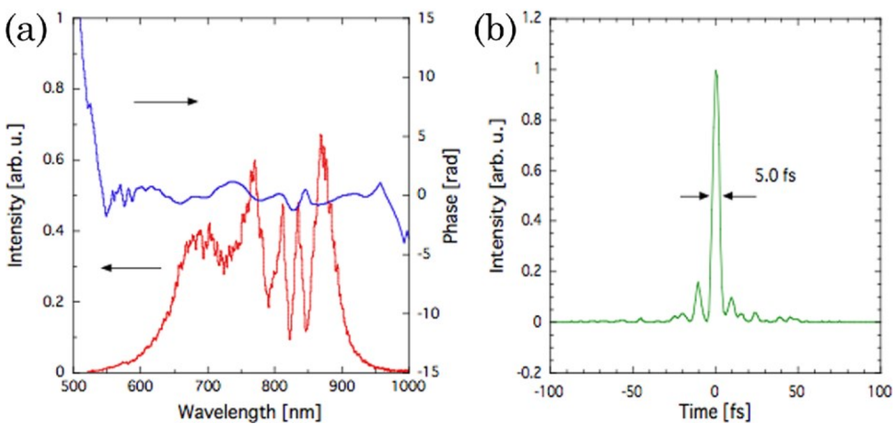
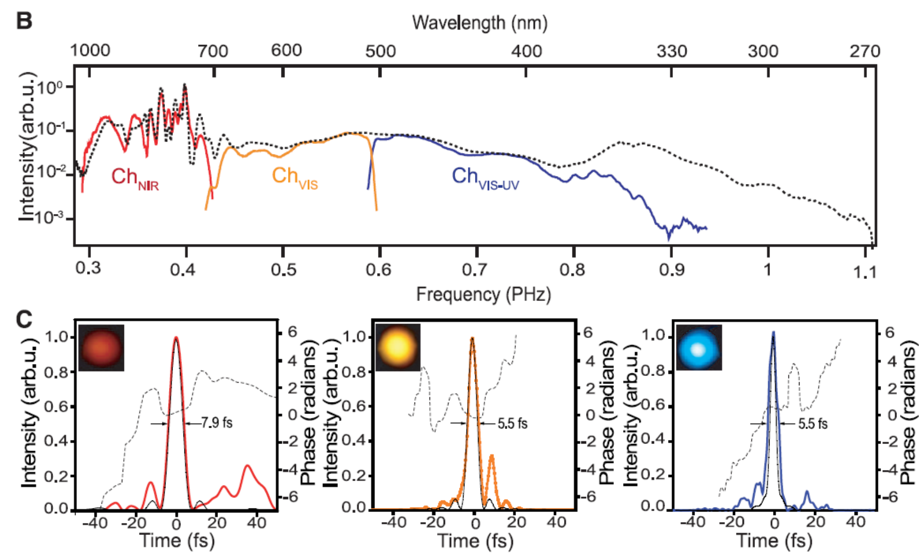
How ssor





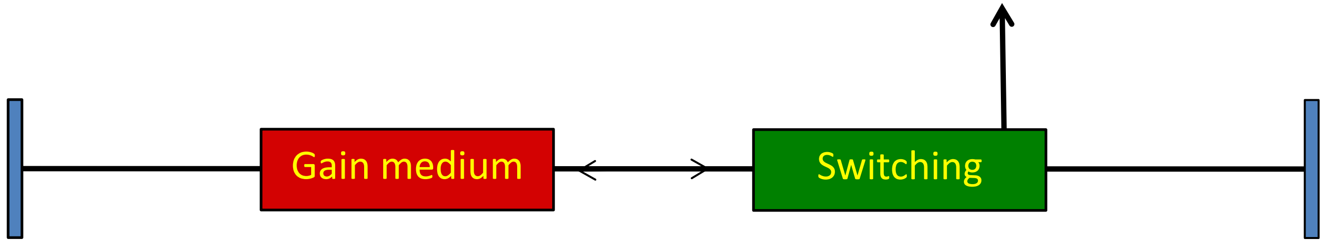


Bohman et al., OL 35, 1887 (2010): 5.0 mJ, 5.0 fs, 1kHz

Wirth *et al.*, Science **334**, 195 (2011): 30 µJ, sub-cycle

Pump line: Amplifiers

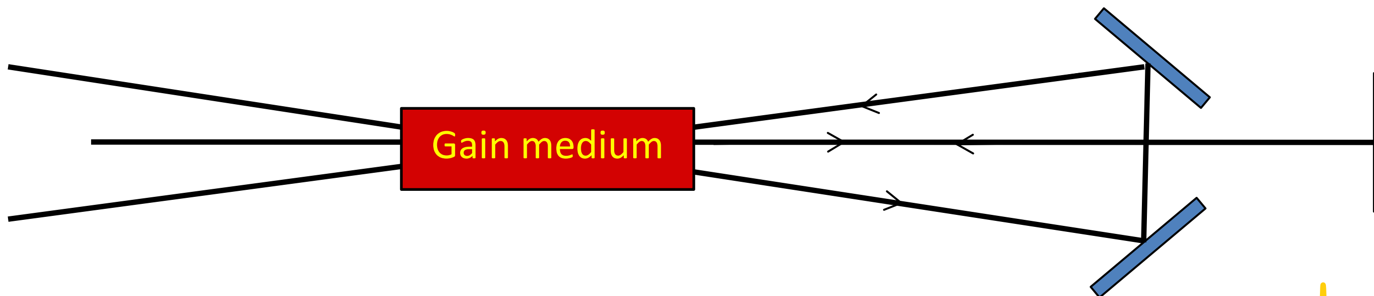
Regenerative amplifier

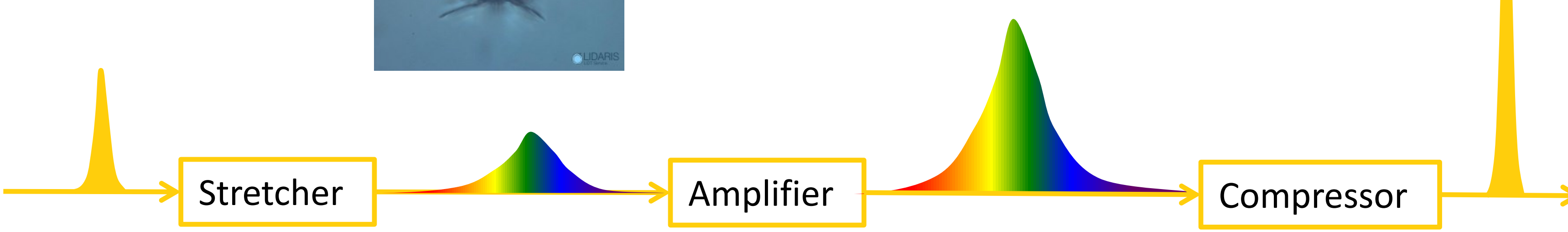


Single-pass

Double-pass

Multi-pass





Front-end: White-light generation

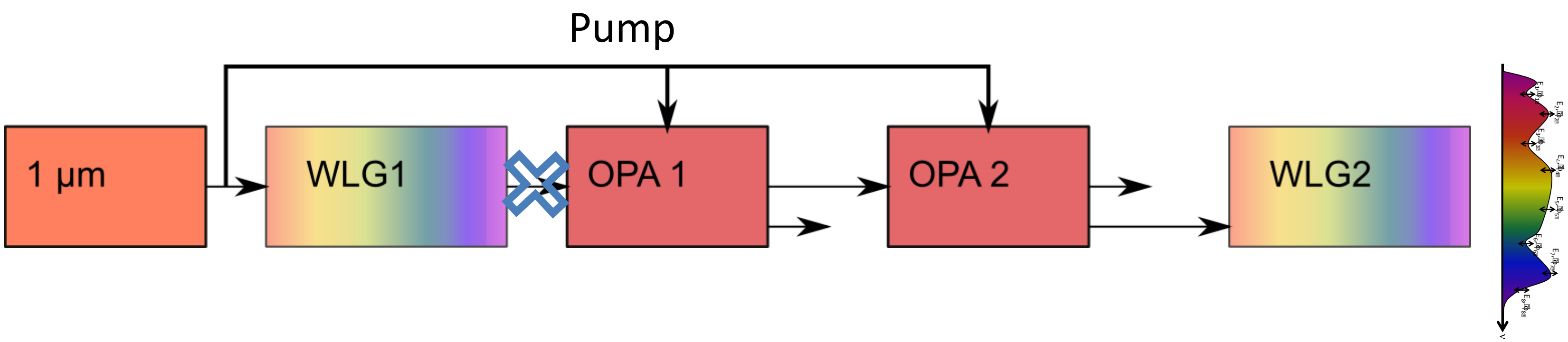
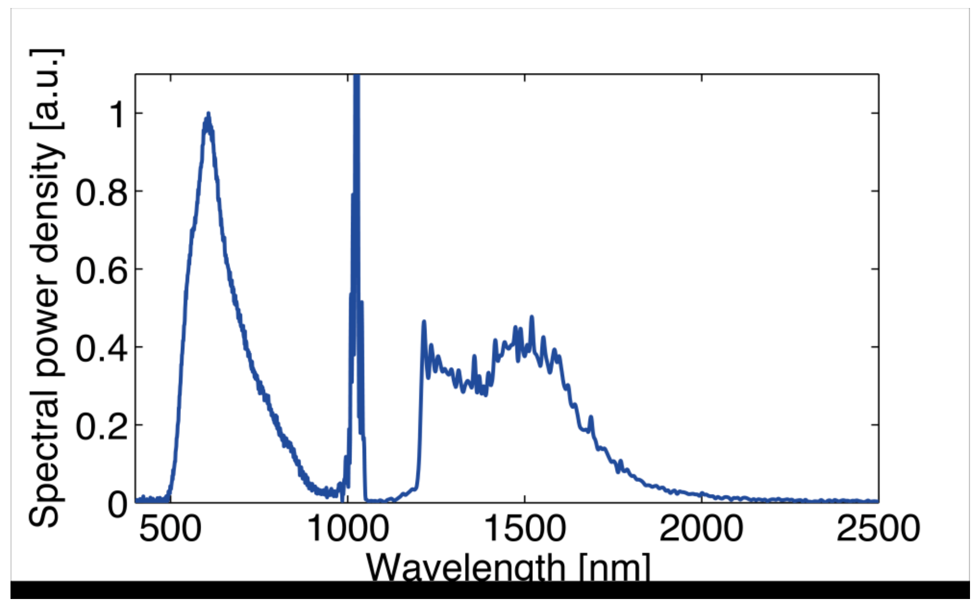
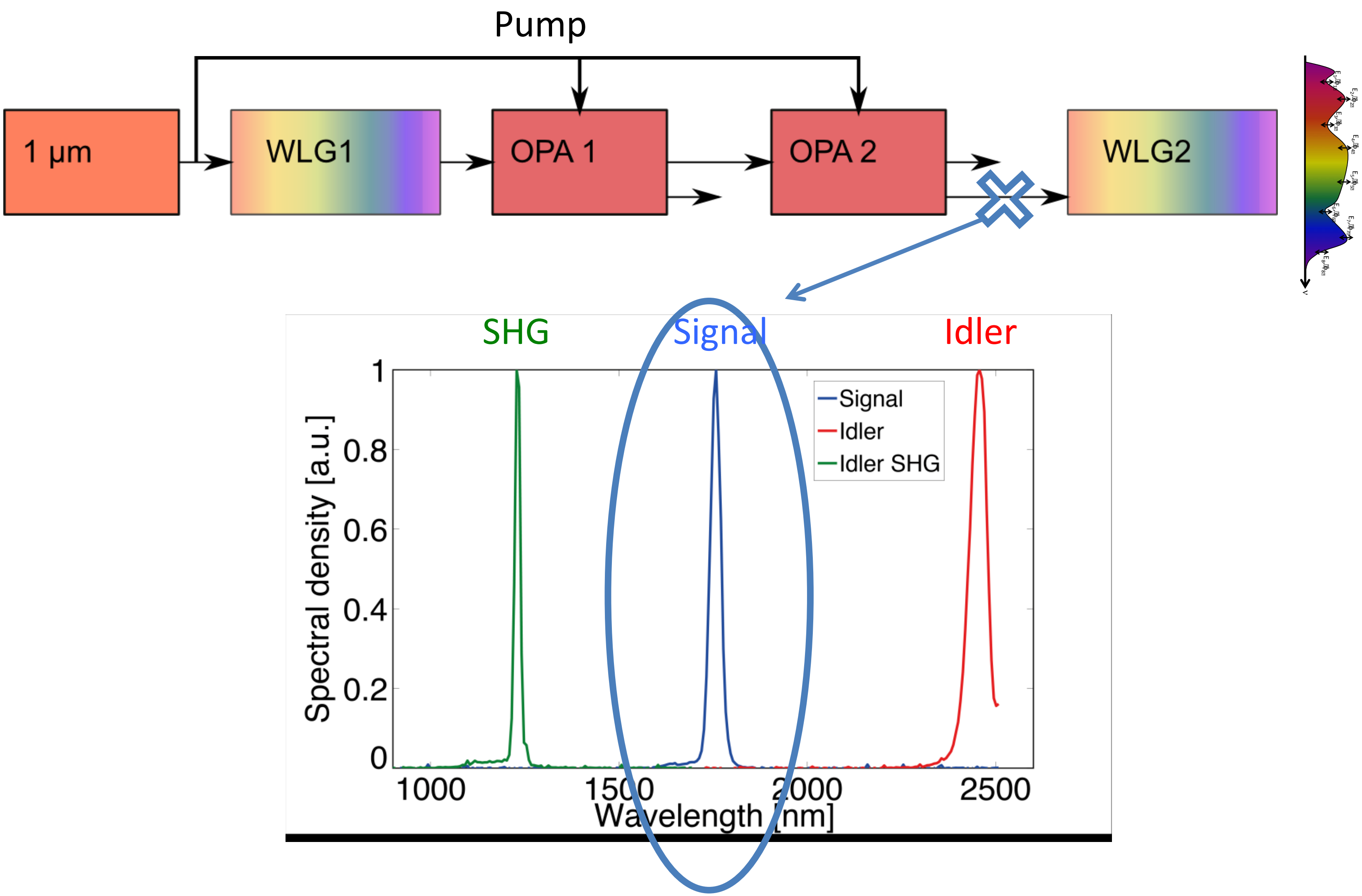


Photo WL



Calendron *et al.*, submitted CLEO 2015
Calendron *et al.*, manuscript in preparation

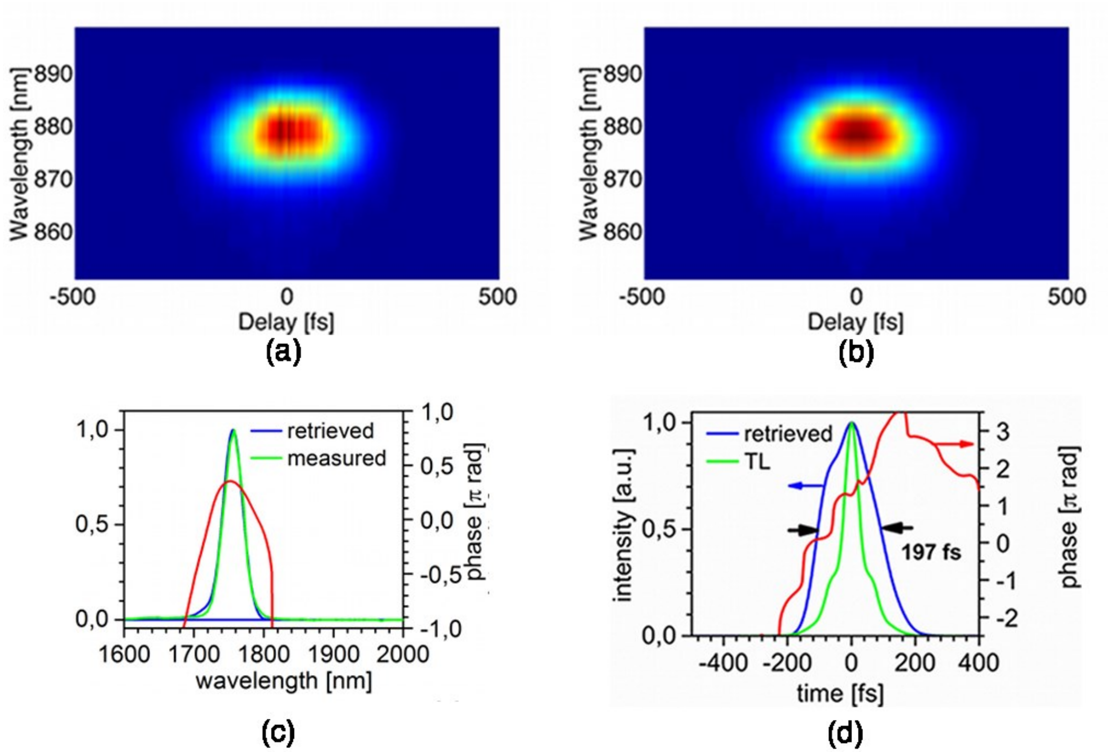
Front-end



Cankaya *et al.*, submitted CLEO 2015

Compressibility

FROG measurement: 1750 nm after OPA



Calendron *et al.*, submitted CLEO 2015
Calendron *et al.*, manuscript in preparation

Pump line

Pump chain as OPCPA driver

- 100 mJ to to pump the OPCPA’s, scalable to high energies
- Combination of different technologies, adapted to each stage
- λ = 1030nm

Seeder
42.5 MHz
210 fs, n
J

→

Stretcher
42.5 MHz
3.2 ns, 0.
6 nJ

→

Regen
1 kHz
2.3 ns, 6.
5 mJ

→

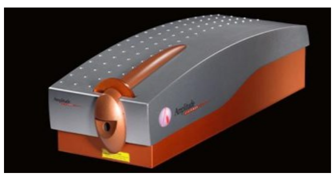
Compressor
1 kHz
650 fs, 4.5
mJ

→

Cryo Amp
0.1-1 kHz
1 ns, 10
0 mJ

→

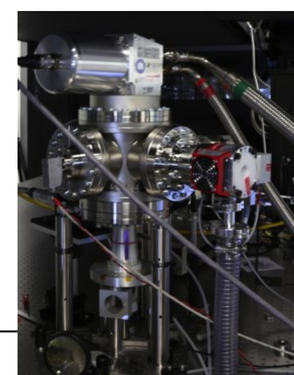
Compressor
1 kHz
650 fs, 4.5
mJ



Amplitude System

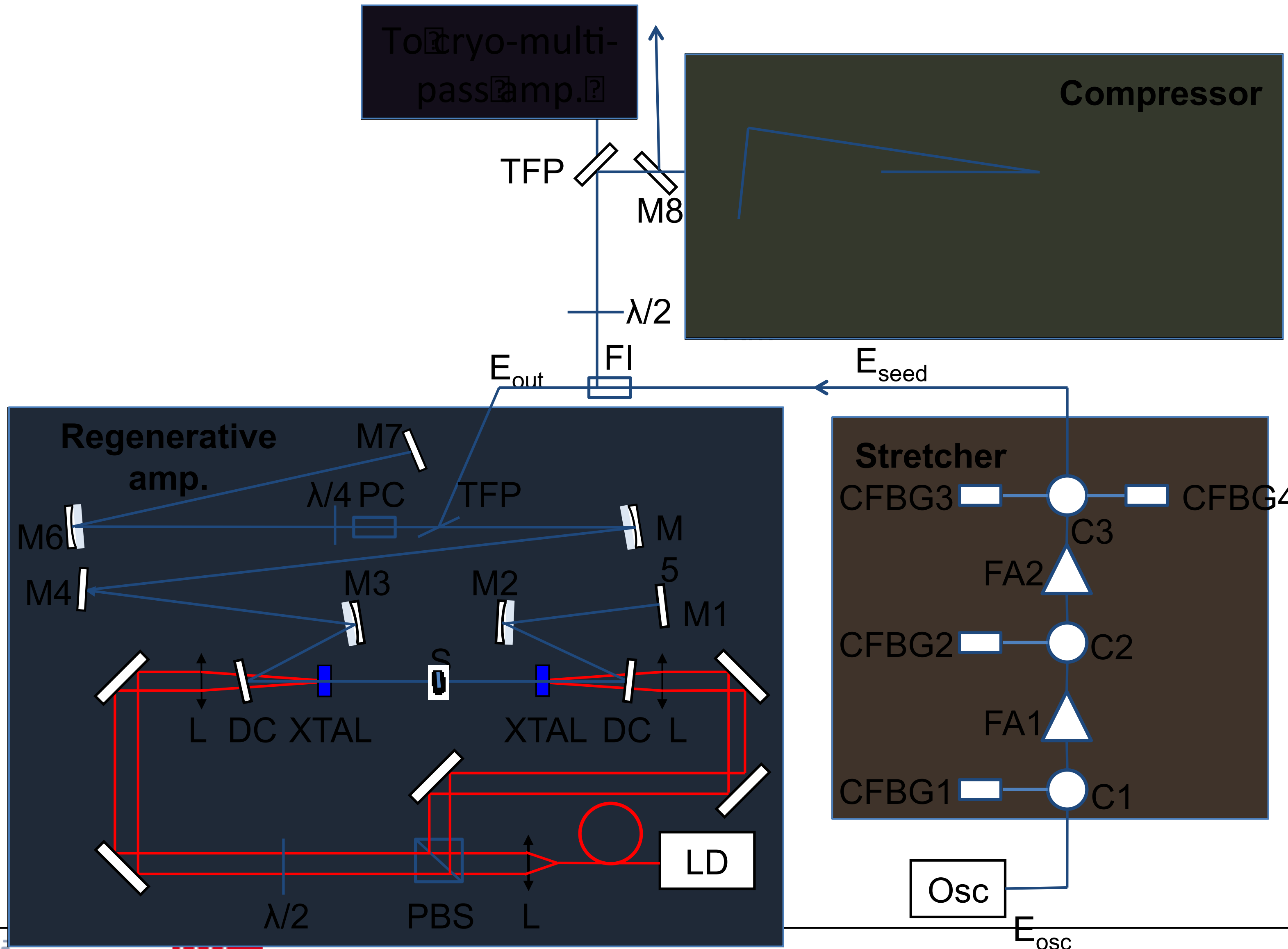
CFBG + fiber amplifiers

Home-made

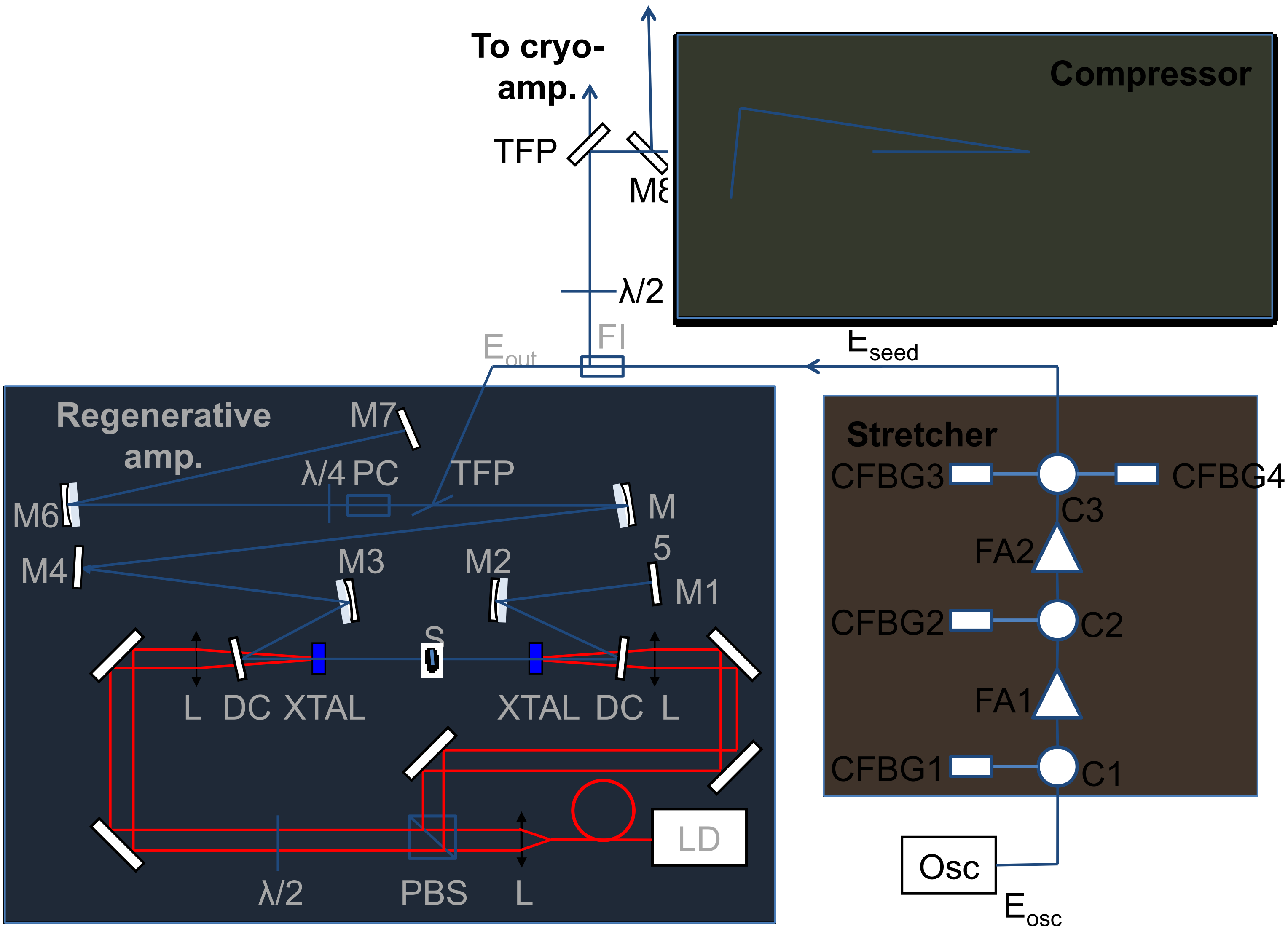


Home-made
(Development with Luis and Hua)

Pump line


To cryo-multi-
pass amp.
Compressor
TFP
M8
λ/2
FI
E_out
E_seed
Regenerative
amp.
M7
λ/4 PC
TFP
M6
M
5
M4
M3
M2
M1
S
L
DC
XTAL
XTAL
DC
L
λ/2
PBS
L
LD
Stretcher
CFBG3
CFBG4
C3
FA2
CFBG2
C2
FA1
CFBG1
C1
Osc
E_osc

Stretcher and compressor



Simulations: Pulse stretching and compression

- **With split-step Fourier: Propagation in a fiber to simulate the stretcher**

- **Grating formula (Fork):**

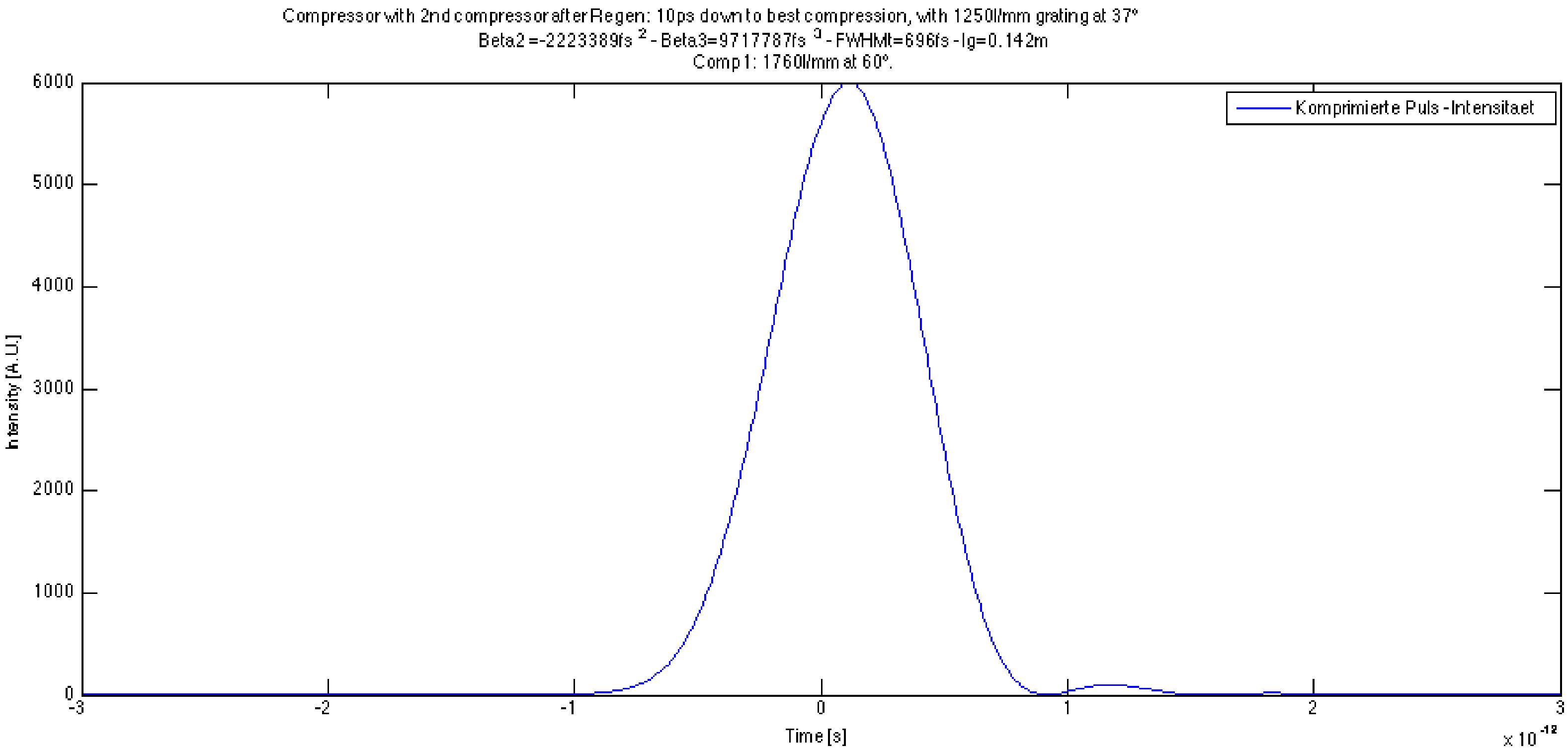
$$\text{Grating equation}$$

$$\text{GVD}\ \frac{d^2\phi_g}{d\omega^2} = \frac{\lambda_L^3 l_g}{\pi c^2 d^2}\left(1-\left(\frac{\lambda_L}{d}-\sin\gamma\right)^2\right)^{-3/2}$$

$$\text{TOD}\ \frac{d^3\phi_g}{d\omega^3} = -\frac{d^2\phi_g}{d\omega^2}\frac{6\pi\lambda_L}{c} * \frac{1+\frac{\lambda_L}{d}\sin\gamma-\sin^2\gamma}{1-(\frac{\lambda_L}{d}-\sin\gamma)^2}$$

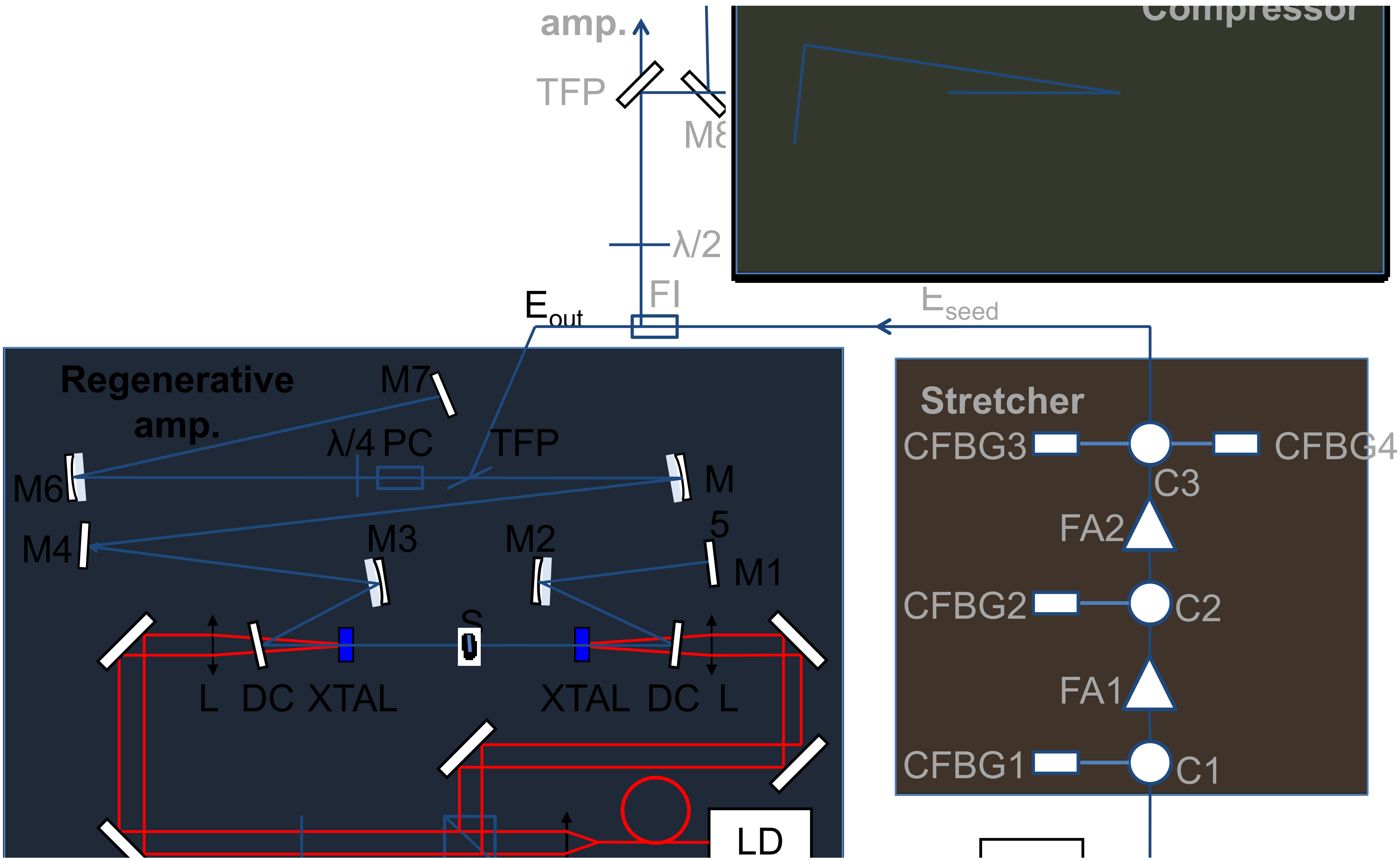
Pulse after compression

1. **Compressor: 1740l/mm, 60°, Lg=1.15m**



Pulse duration: 770fs theoretically. Wings not too strong => ok!

Pump line: Regenerative amplifier

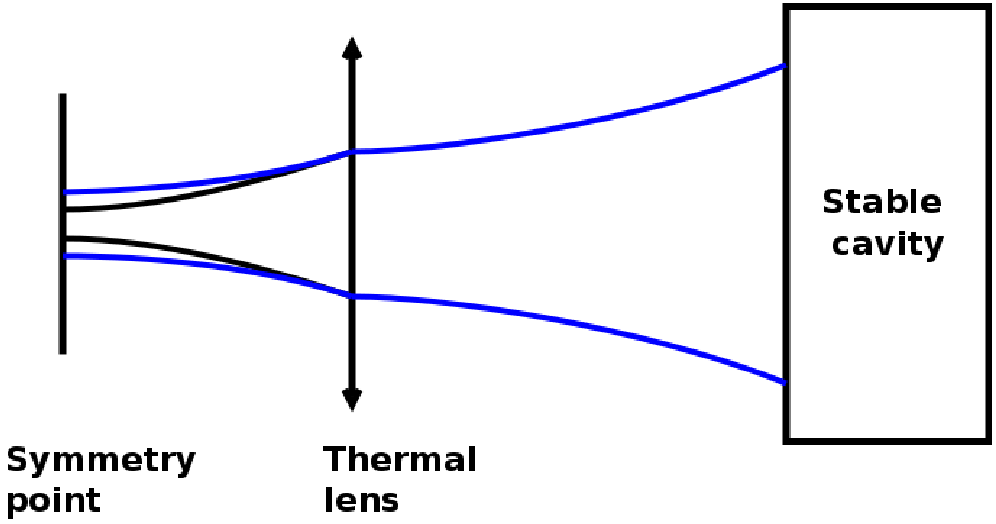


Goals

- Energy: 10 mJ
- Wavelength: 1030 nm (for seeding of the cryogenic Yb:YAG amplifier)
- Repetition rate: 100 Hz – 1 kHz
- Pulse duration: <1 ps after compression

Simulations: Thermal lensing

- **Insensitive cavity against thermal lens**
  - Simulations with Paraxia
  - w_0 constant for f_{th} between 280 mm and > 800mm
  - Possibility of CW and QCW pumping



K. Wentsch et al., Proc. SPIE 7193, Solid State Lasers XVIII, 719301 (2009).

Yb-doped materials

- **Doping: ytterbium ion to match the required wavelength and bandwidth**
- **Comparison of hosts for ytterbium doping:**

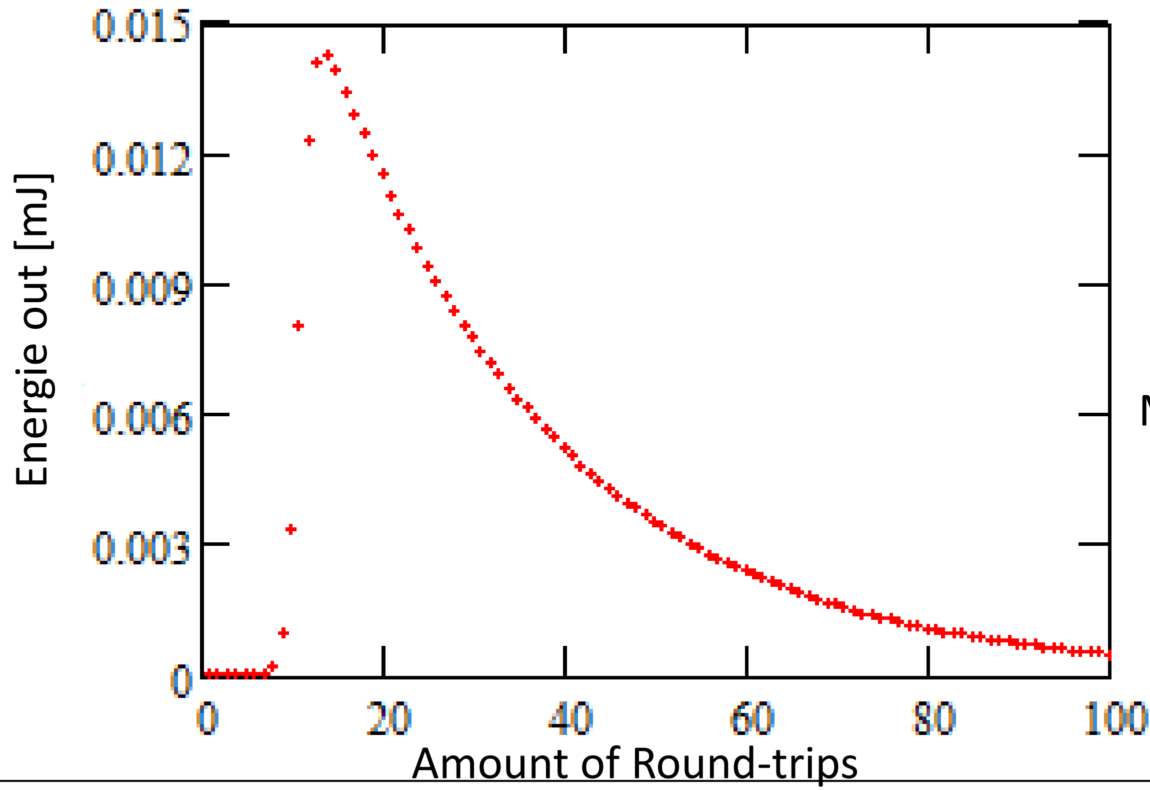
Host	τ_L [µs]	σ_{abs} [10^{-20} cm^2]	σ_{em} [10^{-20} cm^2]	λ_P [nm]	λ_L [nm]	$\Delta\lambda$ [nm]	κ [W K^{-1} m^{-1}]	dn/dT [10^{-6} K^{-1}]
CALGO [1,2]	**420**	1	0.8	979	1030	**50**	**6.3**	?
KYW [3]	320	1.33	3	981	1030	15	3.6	**0.4**
YAG [4]	**950**	0.8	2.1	940	1029	8.5	**11**	10

References:

1. J. Petit et al., Optics Letters, 30, 1345 (2005)
2. S. Ricaud et al., Optics Letters, 36, 4134 (2011)
3. Eksma Website: http://www.eksmaoptics.com/repository/catalogue/pdfai/NLOC/laser%20crystals/YBKGW.pdf
4. Roditi Website: http://www.roditi.com/Laser/Yb_Yag.html

Simulations results: Franz-Nodvik

- **Calculated for Yb:CALGO**

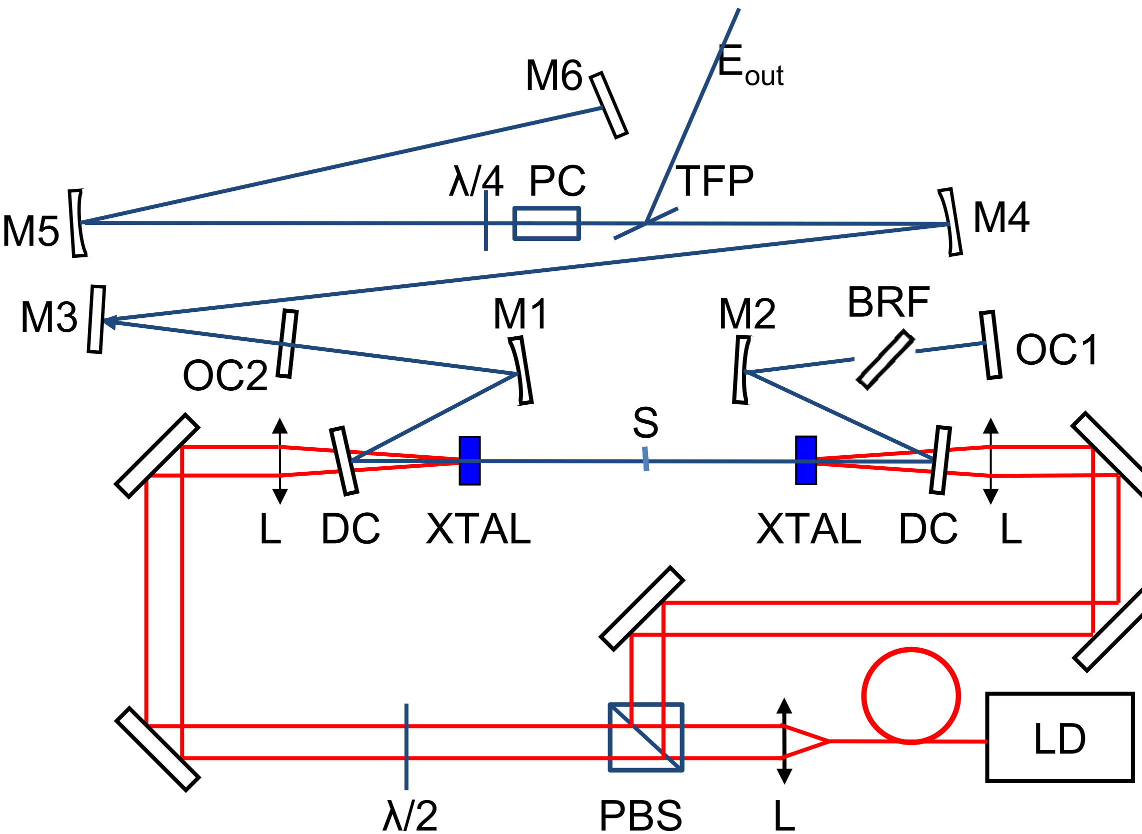


β = 42%

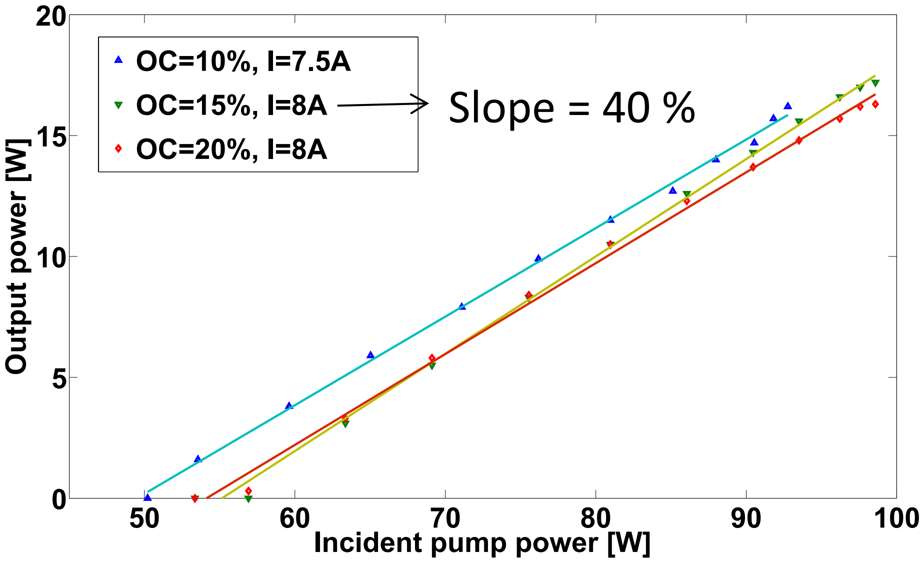
Maximum for ca. 20 RT

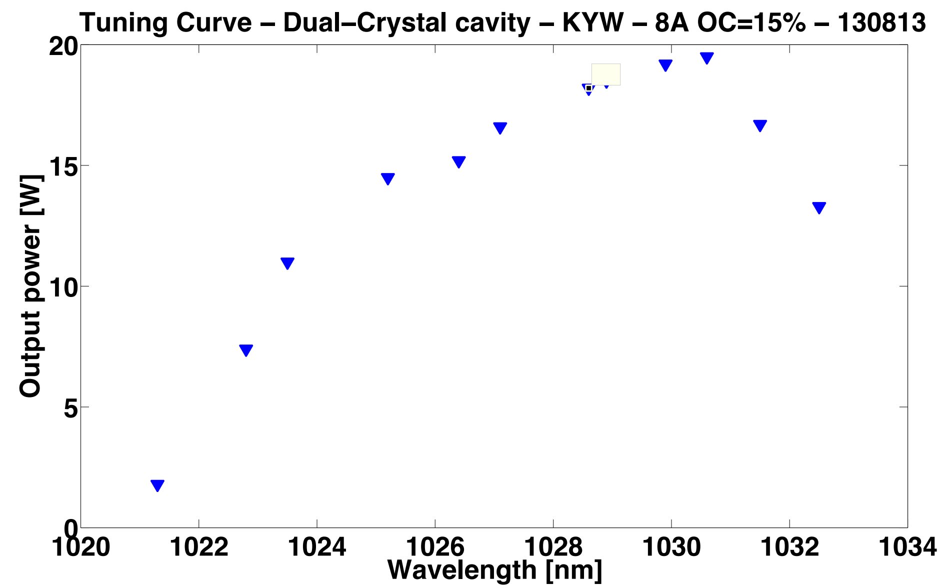
Pump line: Regenerative amplifier

Crystals:
Yb:CALGO
l_c = 2 mm
Doping = 2 %



KYW - Experimental results: CW



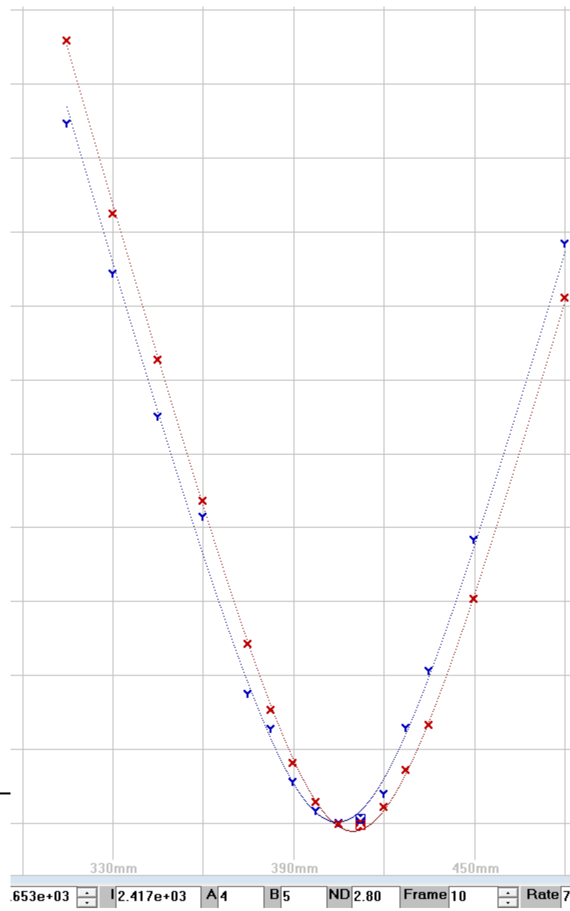


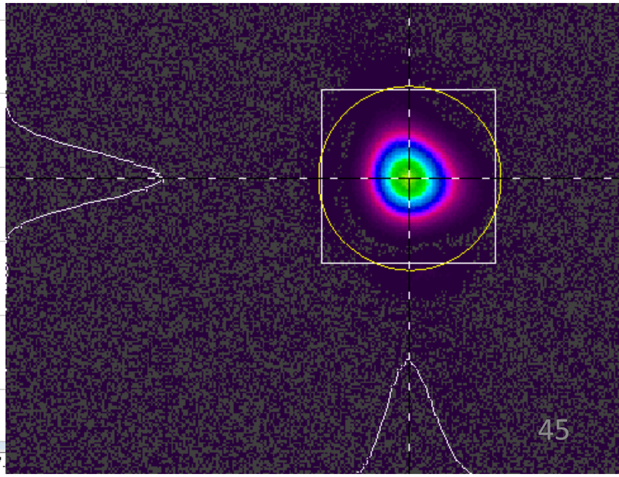
1 crystal, with 7.5% OC – P_{max}= 10.1W with M^2 = 1.1

2 crystals, with 15% OC – P_{max}= 20.4 W with M^2 = 1.1

Experimental results: CW KYW

	Current	Units
Quantitative—4 Sigma		
Total	1,983,842	
Peak	2.436e+03	
Min	-1.088e+01	
Width X	1.985e+02	um
Width Y	2.028e+02	um
Z Location	412.50	mm
Laser—Automated Stepping		
Waist Width X	5.344e+02	um
Waist Width Y	5.762e+02	um
Divergence X*	2.684e+00	mrad
Divergence Y*	2.543e+00	mrad
Waist Loc X	1107.95	mm
BPP Y	3.663e-01	mm mrad
Rayleigh X	199.09	mm
Rayleigh Y	226.63	mm
Astigmatism	0.15	
Asymmetry	1.08	
After Lens		
Number in Run	15	
Waist Width X	1.949e+02	um
Waist Width Y	2.010e+02	um
Divergence X	7.361e+00	mrad
Divergence Y	7.289e+00	mrad
Waist Loc X	409.68	mm
Waist Loc Y	404.43	mm
Rayleigh X	26.48	mm
Rayleigh Y	27.58	mm
Astigmatism	0.19	
Asymmetry	1.03	





CW: 2 Crystals,
OC = 15%
P_{LD} = 123 W

P_{out} = 22.2 W
λ = 1031 nm

Yb:KYW – Thermal lensing

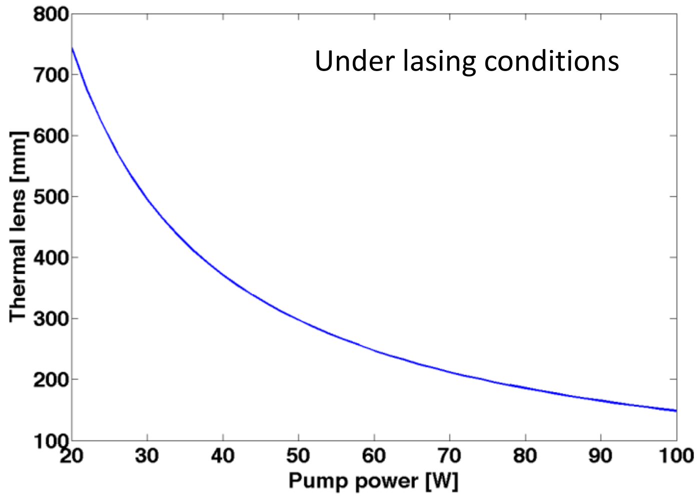
- **For cavity design:** $f_{th} = 300\ mm$
- **From experiment:**
- **According to:**

Thermal lens

$$D_{th,b} = AP_{abs}(1 - \eta_P \eta_r \frac{\lambda_P}{\lambda_F}) \text{ before threshold}$$

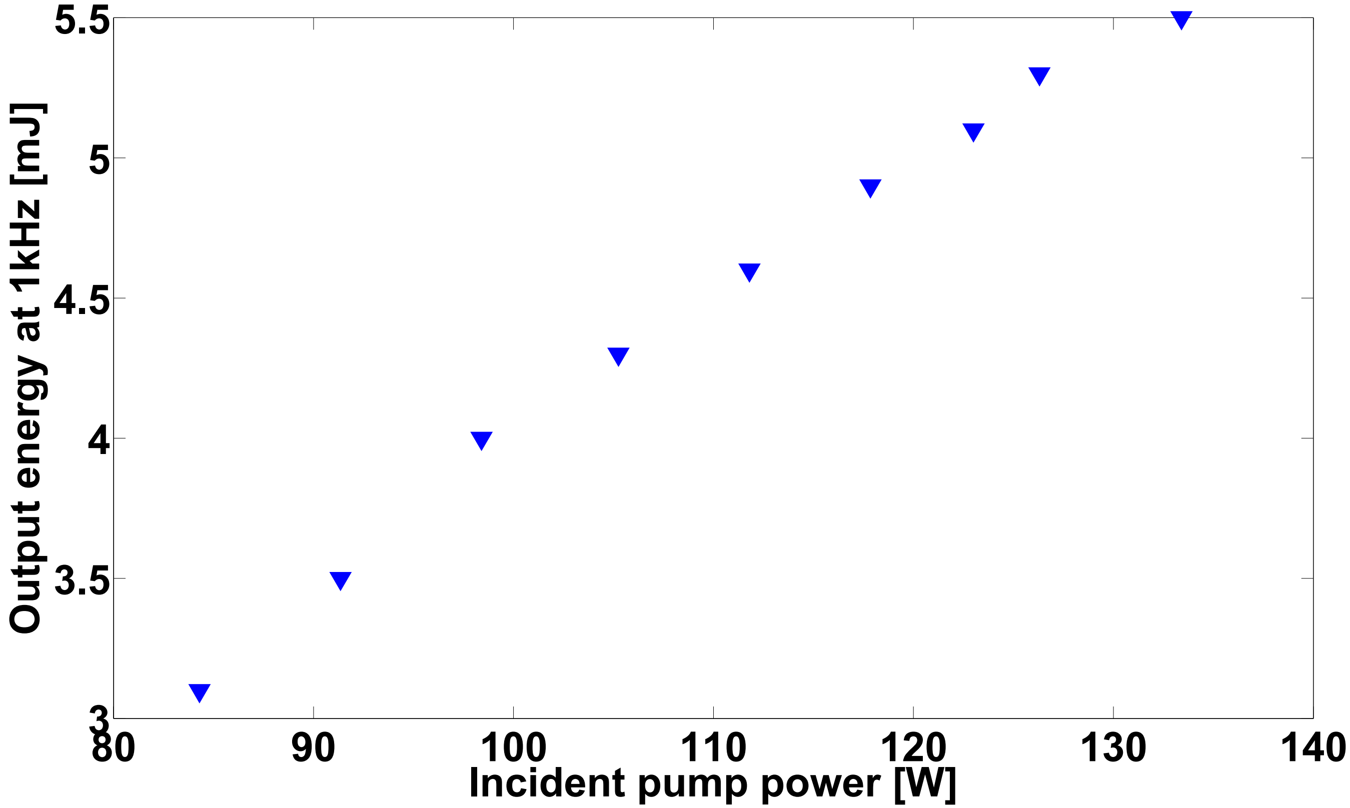
$$D_{th,a} = AP_{abs}(1 - \eta_P((1-\eta_l)\eta_r \frac{\lambda_P}{\lambda_F} + \eta_l \frac{\lambda_P}{\lambda_L})) \text{ after threshold, lasing}$$

$$D_{th,a} = AP_{abs}(1 - \frac{\eta_P \eta_r}{\sigma_{em,L}\frac{I\lambda_L}{hc}\eta_r \tau_{rad}+1}(\frac{\lambda_P}{\lambda_F} + \sigma_{em,L}\frac{I\lambda_L}{hc}\tau_{rad}\frac{\lambda_P}{\lambda_L})) \text{ after threshold, lasing}$$



S. Chenais, IEEE, **40**, 1217 (2004)

Experimental results: Cavity-dumped



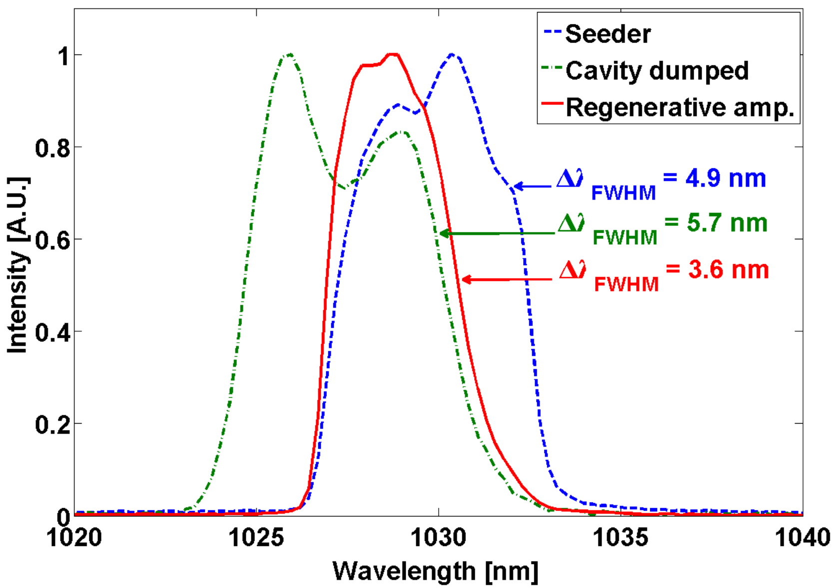
Cavity dumped cavity

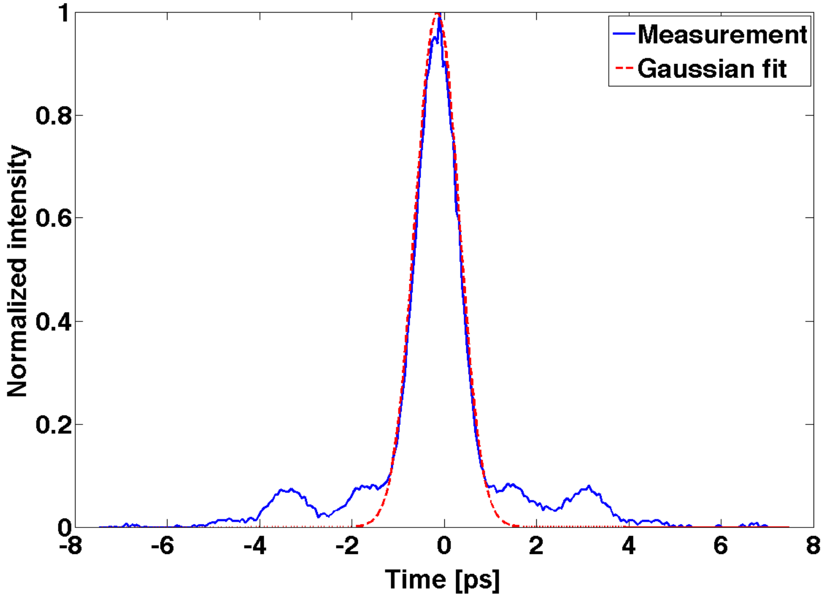
λ = 1025 nm; $\Delta\lambda$ = 2.3 nm

$Gate_{Pumpe}$ = 450 µs

f_{rep} = 1 kHz

Spectra and autocorrelation



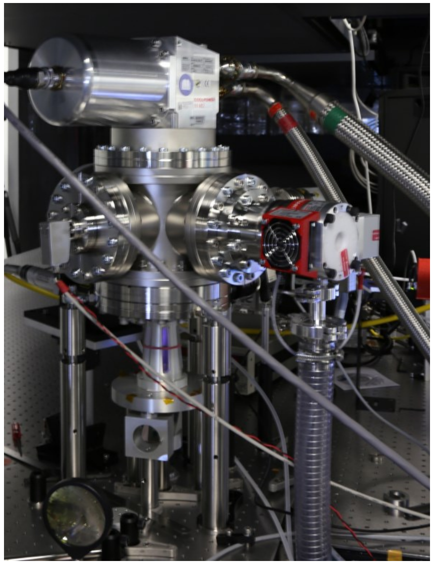


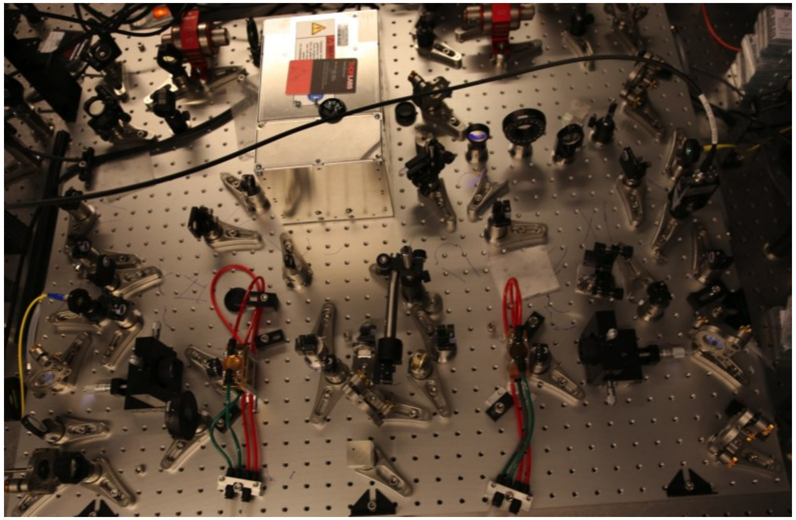
$$\frac{E_{Ped}}{E_{Tot}} = 16\%$$

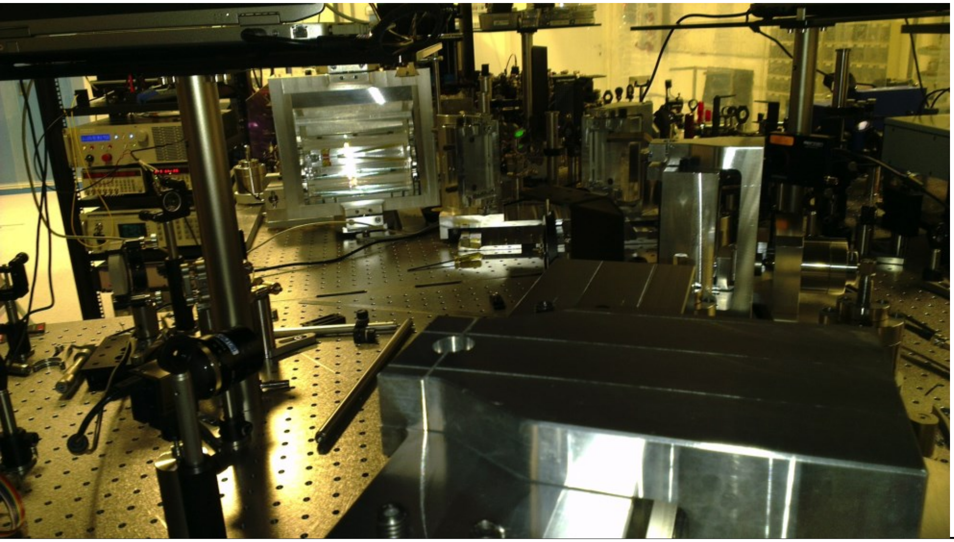
$$\tau_{Gauss,FWHM} = 700\ fs$$

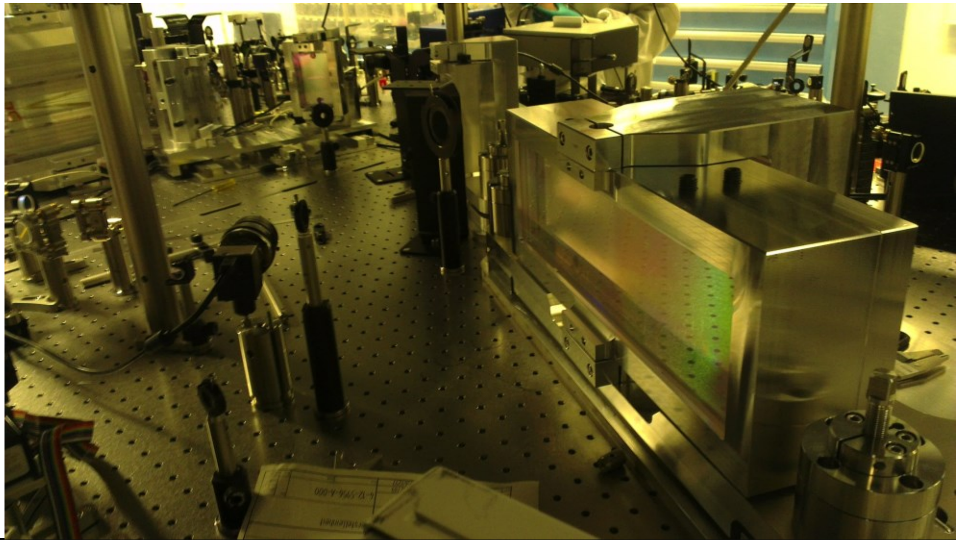
A.-L. Calendron et al., UP 2014 (submitted).

Photos



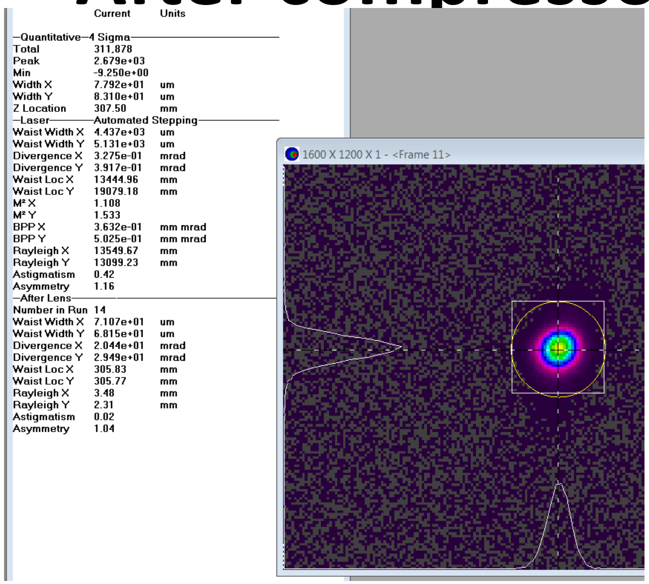


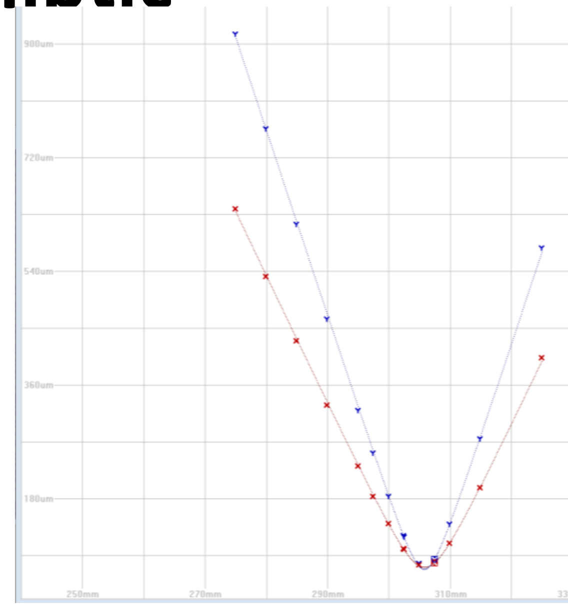




Beam profile

- **After regen: M² < 1.1 , circular**
- **After compressor: Elliptic**

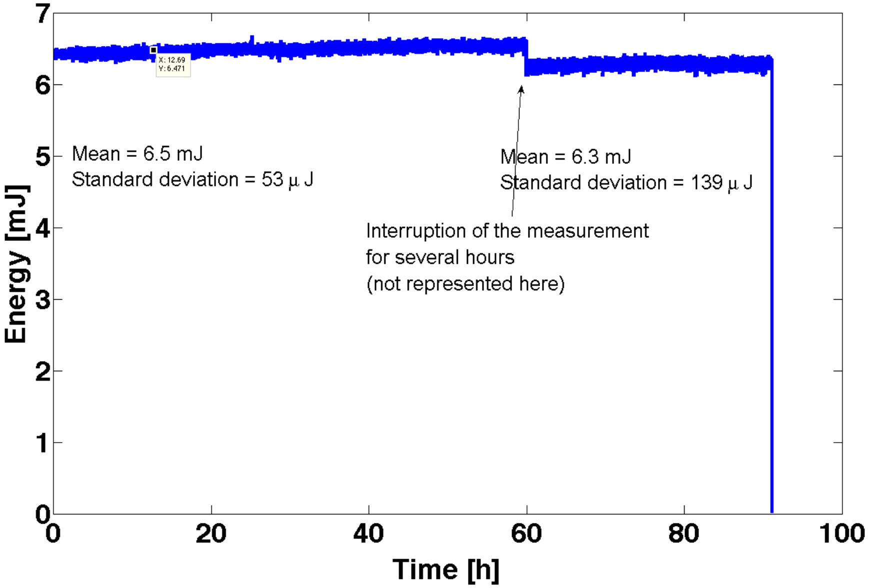


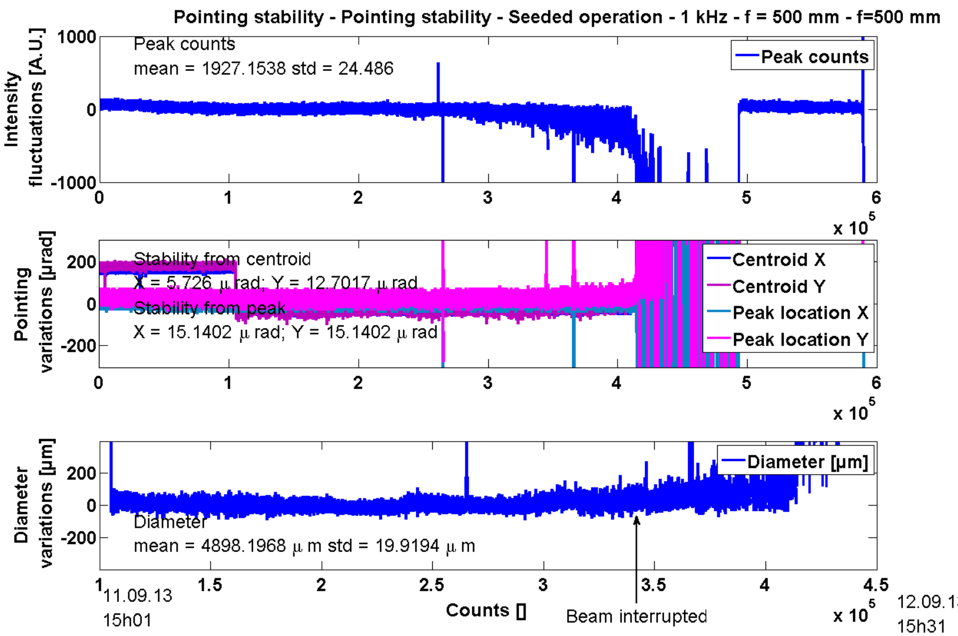


=> Cylindric lenses to compensate

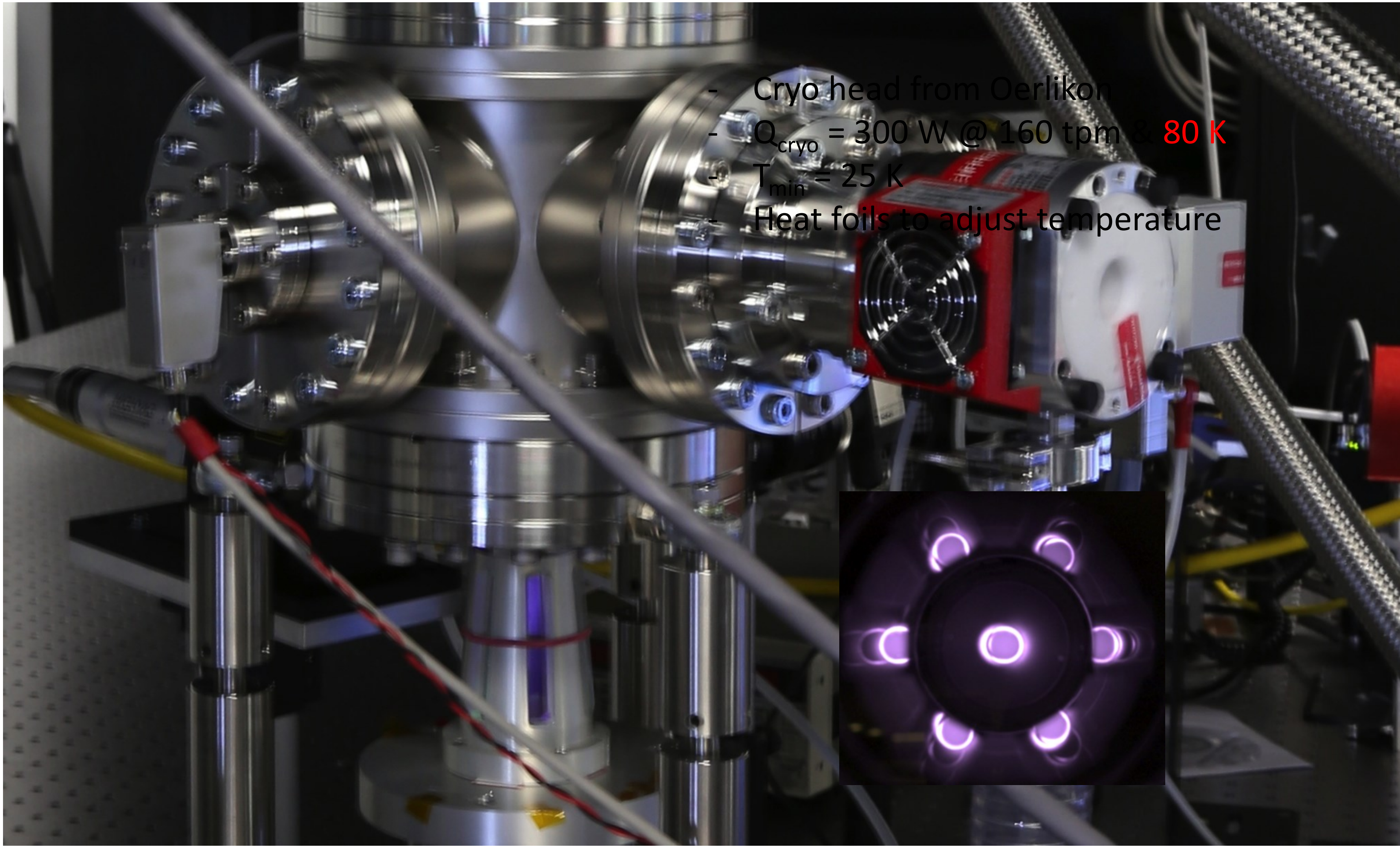
Stability of the regen.

Long term measurement of the seeded regen @ 1kHz -
Interruption for several hours then change of the attenuation -



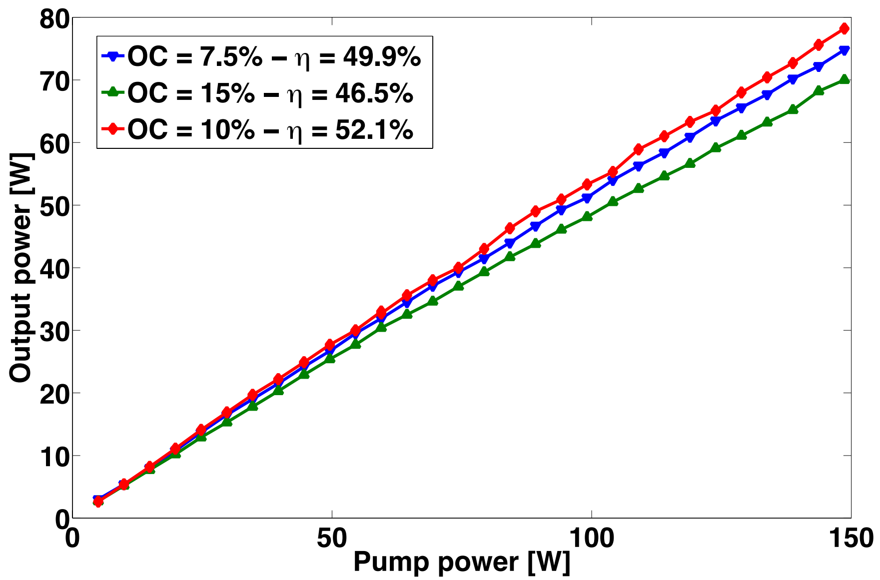


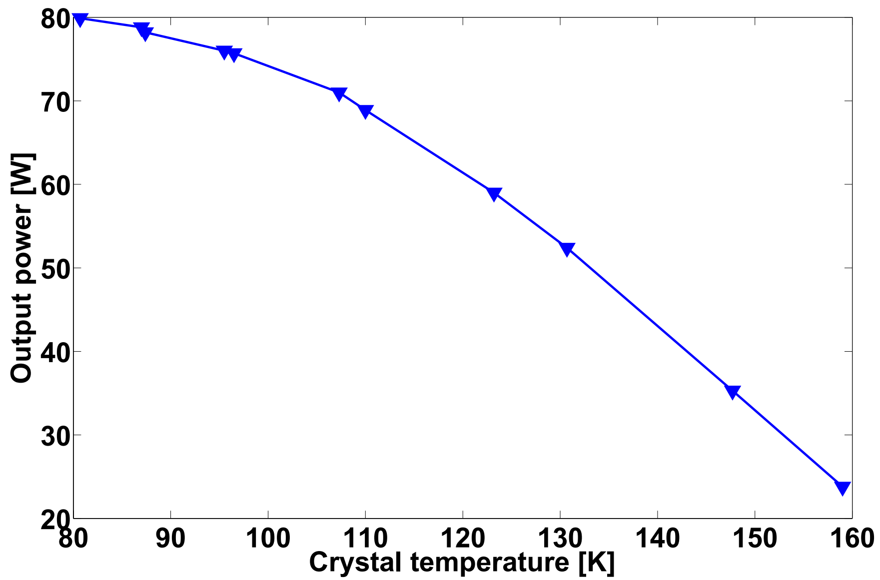
Cryo multi-pass amplifier



- Cryo head from Oerlikon
- Q_{cryo} = 300 W @ 160 tpm & 80 K
- T_{min} = 25 K
- Heat foils to adjust temperature

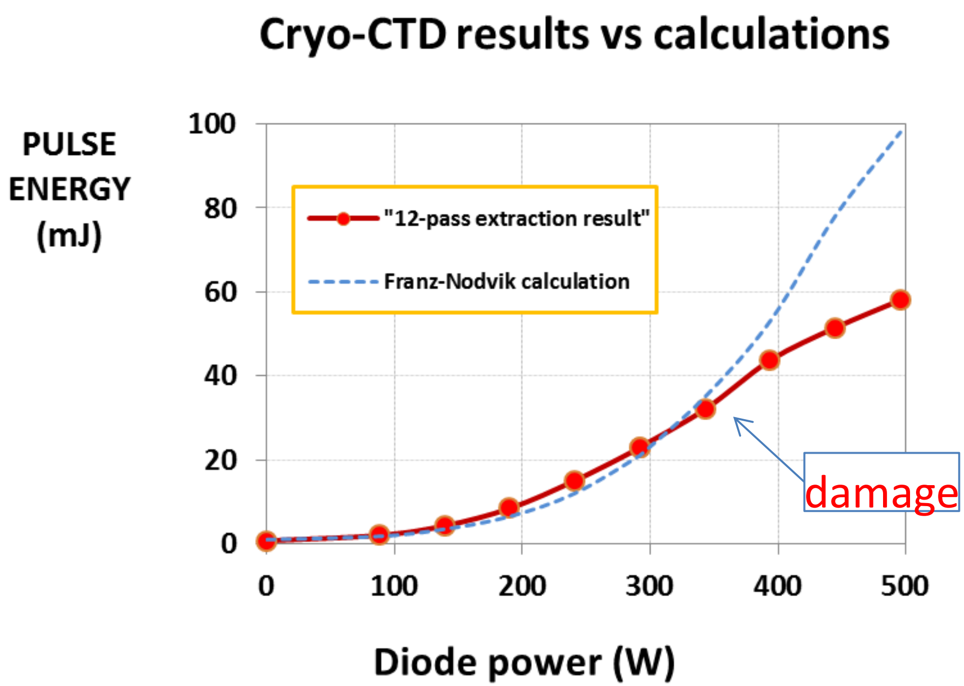
Extracted power

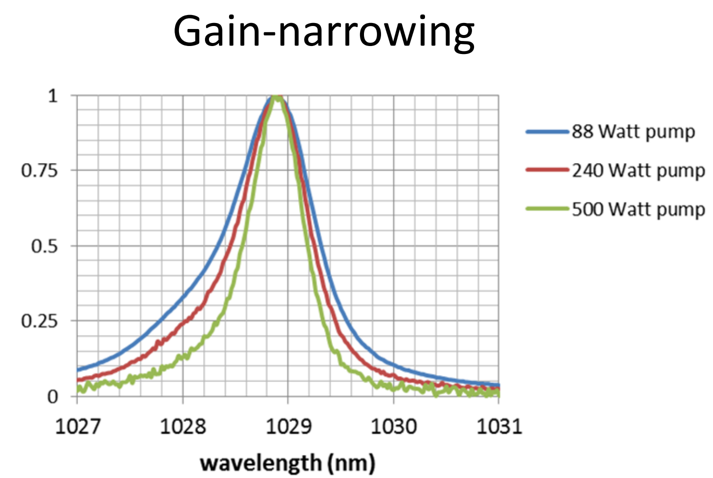




A.-L. Calendron et al., Hilas 2014.

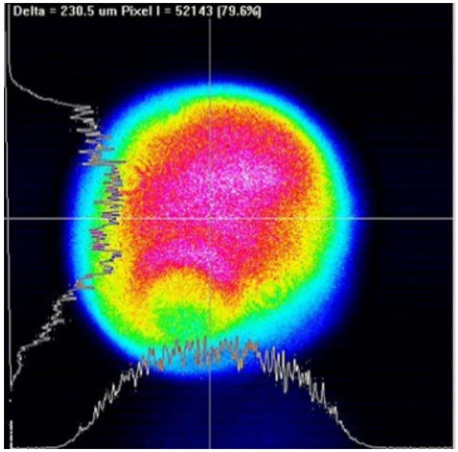
MIT Results





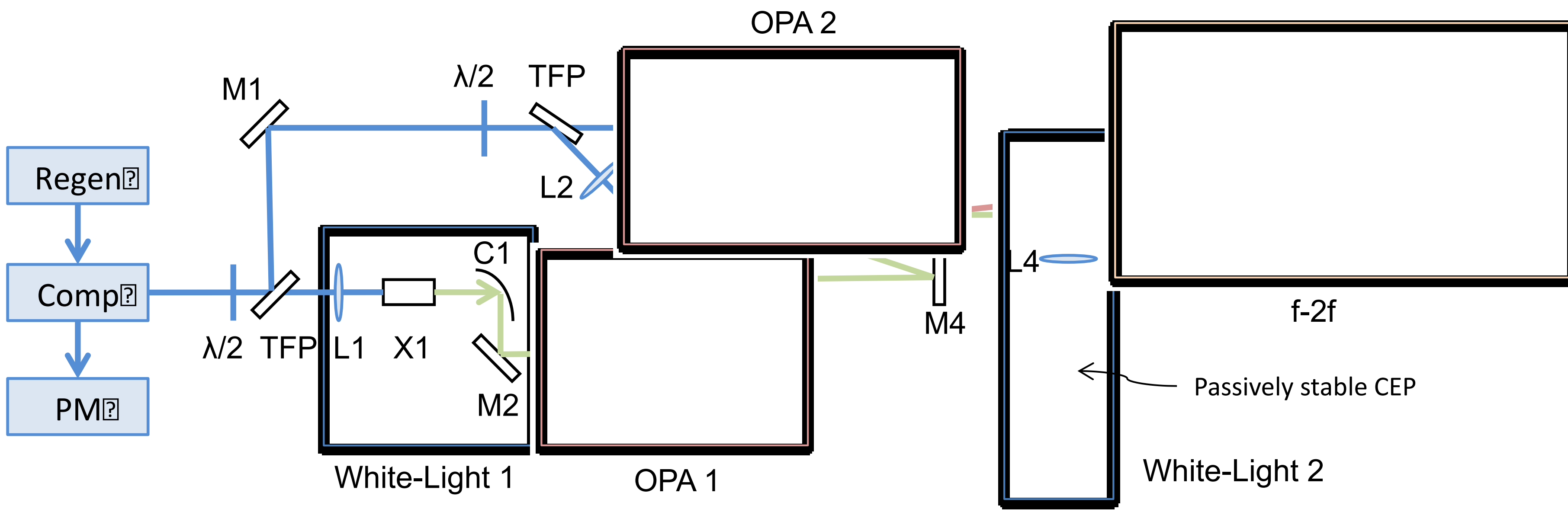
Beam quality at 60 mJ, 200 Hz →

- Damage sustained ~45 mJ
- 200 ps pulse duration

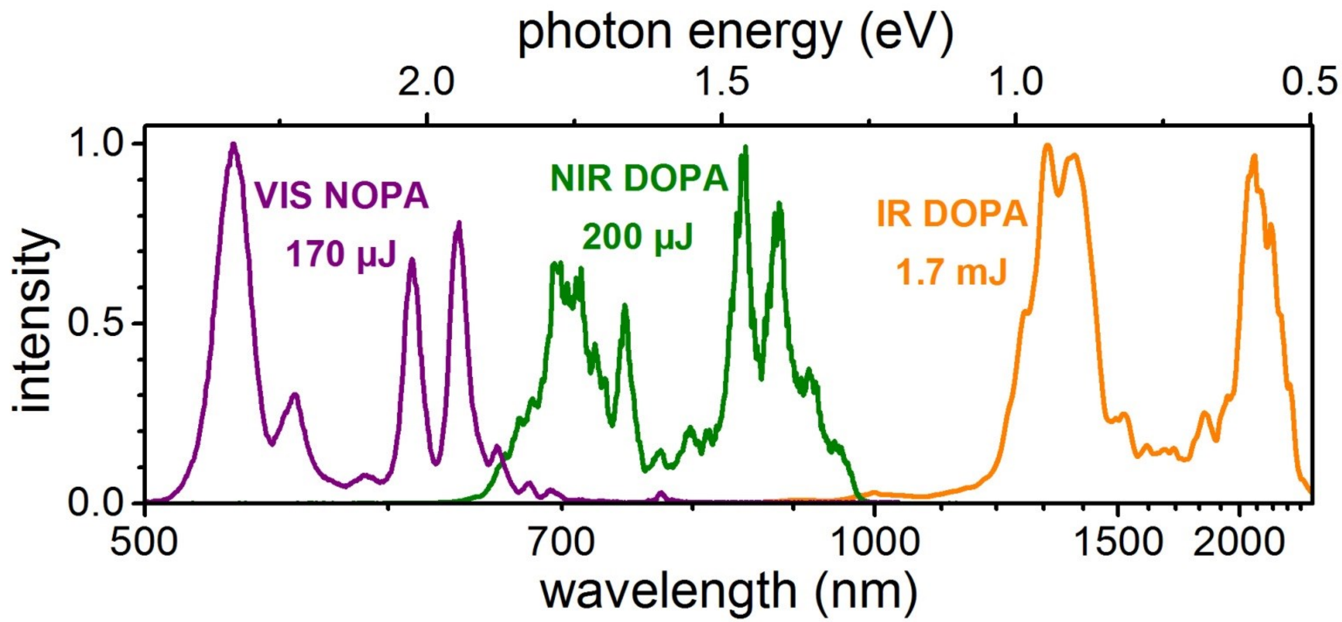


L. Zapata et al., ASSL (2013)

Front end: General layout



3rd stage



VIS NOPA	NIR DOPA	IR DOPA
0.17 mJ signal	**0.20-0.25 mJ signal**	**1.7 mJ octave-spanning signal**
20% (0.8 mJ pump) pump-signal conversion efficiency	**12-15%** (1.7 mJ pump) pump-signal conversion efficiency	**22%** (7.7 mJ pump) pump-signal conversion efficiency
TL 5.6 fs	TL 5.2 fs	TL 5.2 fs
2.9 optical cycles @ λ_c=573nm	2.1 optical cycles @ λ_c=750nm	1.1 optical cycle @ λ_c=1.4um