Ultrafast lasers for demanding applications: State of the art and ongoing prospects

Henry C. Kapteyn
JILA, University of Colorado and KMLabs Inc.

Fermilab 9-2013

Kapteyn-Murnane Research Group @ JILA

Prof. Margaret Murnane
- National Academy of Sciences
- Chair, President's Committee for the US National Medal of Science
- NIC Committee
- Assoc. Director of EUV ERC
- MacArthur Fellow 2000
- Zewail Award ACS 2009
- OSA, APS Fellow

Prof. Henry Kapteyn
- National Academy of Sciences
- OSA Fellow
- Schawlow Award APS, Wood Prize OSA 2010
- Adolph Lomb Medal 1993
- Sloan Foundation Fellow

Murnane-Kapteyn Research Group
- Based at JILA, University of Colorado, Boulder, USA
- ~30 students and postdocs
- First group to develop a reliable 10 femtosecond laser
- World-Leaders in ultrashort-pulse, ultrahigh-intensity lasers
- NSF Engineering Research Center (ERC) for Extreme Ultraviolet (EUV) Science and Technology

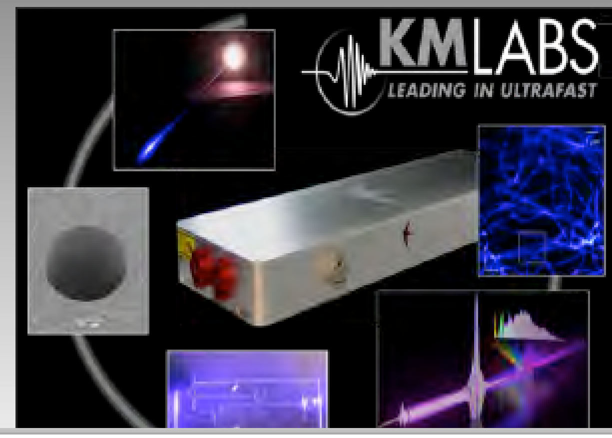
JILA AMO Physics Center

EUV

KMLABS inc. LEADING IN ULTRAFAST

KMLabs Inc.

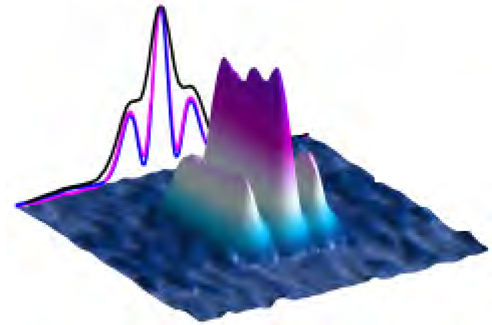
- Founded in 1994 - bootstrapped
- Boulder, CO, ~35 employees
- Delivers advanced laser systems worldwide
- Scientific market
- Now developing OEMs for larger markets



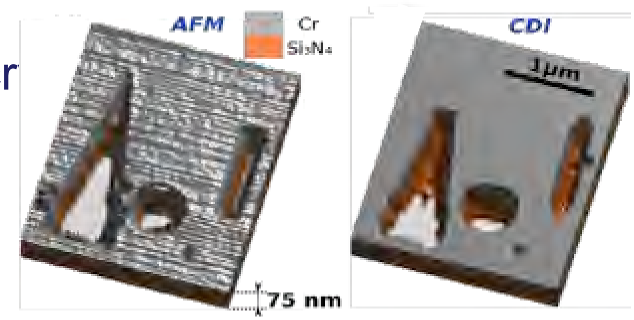

The latest photonics industry news in the palm of your hand
LaserFocusWorld Mobile Apps
DOWNLOAD TODAY
LaserFocusWorld
Optics,Coatings,Mechanics,Motor Stages
HOME | BROWSE BY TOPIC | BUYERS GUIDE | PRODUCTS | BUSINESS CENTER | EDUCATION | RESOURCES | VIDEO | MOBILE | JOBS
Home > More Photonics Business Articles > KMLabs wins 2013 CLEO/LFW Innovation Award; three honorable mentions named
KMLabs wins 2013 CLEO/LFW Innovation Award
04/23/2013
Posted by Gail Overton
Senior Editor
iPhone iPad Android
Sponsor Information

Outline

- **Commercial state of the art in ultrafast lasers—**
  – Cryogenically-cooled ti:sapphire

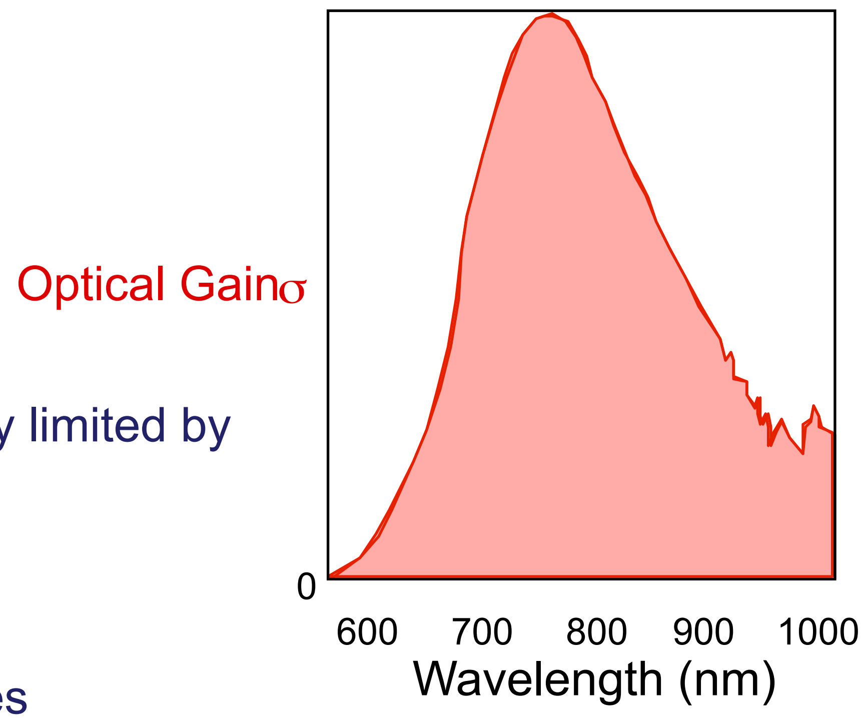


- **Next generation–**
  – direct diode pumped
  – Parametric frequency conversion into mid-IR
  – Combining fiber laser technology with high power cr simple and powerful



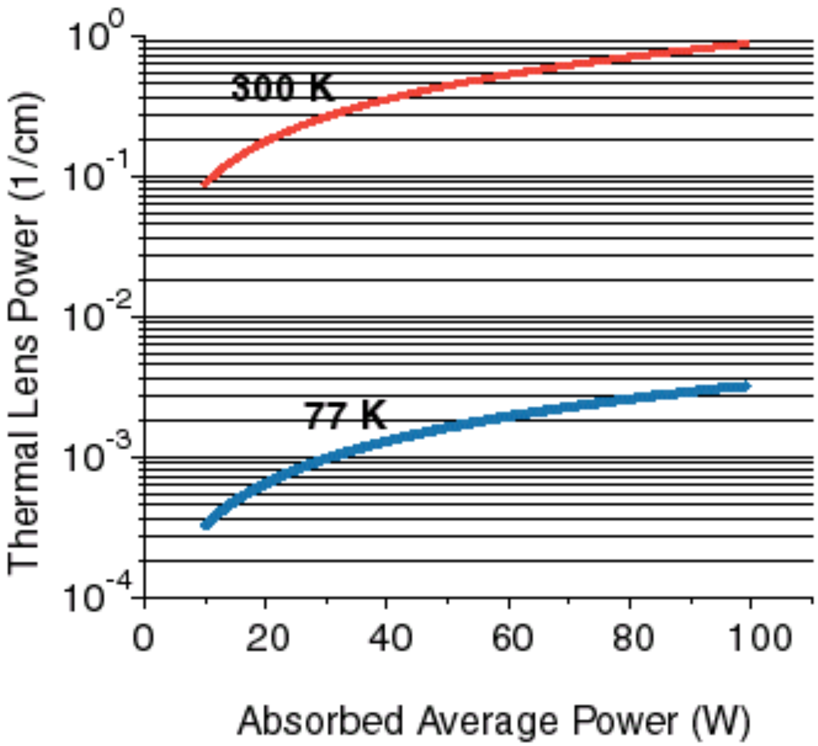
Commercial state of the art in ultrafast

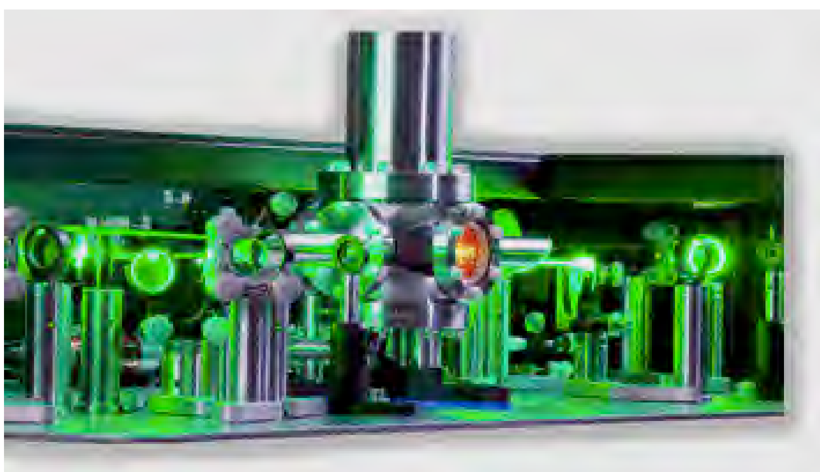
- **Cryogenically cooled ti:sapphire**
  - Bandwidth 230 nm FWHM
    - 3 fs transform limit
  - Energy extraction ~1 J cm^{-2}
- **Typically pumped with 532 nm**
  - Average power performance primarily limited by pump lasers
- **Excellent thermal properties**
  - Even better at cryogenic temperatures
  - Low gain cross section requires high energy density
- **Typical high-energy gain-narrowed pulse duration 20-40 femtoseconds**



from Moulton, JOSA B(3), p. 125 (1986)

Cryogenic cooling for ultrafast ti:sapphire lasers

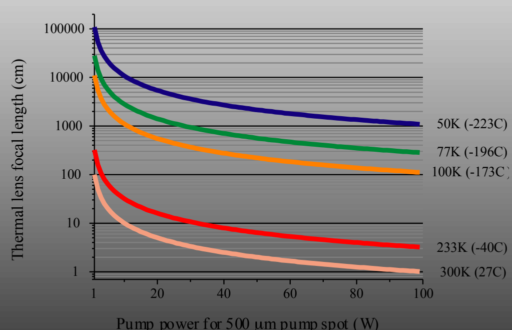


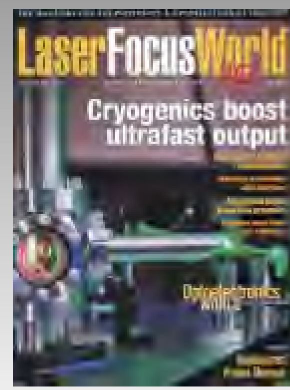


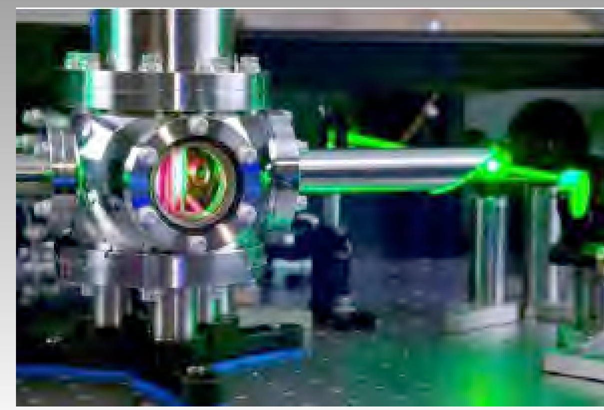
- **Cryocooling reduces thermal lens by ~250x:**
  - At 300 K, 100 W, f=0.012 m
  - At 77 K, 100 W, f=2.85 m
- **Allows high gain, broad bandwidth amplification**
- **Small-scale 10-50 W systems**
- **Scaling: 532 nm lasers used in flat-panel annealing**
  - 100->200->3200W

High Performance Ultrafast Amplifiers
- Robust, Scalable, Versatile -

- Low maintenance cryo cooling
- Power to 50W
- Pulse energy to 30mJ
- < 25fs to > 100fs
- 1 to 500 kHz
- Software control of rep. rate, energy, power



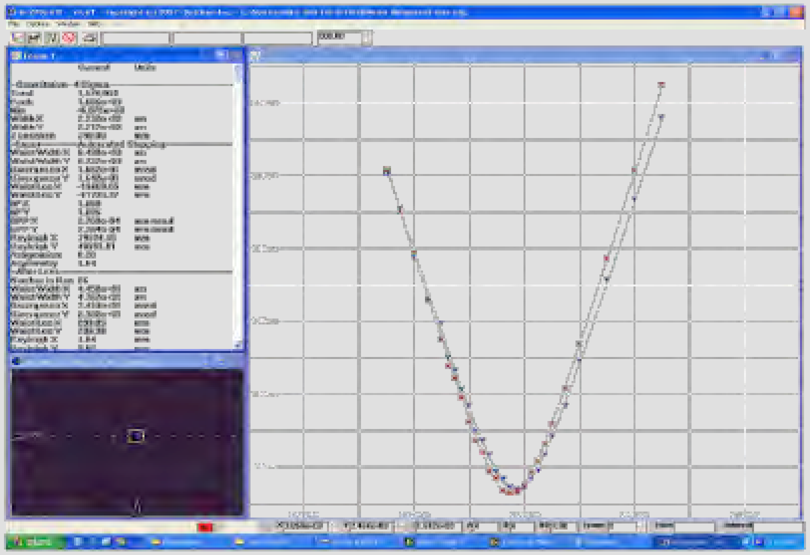




KMLABS LEADING IN ULTRAFAST

Wyvern 1000 series–

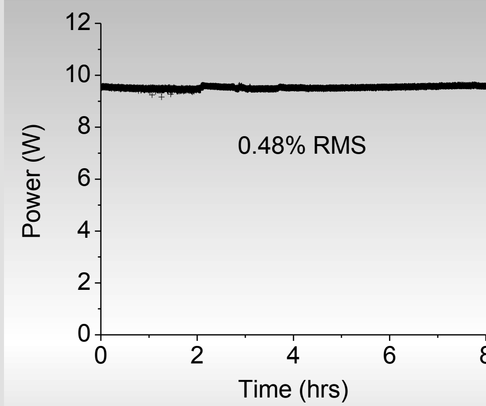
- Cryogenically-cooled Ti:Sapphire regenerative amplifier
  - ~60x180cm
- Pumped by robust and cost-effective Nd:YAG laser
- Obtainable Performance:
  - 5 kHz
    - Up to 3.5 mJ
    - 13.5 - 17.5 W
    - M^2 1.07
  - 3 kHz
    - 3.7 - 4 mJ
    - 11 - 12 W
    - M^2 1.07

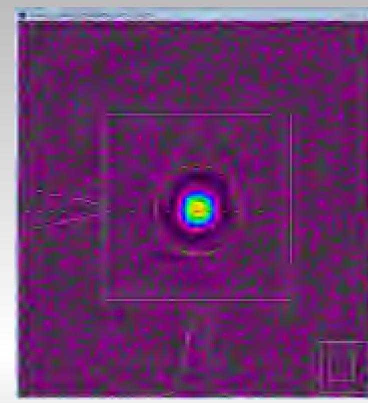


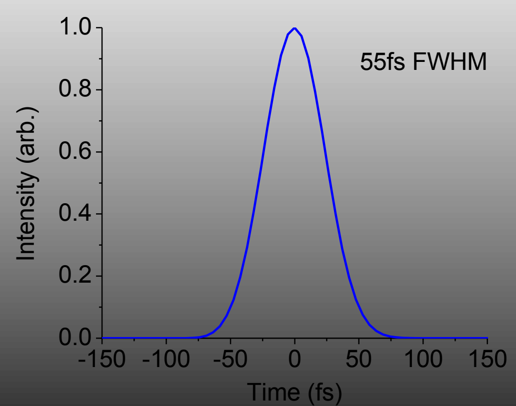
- No thermal lens– rep rate adjustable up to >15 kHz

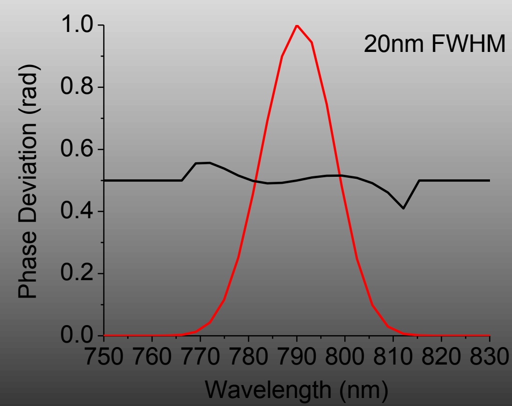
Wyvern 500 series– the first 30-50 kHz ultrafast ti:s systems

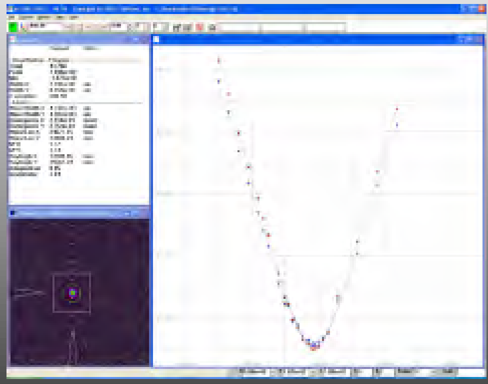
- Cryogenically-cooled Ti:Sapphire regenerative amplifier
- Pumped by pulsed $Nd:YVO_4$ laser
- Rep-rate adjustable from 10 to 50 kHz
- Performance at 30 kHz:
  - >9.6 W output power
  - $M^2 \sim 1.15$
  - >320 μJ
  - 55 fs







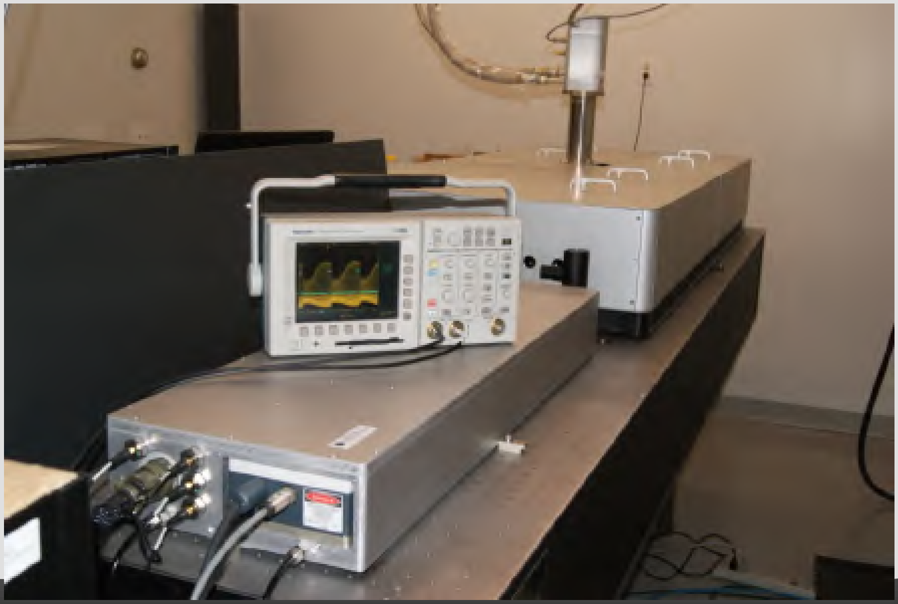




DOE SBIR Phase II: Laser System Development for ILC Photoinjector

- Project complete, laser delivered to SLAC, 2010
- Tunable 1.5-3 MHz laser for ILC photonjector
    - 1.5-3 MHz repetition rate
    - 3 μJ energy, ns-duration "square" pulses
    - Tunable around 780 nm (for spin polarized GaAs photocathode)

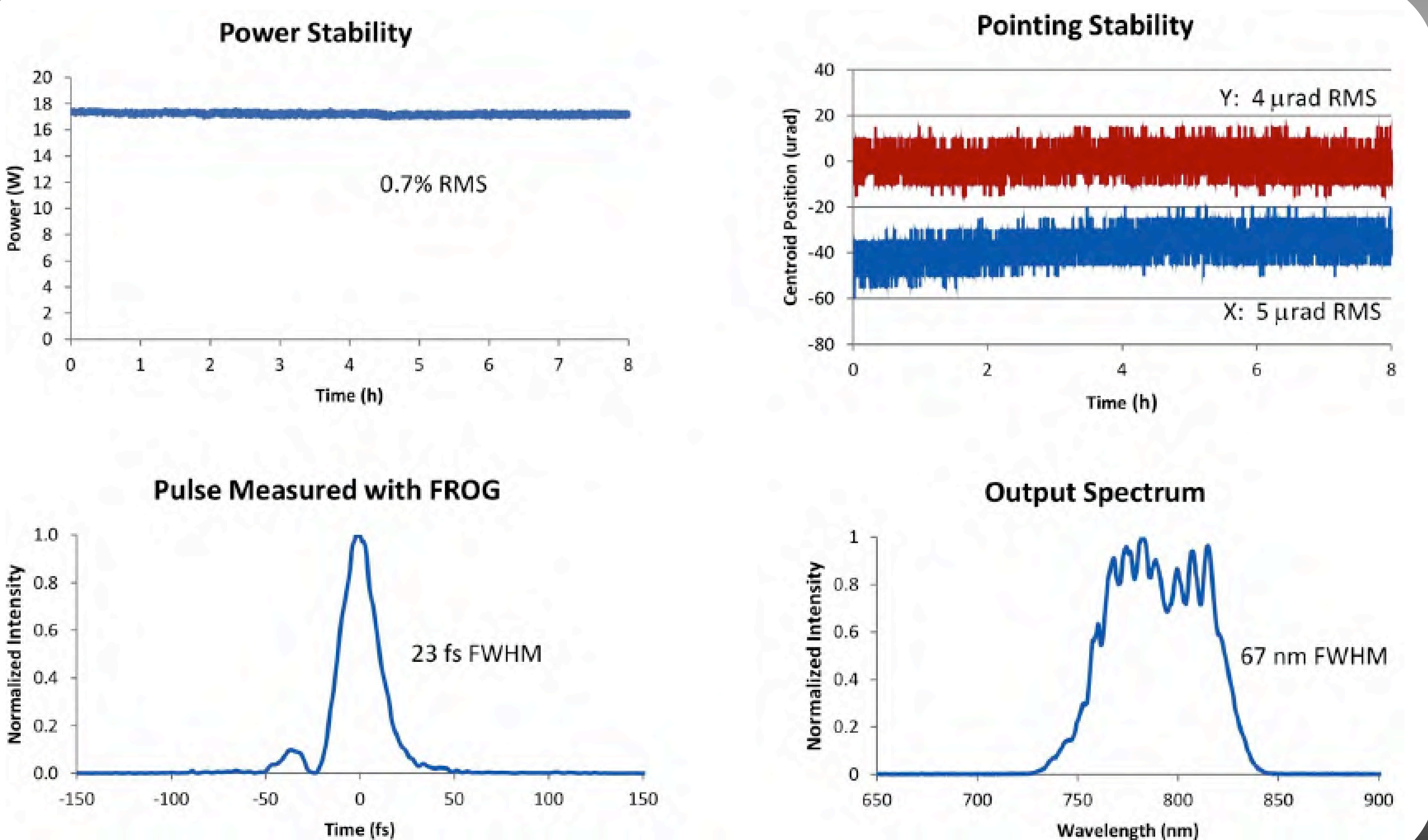
Rep Rate (MHz)	Power (W)	Energy (μJ)
0.2	9.0	45.0
0.5	8.1	16.1
0.7	7.8	11.1
1.0	7.1	7.1
1.5	6.2	4.1
3.0	4.5	1.5



Higher energies: multistage amplification--

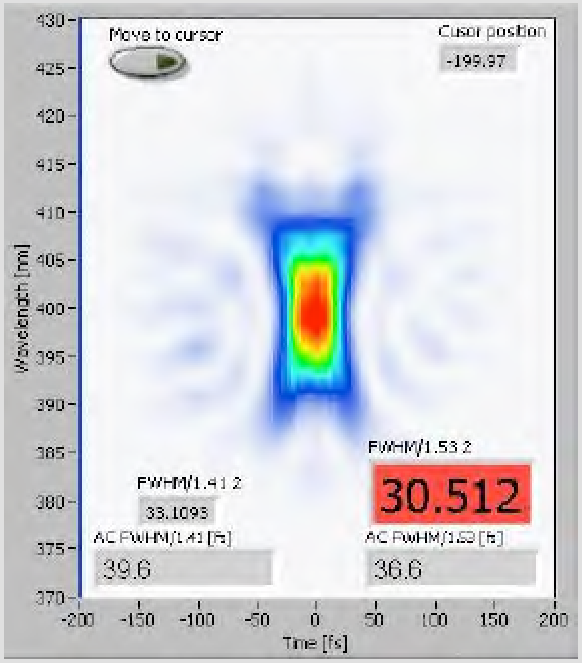
- "Red Dragon"
- 6.4 mJ, 5 kHz repetition rate

First TW/kHz: Red Dragon™ 20 mJ, 1 kHz



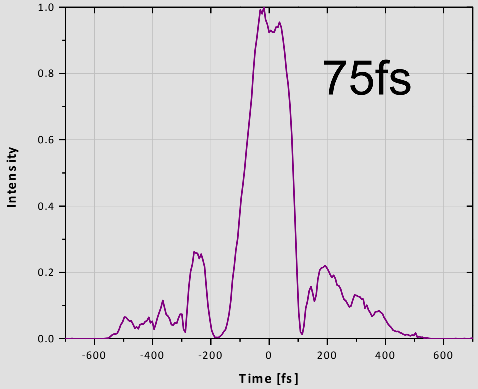
20 mJ/ 1 kHz Second and Third Harmonic

- 400 nm SHG
  - 8 mJ output
  - 30 fs pulse
  - Excellent mode quality

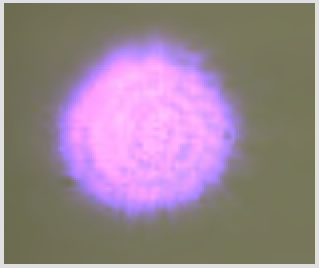


- 270 nm THG
  - 2.6 mJ

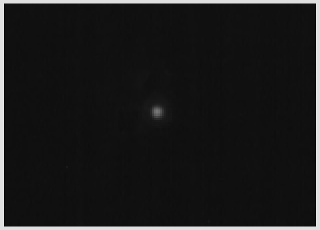
Pulse measured with SD Frog



Far field output mode

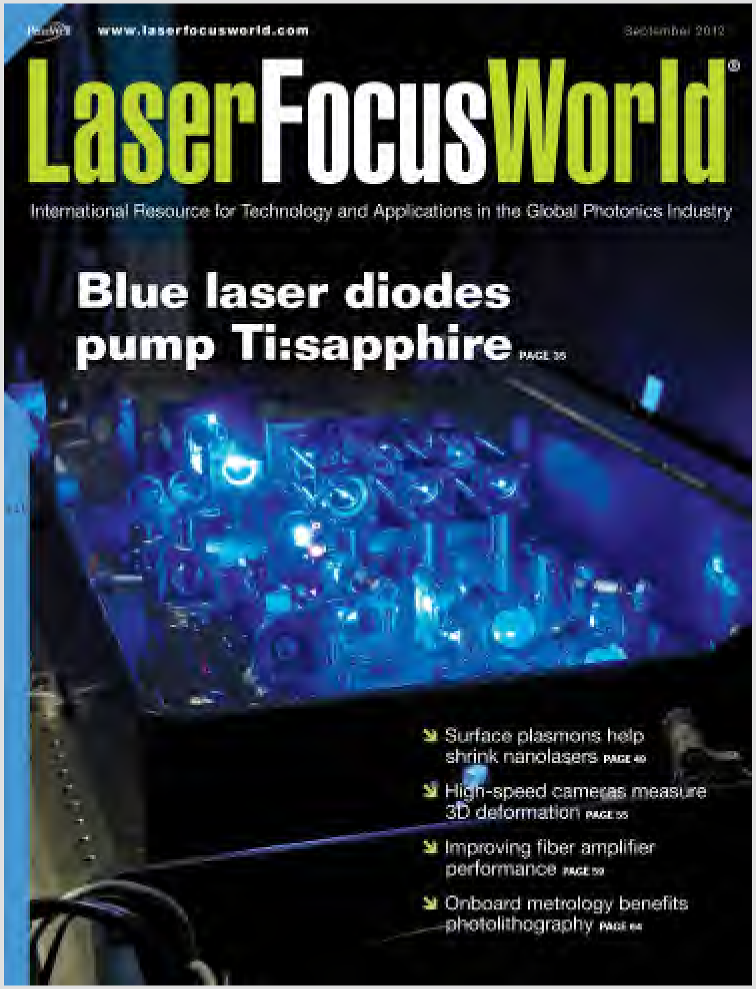


At Focus



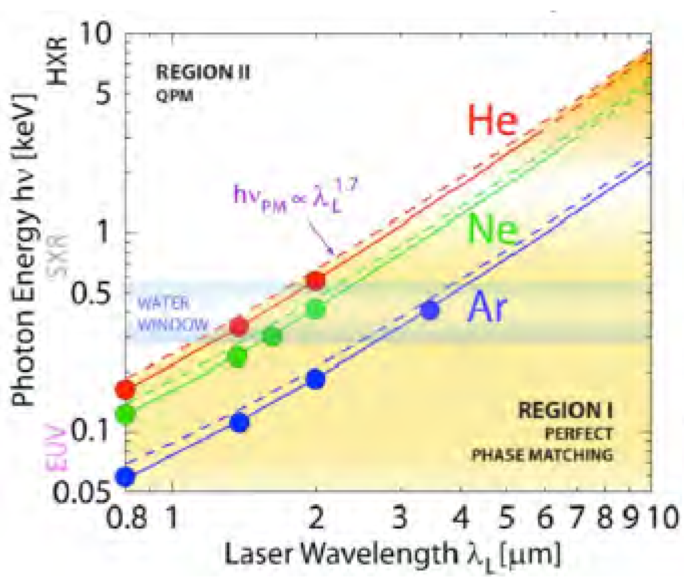
Ti:Sapphire development– First Diode-Pumped fs Ti:Sapphire

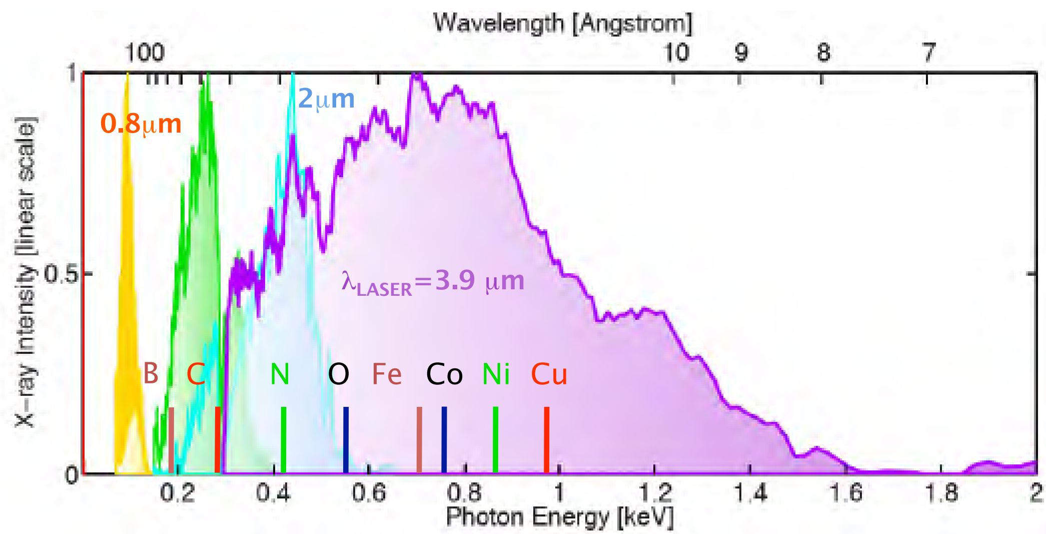
- Use 445 nm diodes
  - 3 diodes -> 5 W to crystal
  - 60% (3W) absorption
- 120mW KLM mode-locked
- ~15fs pulse width
- Technology extensible to high power amplifiers as technology advances
  - Higher power per diode
  - Fiber coupling



Research: Direct diode-pump Yb-based ultrafast lasers

- **Interest:**
  - Efficient small-scale generation of femtosecond pulses in mid-IR
- **Start with 1 μm Yb system**
- **Parametric conversion (OPCPA) to 1.5-4 μm**

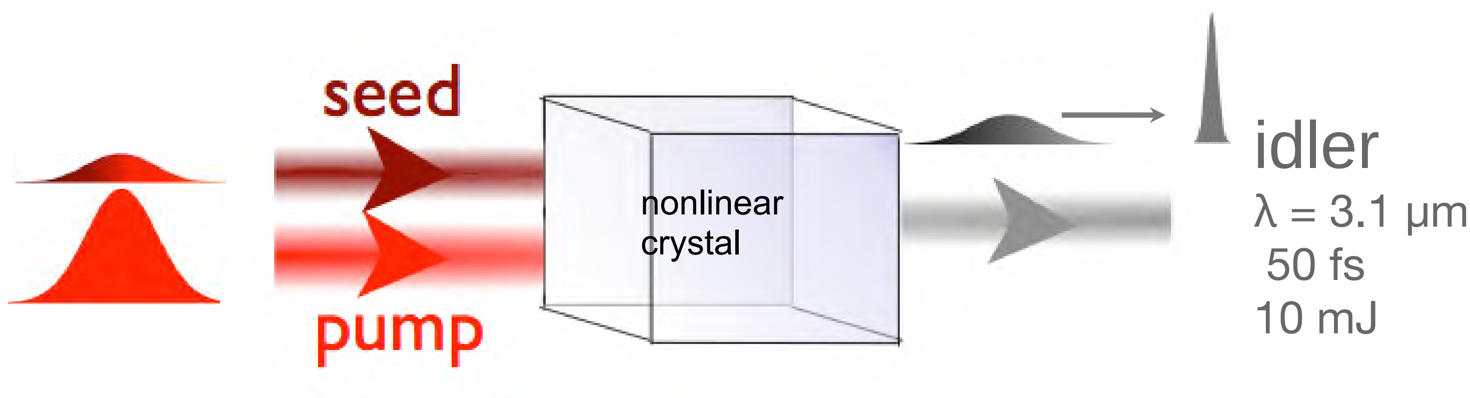




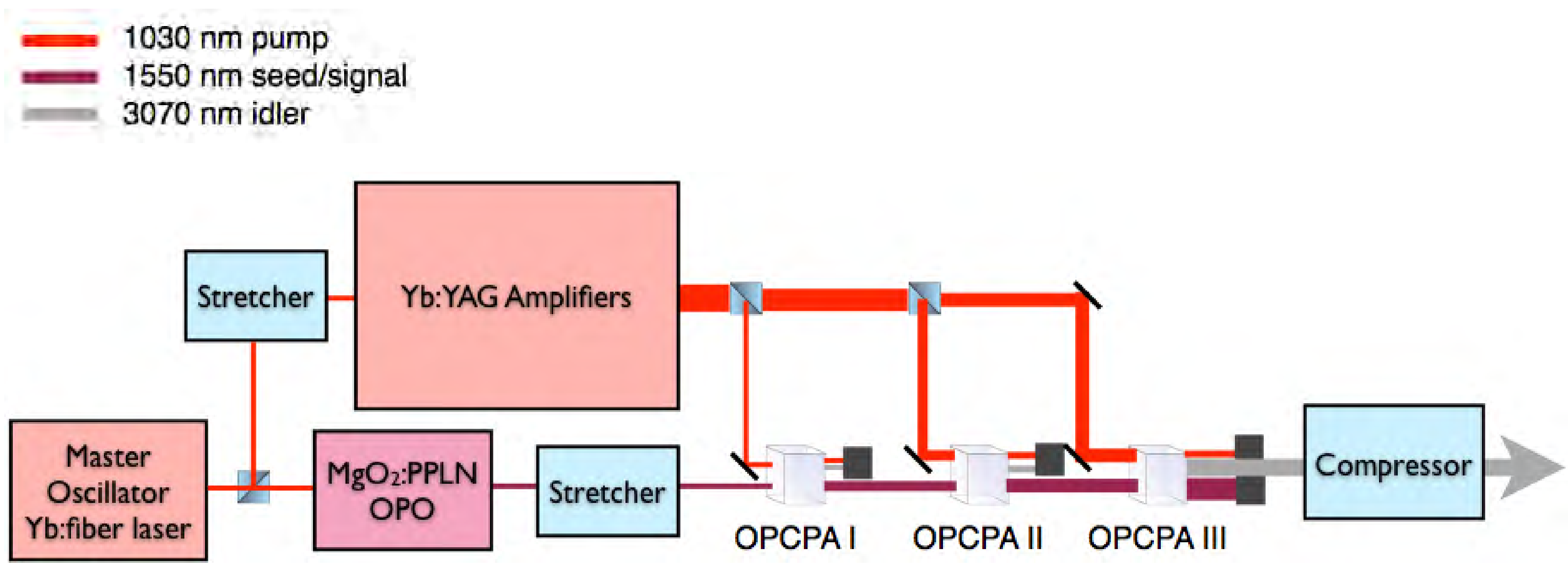
(Science ***336***, 1287 (2012)), ***Popmintchev et al.*** *Opt. Lett.* ***33***, *2128 (2008); PNAS* ***106***, *10516 (2009); PRL* ***105***, *173901 (2010);Nature Photonics* ***4***, *822 (2010);**Midorikawa,** PRL* ***101***, *253901 (2008)*

Goals

- **MIR light, 3-4 μm wavelength idler**
- **Short pulses: ≈ 50 fs**
- **Enough energy for HHG in He: ≈10 mJ**
- **High rep. rate: 1-100 kHz**

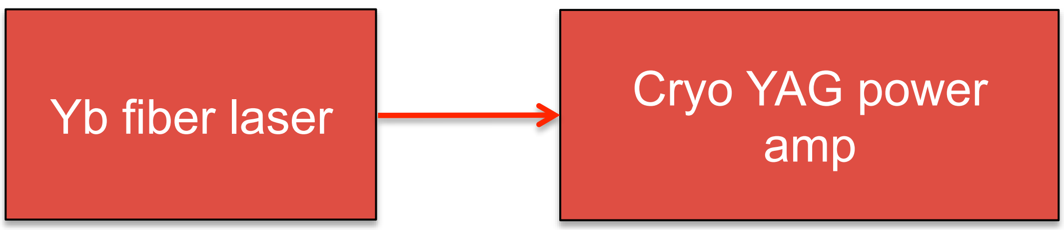


OPCPA Architecture



Cryocooling for Yb:YAG

- **Diode-pumped cryo Yb:YAG >75% efficient**
  - 50% routine for USP amplification
- **4-level laser; 9% quantum defect**
  - ~1/3 that of ti:s– reduced cooling capacity
- **High gain, match of saturation fluence and damage allows simple architectures:**

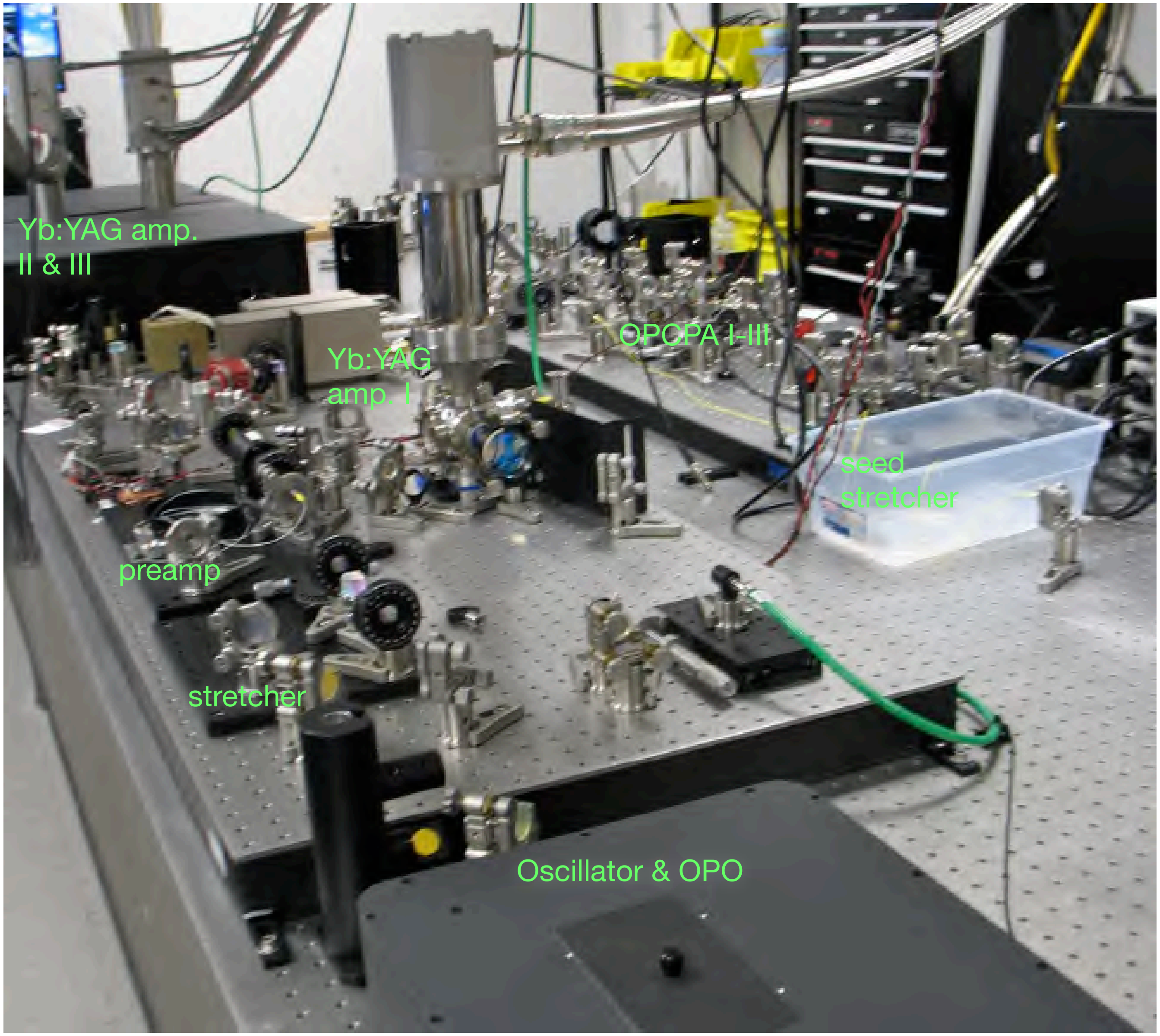


5 W 10 MHz (0.5 µJ)
~25 x 50 x 10 cm

50-500 W 10 MHz (5-50 µJ)
25 x 50 x 20 cm + comp

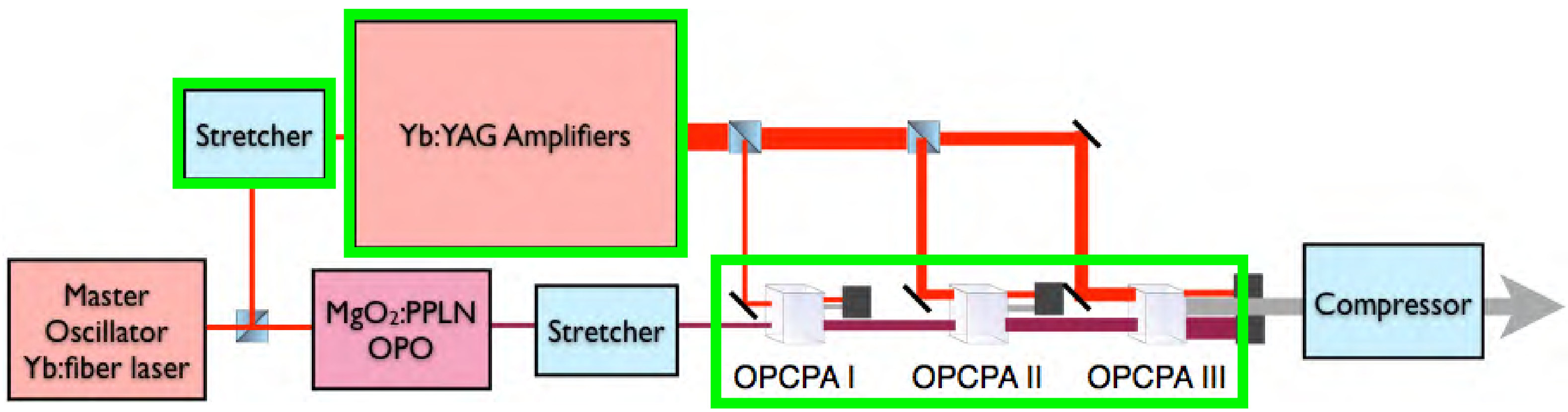
- **Also Yb:CaF_2 (Yb:YLF)**
- **Cryocooling is "compatible" with macropulse formats**

OPCPA Architecture



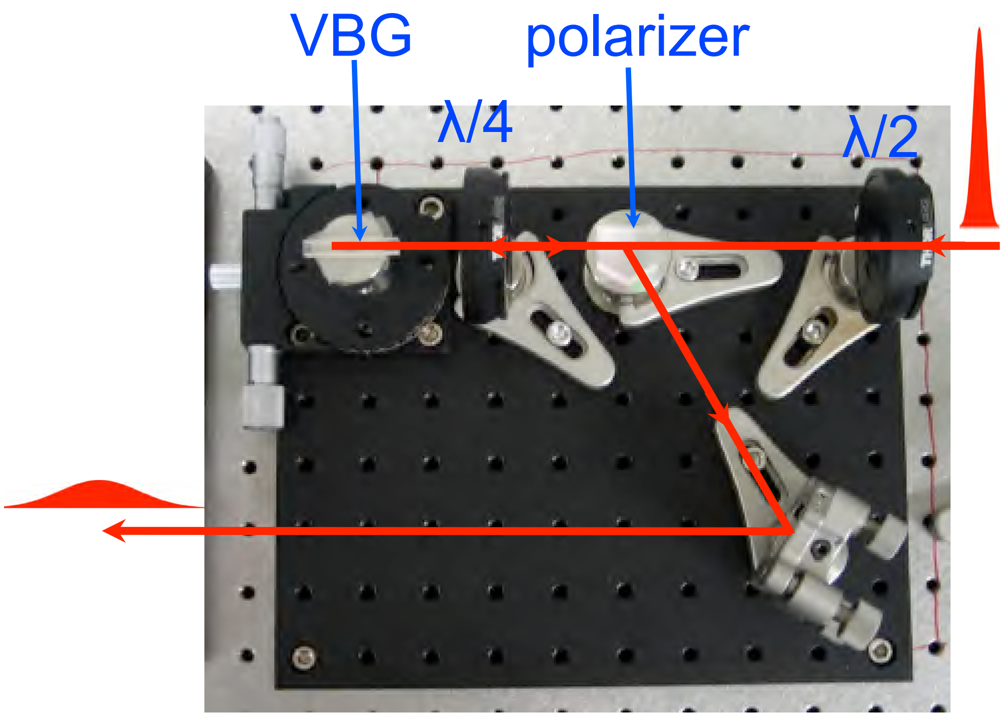
Progress to-date

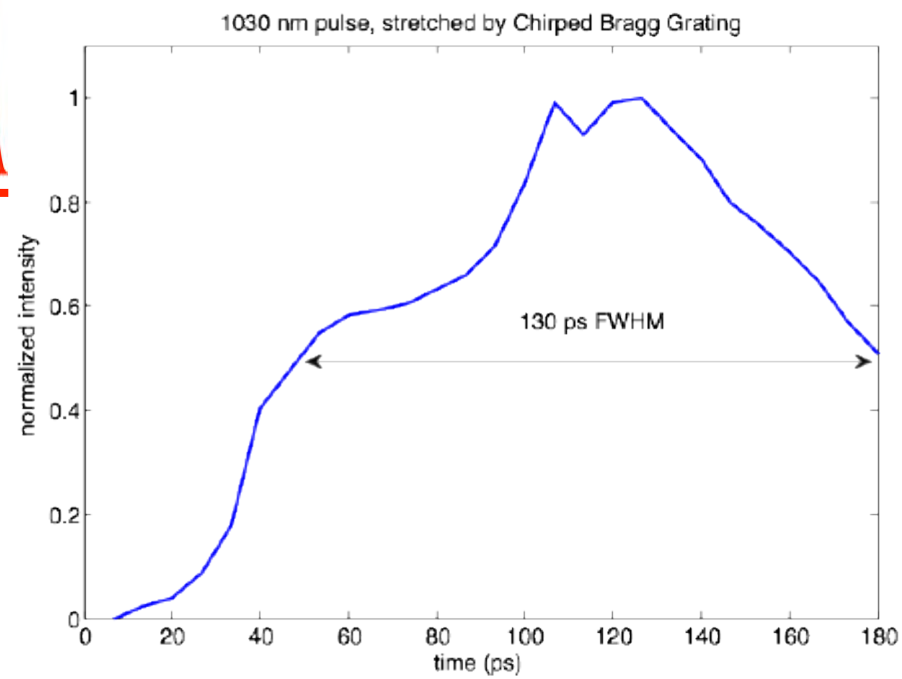
- **Front end– synchronized 1.03 + 1.55 μm**
- **Pump stretcher**
- **Yb:YAG amplifiers**
- **OPCPA stages I-III**



Volume Bragg Grating Stretcher for Yb:YAG

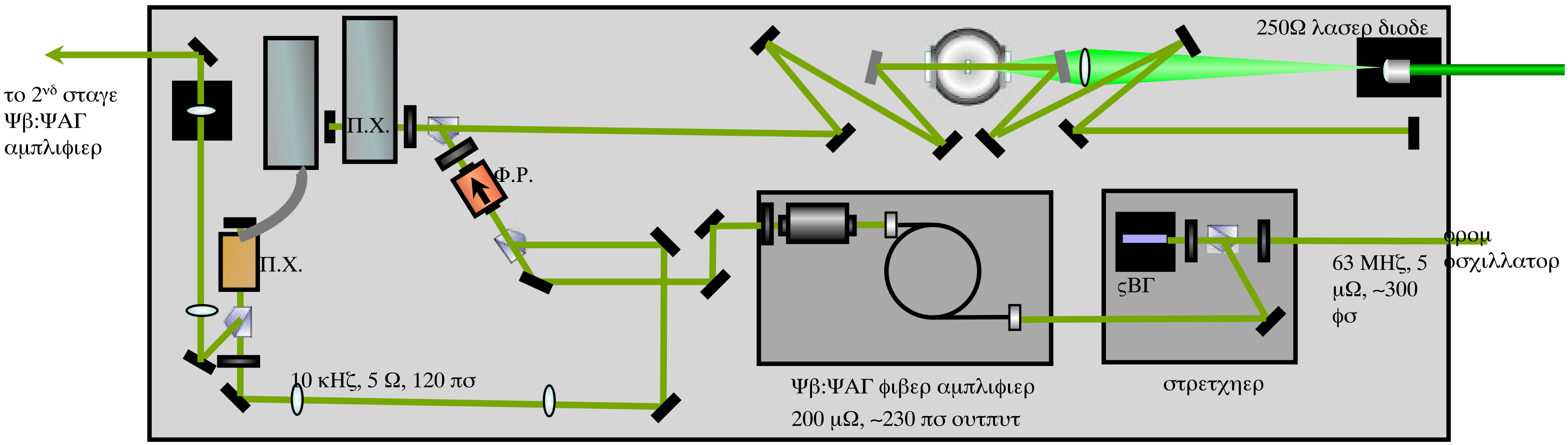
- **no timing jitter, compact, stretch pulse to 130 ps**





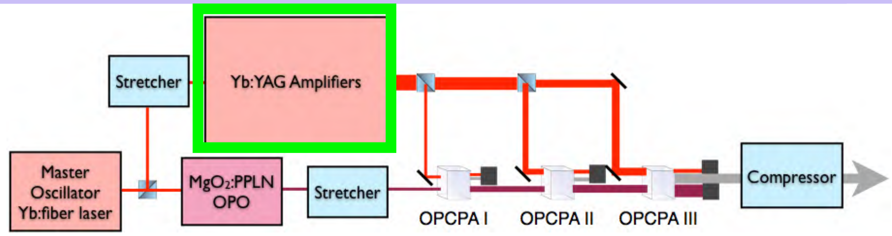
Amplifier Stage I

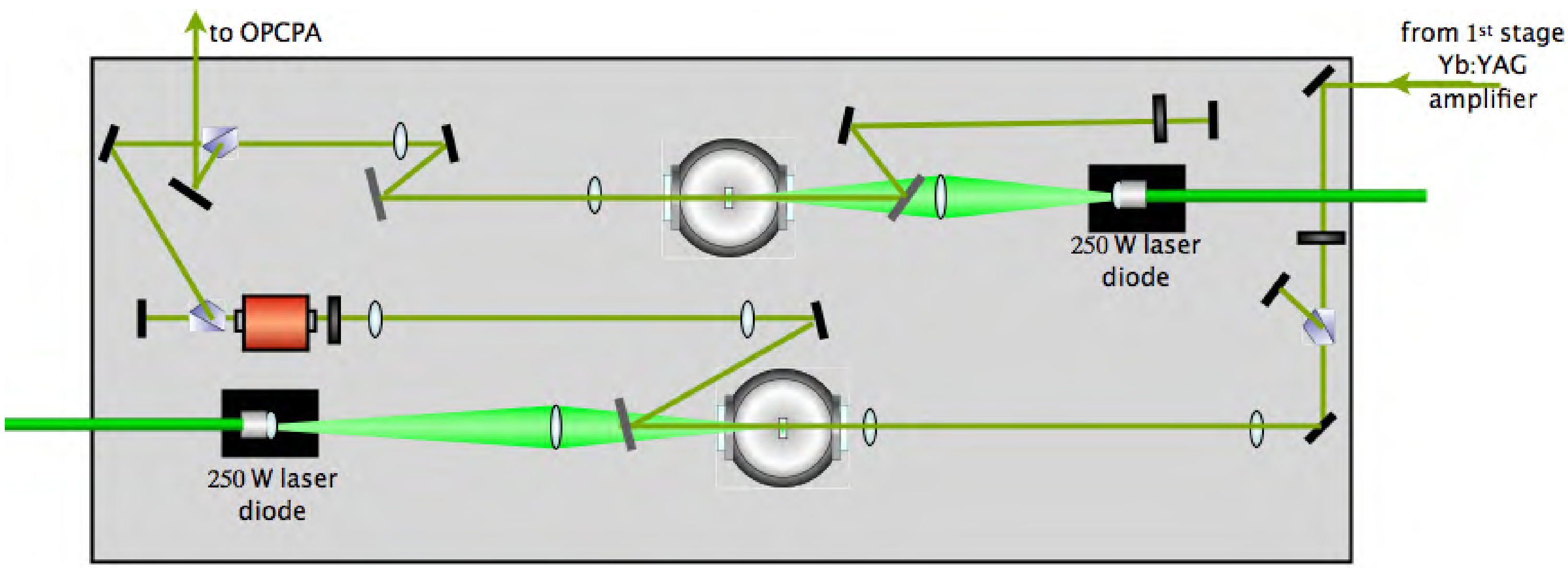
- **Regenerative amplifier**
- **10 kHz, 5W (500 μJ), 130 ps pulse duration**



Stages II & III

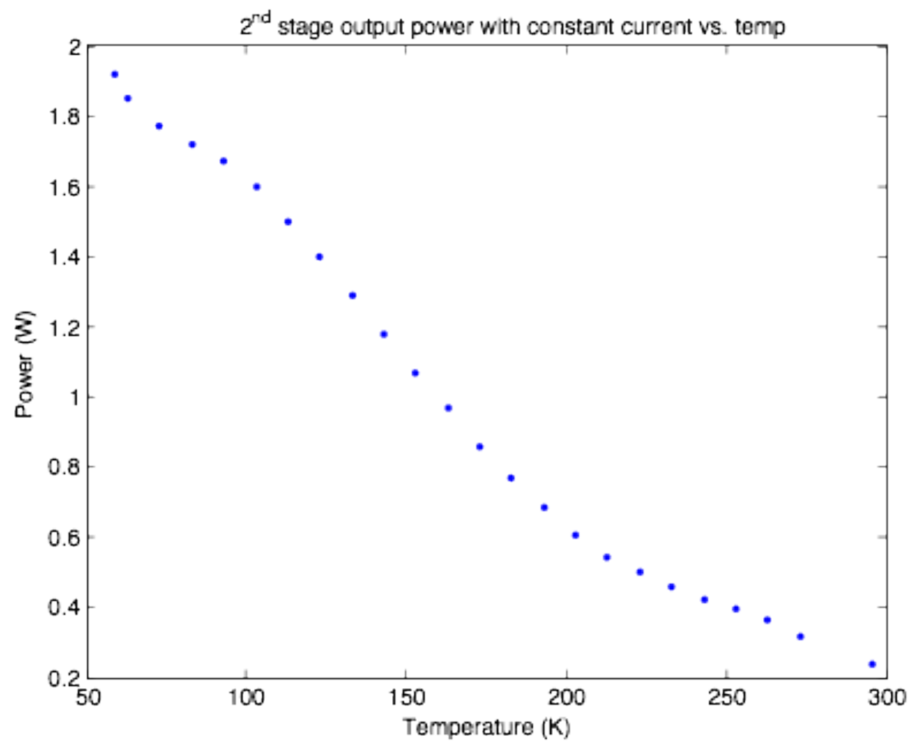
- **Improved mode quality**
- **2nd stage: 10 kHz, 30 W (3 mJ)**
- **3rd stage:**
  - 10 kHz, 65W (6.5 mJ)
  - 5 kHz, 40 W (8.0 mJ)
  - 2.5 kHz, 23 W (9.2 mJ)





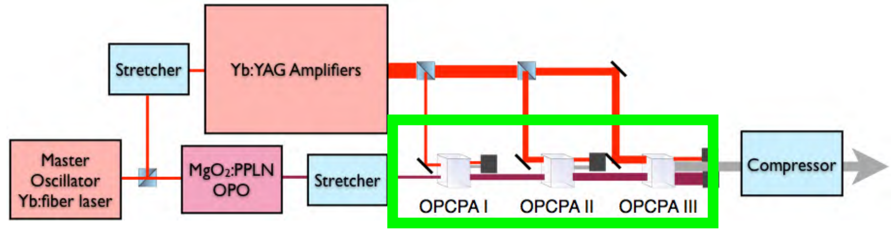
Pump amplifier: current limitations

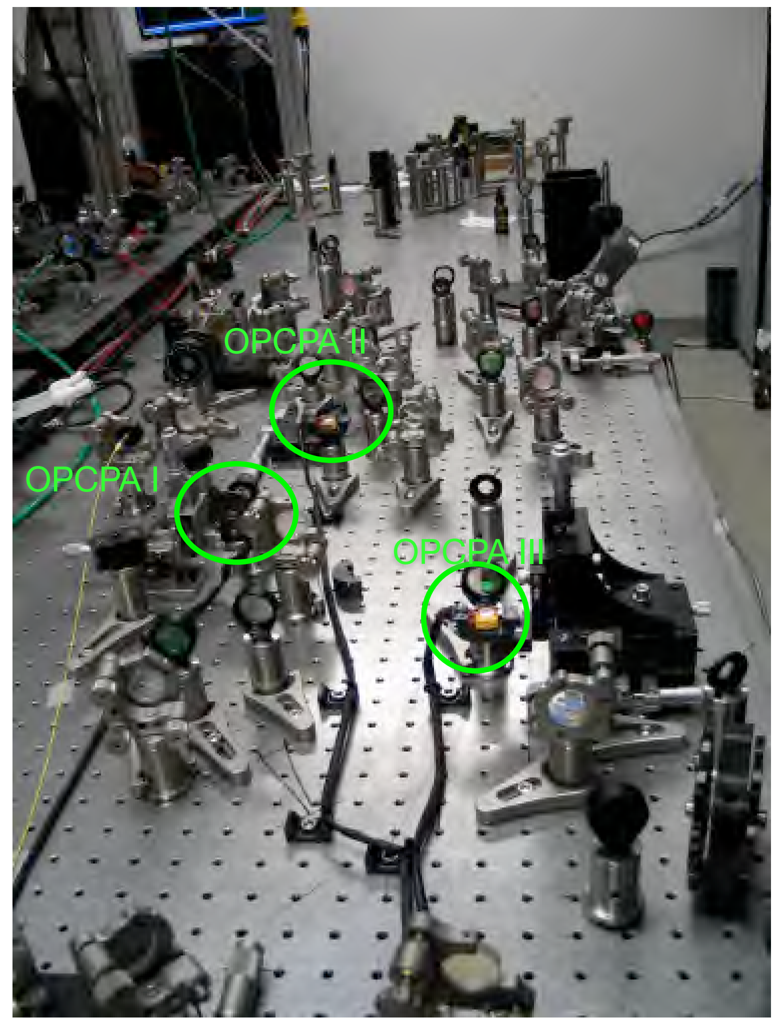
- **Yb:YAG works best when coldest**
- **Thermal loading causes temperature runaway**
- **Decreasing pump spot size or increasing number of passes leads to mode distortion**



Progress: OPCPA

- **Three stages**
- **Pump and seed overlap in time and space in each crystal**
- **MgO_2:PPLN in all three stages**
- **Output after 3 of 4 stages:**
  - 5kHz 3.4W (680μJ) 1550nm
  - ~20 W pump (4 mJ)
  - 0.92 mJ signal + idler



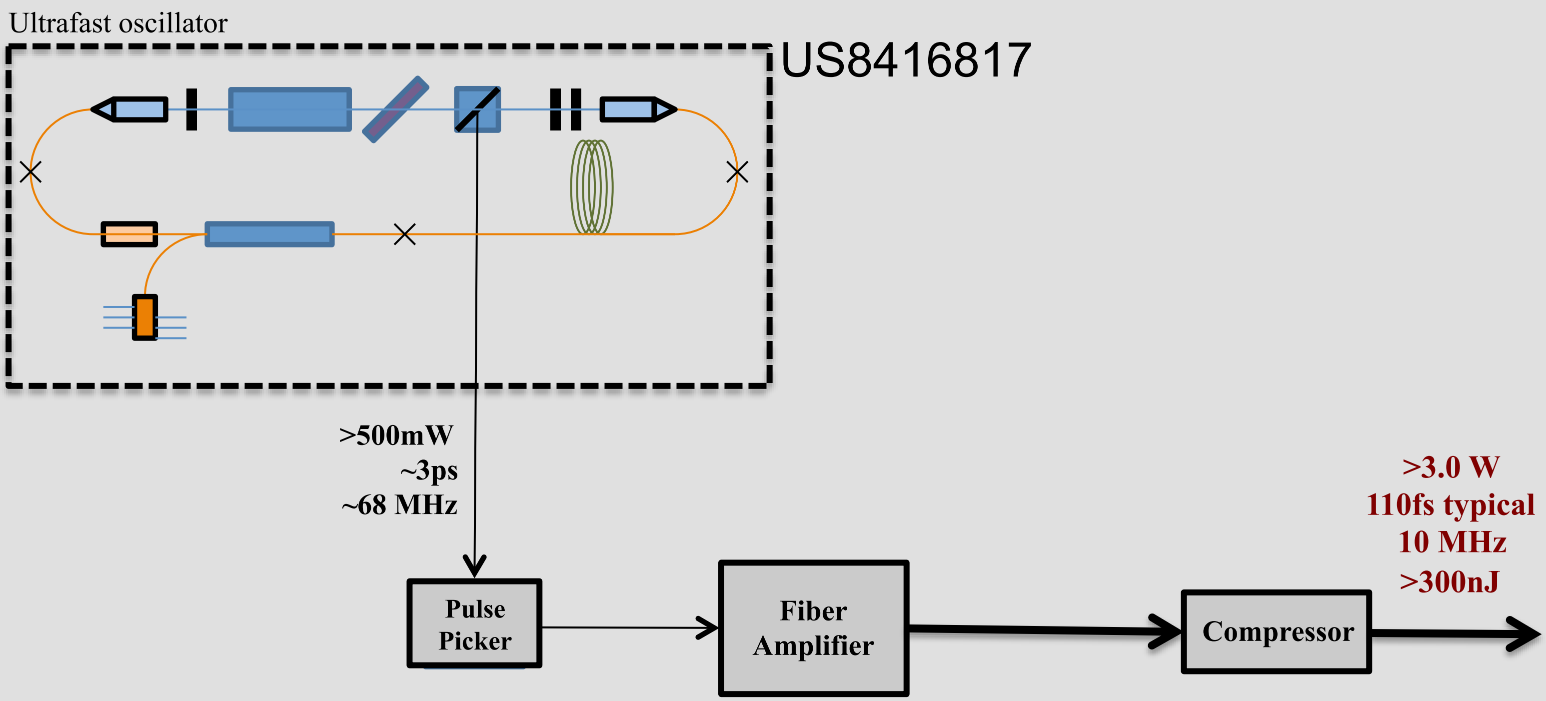


Next steps: use combined bulk/fiber technology

- **Fiber lasers can provide compact, robust, front-end systems**
- **High peak power, dispersion sensitivity make fibers problematic for high energy USP lasers**
  - "Hero" (mJ energy) fiber lasers make use of
    - Very large footprint compressors (~2m)
    - Interferometrically sensitive beam combining
    - Intrafiber peak powers very near damage limits

KMLabs Y-Fi Ultrafast fiber laser

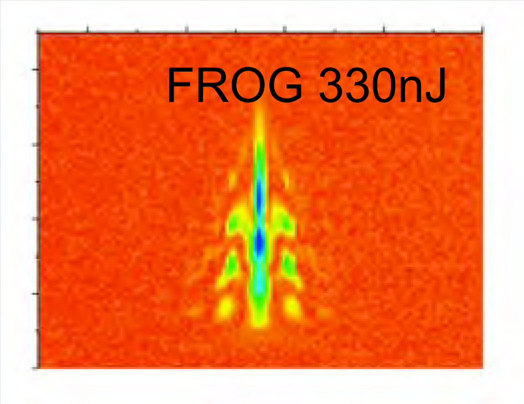
Novel, fully-licensed ultrafast oscillator enables higher powers and simpler amplification

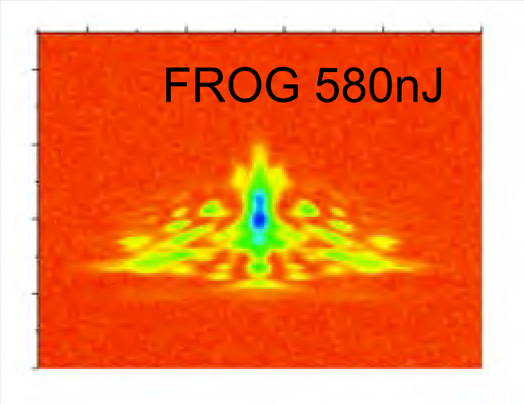


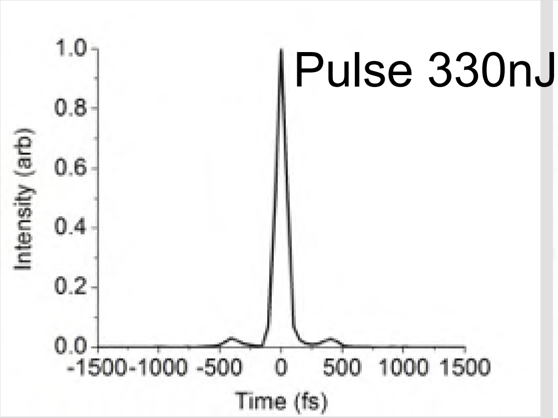
Y-Fi Performance

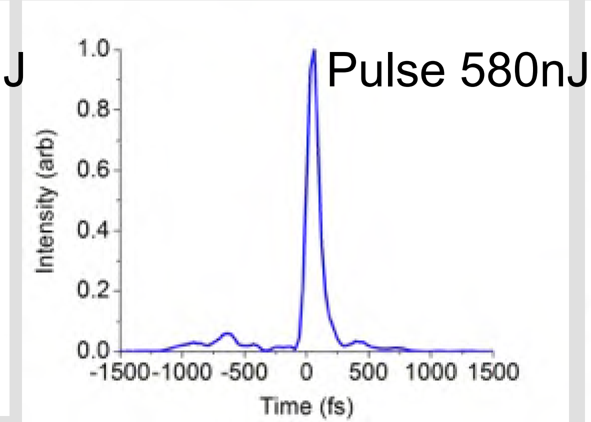
Pulse results

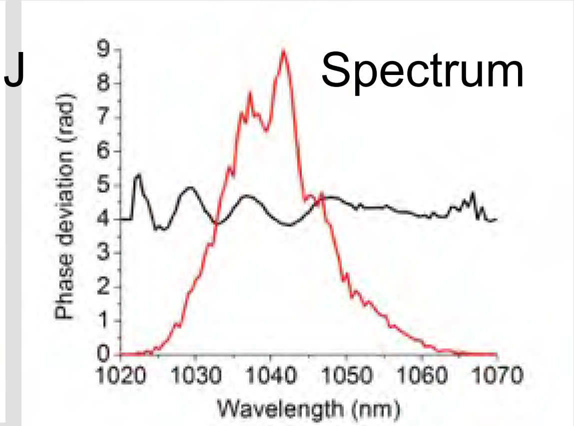
- >700nJ before compression
- >500nJ after compression
- 105 fs FWHM at 330nJ
- 3 MW peak power
- < 4% amplitude > 250fs
- <10 MHz rep rate







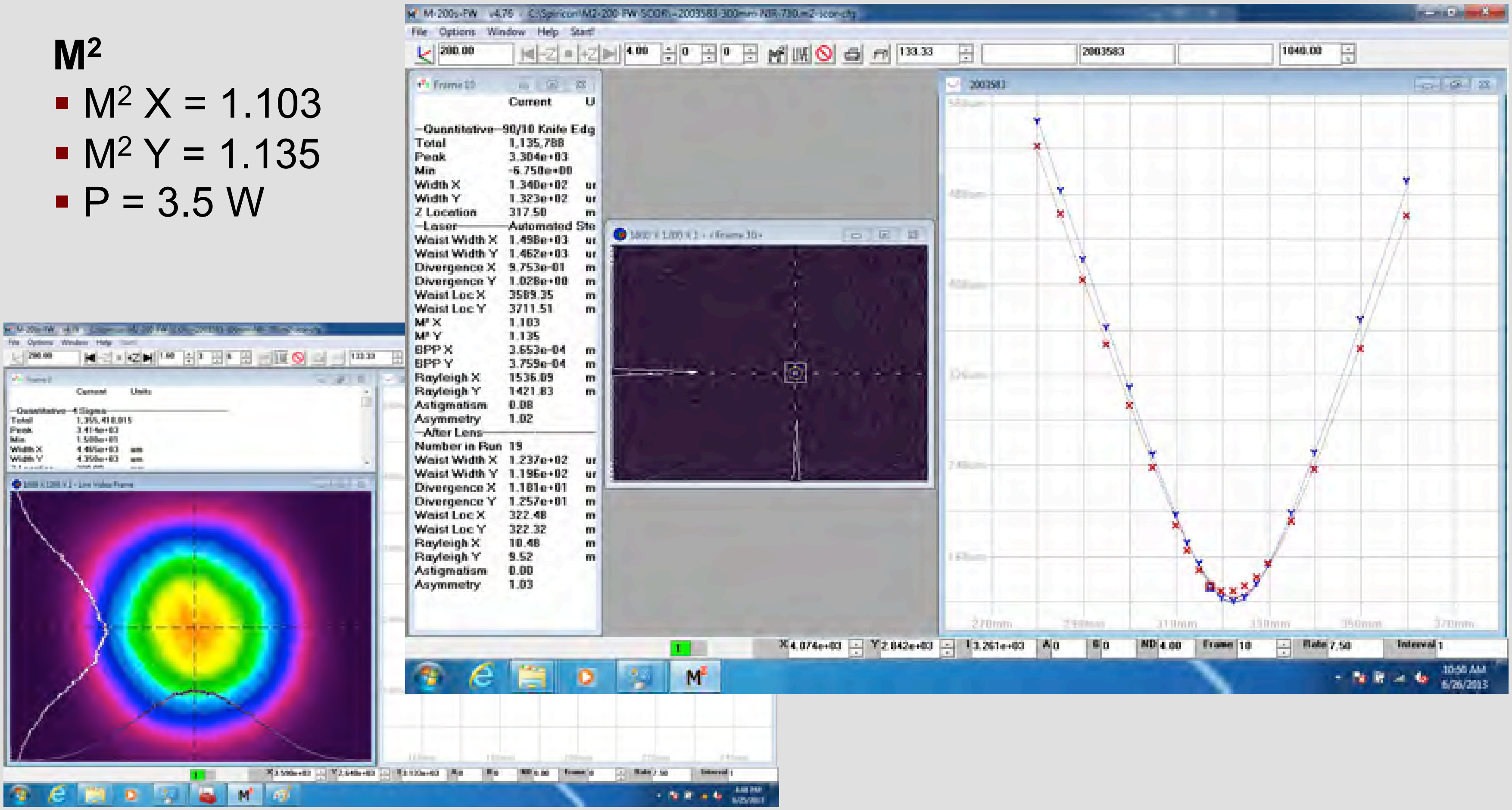




Y-Fi Beam Quality (M^2)

M^2

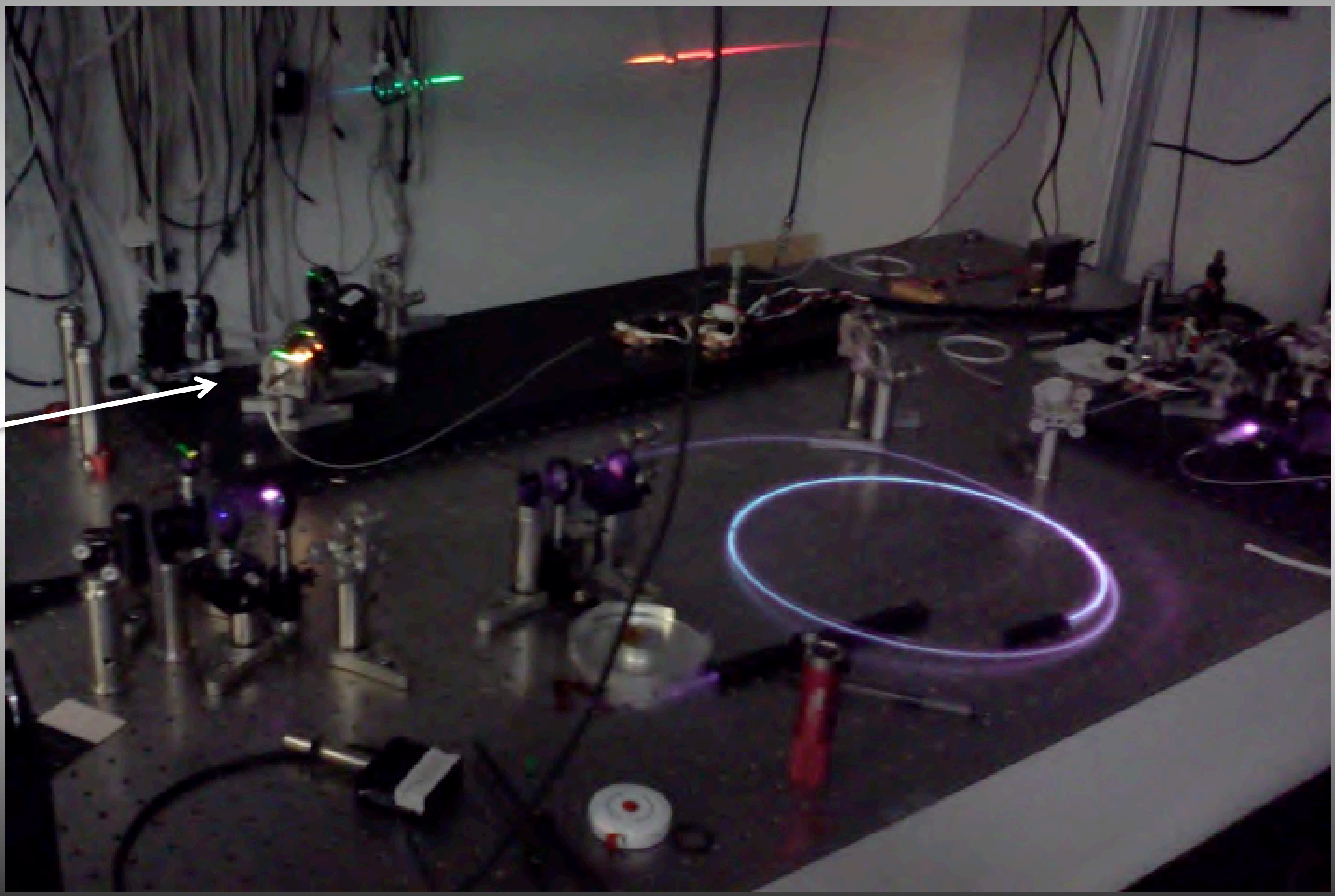
- M^2 X = 1.103
- M^2 Y = 1.135
- P = 3.5 W



Prototype: White Light Generation in bulk

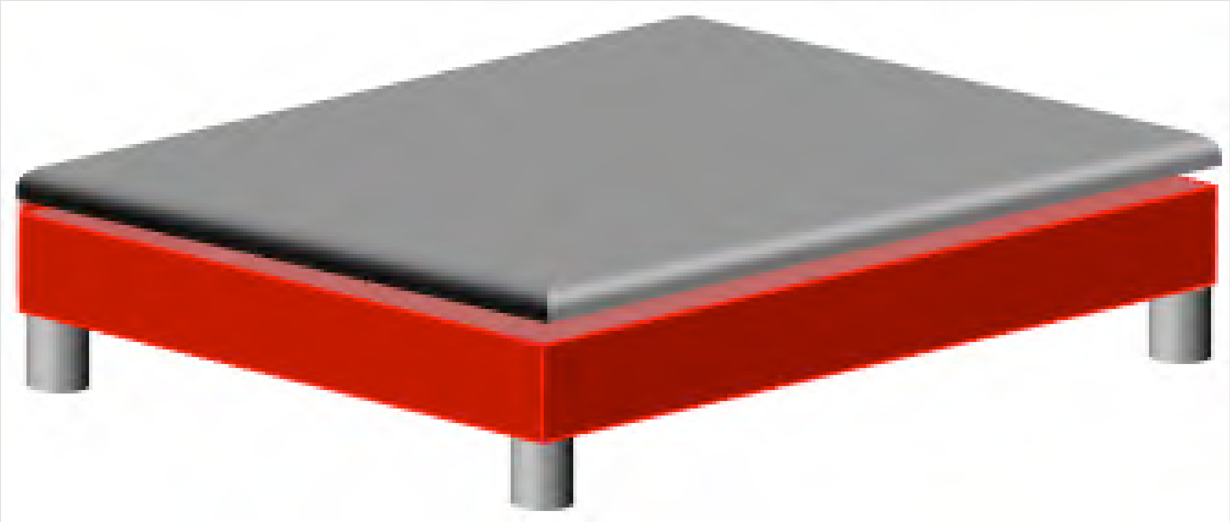
Excellent Indicator of very clean, short pulses with high peak power

Yellow portion of spectrum is being clipped here by a mount



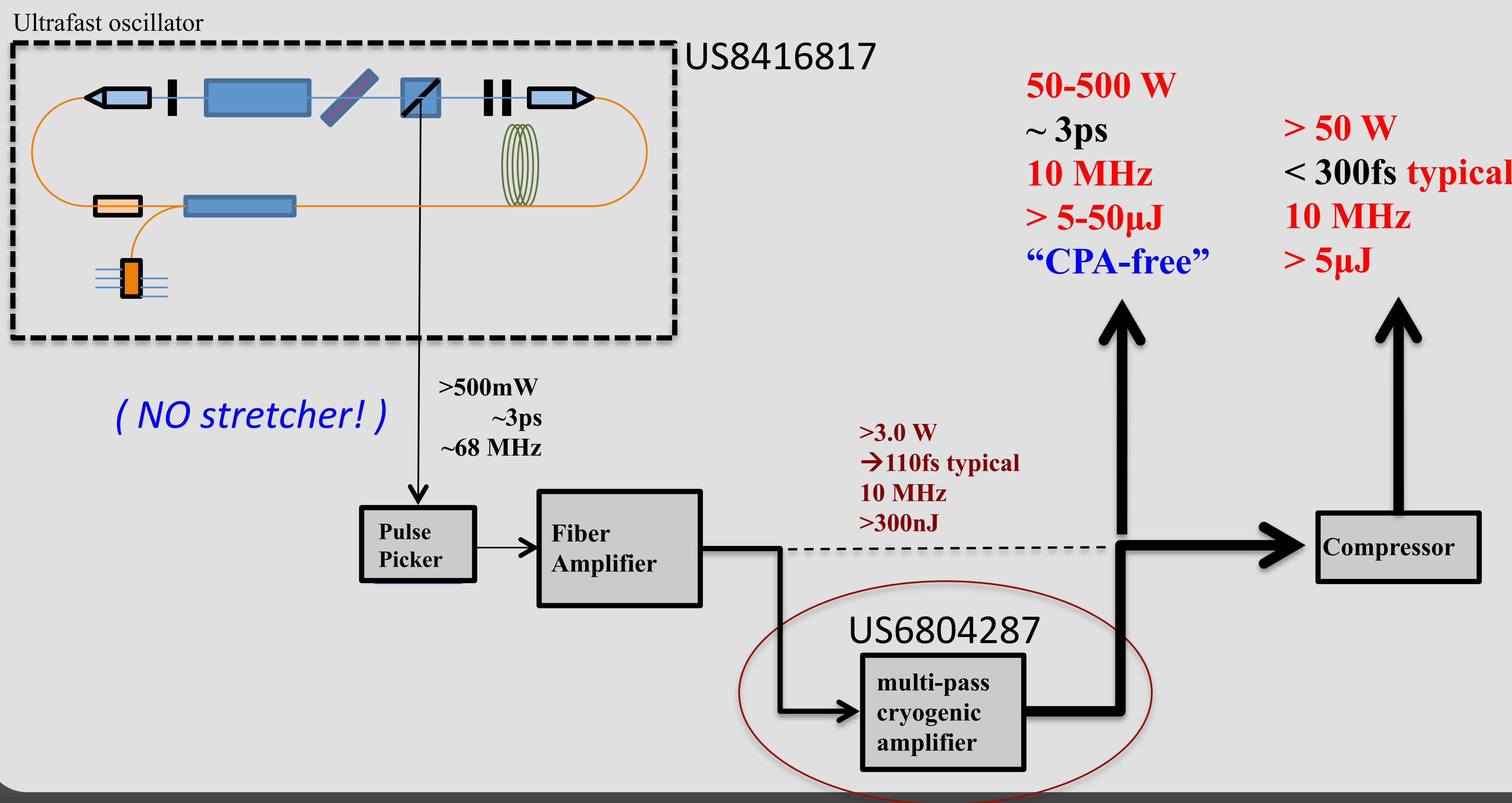
Y-Fi Form Factor

- Developed for OEM medical customer
- 12” x 15” x 5”
- Air-cooled



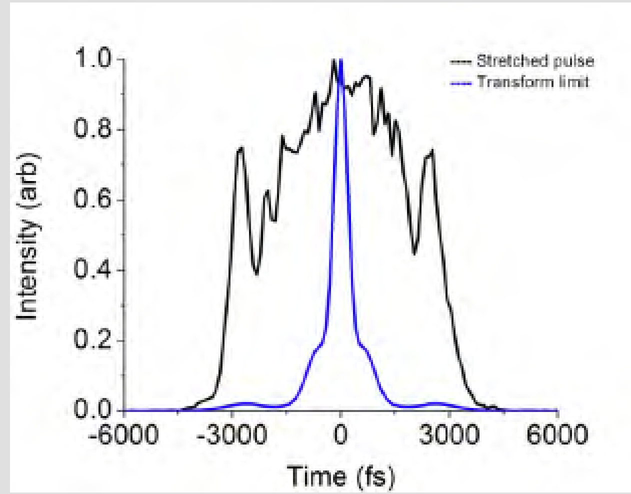
Simple + *High average and peak power*

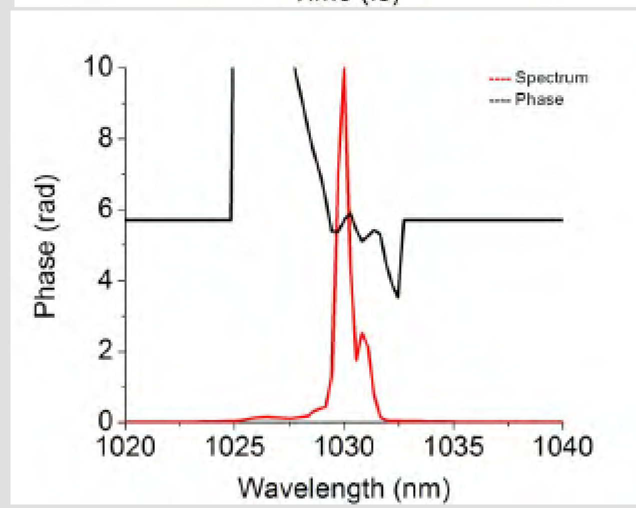
Novel, fully-licensed ultrafast oscillator enables higher powers and simpler amplification



Yb Fiber/ Cryo final amplifier

- Patented Fiber laser seed.
- Repetition rate selectable (100kHz to 4.5MHz).
- Power
  - **> 62W at 100kHz.**
  - **> 150W at 1MHz.**
- 5.8ps square pulses compressible to 500fs.





Conclusion / future directions

- **Cryogenically-cooled lasers very useful for scaling up power for ultrafast lasers**
- **Combined use of fiber lasers and high-power final amplifiers very effective**
- **Development of OPCPA technology will yield new ultrafast laser sources in the mid-IR**