High Power Laser Technology & Challenges in Accelerator Applications

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Thomas Jefferson National Accelerator Facility

3rd Workshop on H- Laser Stripping and Accelerator Applications

September 26~27, 2013, Fermilab, Chicago

Outline

- Introduction / Charge of the Session
- Quick overview
- Applications & Challenges in accelerators
- The state-of-the-art Laser & Technology
- What are Needed
- Summary

The Goal of "Laser Technology" Session

- Bring in experts and latest info about state-of-the-art laser technology. Review the status of laser R&D/capability in accelerator applications. Enhance collaboration.
- Help to identify and assess the key laser specifications needed by on-going and future H- laser stripping/H- accelerators.
- Identify the prospects and possible technical routes to bridge the gap between the "available" and the "will-be-available" technology that will enable challenging tasks in H- accelerator applications in near future.
- More? (your comments are welcome, more time available in discussion session).

Lasers Today- after Over Half a Century R&D

The rapid growing ***Laser Diode/Fiber*** technology brought in enormous advancement,

- High Peak power: PW
- High Average power: 10s' kW/MW
- High Energy: multi-MJ
- Ultrashort pulse: fs/as
- THz~IR ~ UV/Soft-X ray (Hard X-ray FEL)
- High stability (turn-key, 24/7 operation)
- High beam quality (~DL)
- Compact (Palm-size, suitcase-size/100s W)
- Commercially available
- ……

May 16, 1960

Ted Maiman demonstrates the first ruby laser.

Hughes Research Laboratory

LASERFEST

CELEBRATING 50 YEARS OF LASER INNOVATION

Powerful

- We don’t know how much power Theodore made, maybe <mW
- Here are what we have now,

- Northrop Grumman 100kW CW laser
- Laser Photonics 10kW CW
- Boeing 25kW CW Laser
- Southampton U. 1.36 kW Yb-doped fiber laser
- IPG 1kW/SM, 50kW/LOM, CW Yb LM Fiber Laser

Northrop Grumman Makes A 100kW Laser

Posted March 26, 2009 at 5:00 pm by Jim in Laser, Military and Defense Light, Research and Development

Defense contractor Northrop Grumman just recently released information that they've created a solid state laser that fired over 100kW in a beam - 105.5kW, to be relatively exact. This mile marker is apparently a big deal, because now Northrop Grumman has entered the weaponized laser market. This is also significant, as they've now created the most powerful ray from an electric laser, ever. Northrop is part of something called the JHPSSL - The Joint High Power Solid State Laser program, which is dedicated to creating a weaponized laser system, obviously solid state.

Boeing Successfully Fires 25 kW Solid-State Lasers, Laser Weapons One Step Closer to Being a Reality

By Adam Frucci, 12:00 PM on Wed Jun 4 2008, 54,810 views

IPG PHOTONICS

TiTAN Series

Laser Photonics Unveils First Ever 10-Kilowatt Laser Cutting System

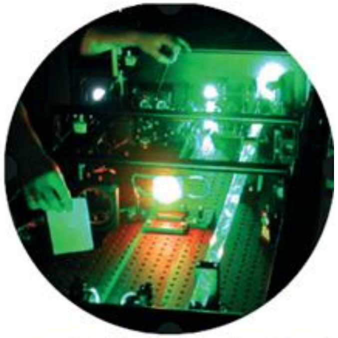
Lake Mary, FL., December 2, 2008

Robust

1. A few ps ~ 10s ps
2. *100s KHz to 100s MHz*
3. Average power >25W (IR)
4. DPSS with SASEM passive mode-locking
5. Good beam quality (<1.5), stable
6. fs Ti:sapphire PW laser

Off the shelf!

KMLABS LEADING IN ULTRAFAST



THALES LASER
- UP TO PW PEAK POWER !
- 10 HZ REPETITION RATE
- PULSE DURATION DOWN TO 25 FS

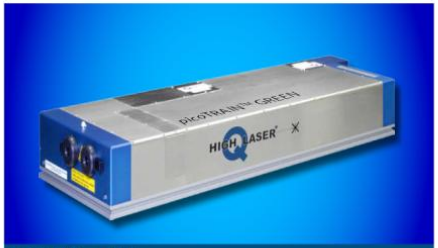
POWERLASE

200W 10ps Nd:YAG Slab Laser

HIGH Q LASER Think Ultrafast!

picoTRAIN™ Green & UV / CARS

Compact, all-diode-pumped, solid state picosecond oscillator with harmonic generation



picoTRAIN™ Green & UV

	IC-532-4000		IC-532-12000		IC-355-5000		
Wavelength	1064 nm	532 nm	1064 nm	532 nm	1064 nm	532 nm	355 nm
Pulse width (FWHM), typical	6 ps		6 ps		< 6 ps		
Average output power	> 8 W	> 4 W	> 25 W	> 12 W	> 25 W	> 12 W	> 5 W
Pulse repetition rate	76 MHz		76 MHz		76 MHz		
Laser material	Nd:Vanadate (Nd:YVO_4)						
Power stability, typical	< 1 % RMS (12h)				< 1.5 % RMS (12h)		
Beam quality	TEM_{00}; $M^2 \le 1.2$						

ARGOS™

High-Power Picosecond Laser

SESAM® Technology

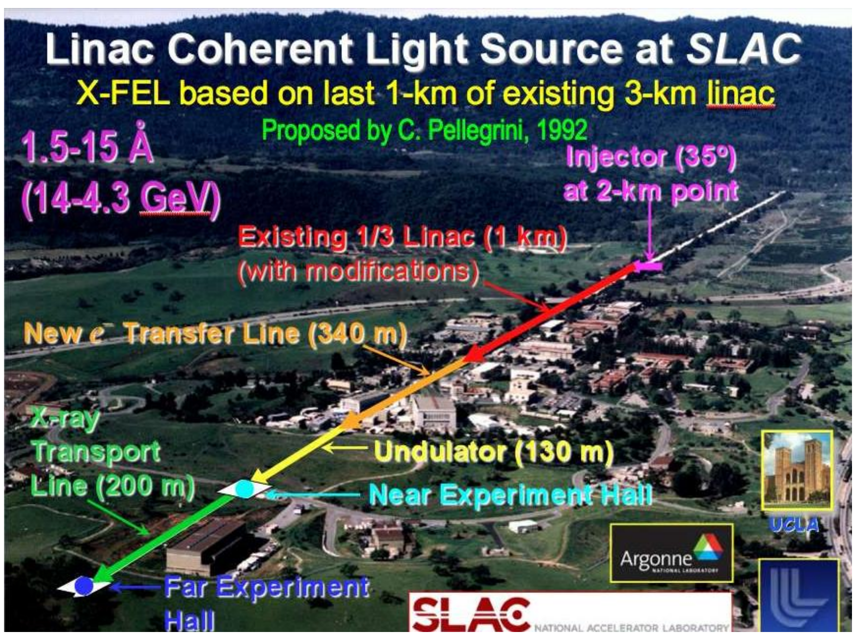
Customizable

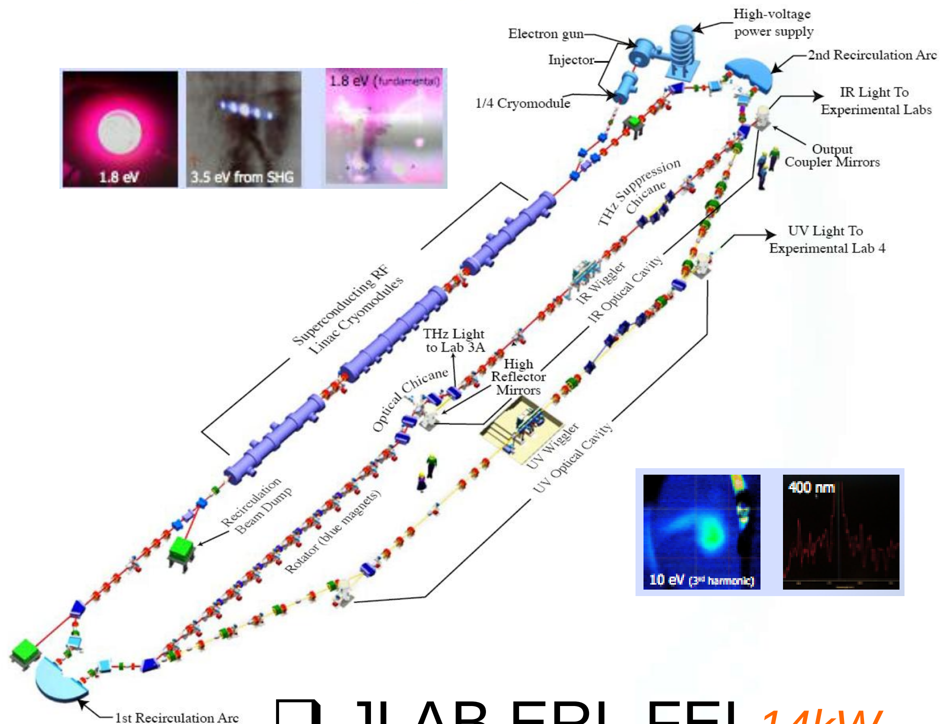
>45 W
50 MHz to 100 MHz
1064 nm
< 15 ps

Lasers Built on Accelerator Technology

- SLAC LCLS-I
  - ✓ 2mJ, *1.5Å*, <20fs, 60Hz (2009)

	Baseline	Achieved	
Electron energy	4.3 – 13.6	3.3 – 15.4	GeV
Bunch charge	200 & 1,000	20 - 250	pC
Emittance	1.2	0.13 – 0.5	µm (norm.)
FEL energy	830 – 8,300	480 – 10,500	eV
FEL pulse energy	< 2	< 4.7	mJ
FEL pulse length	230	< 5 – 500	fs (FWHM)
Repetition rate	120	120	Hz





- JLAB ERL FEL *14kW* /1.6um/100fs/75MHz (2004)

Wavelength	Power/pulse	Bandwidth
THz nominal	0.1 µJ	1.5 THz
THz optimized	1.0 µJ	2.5 THz
IR 1-5 microns	90[a,b] µJ	1%
UV 370-900 nm	(8[a], 30[b]) µJ	1%
VUV 4–10 eV	(5[a], 30[b]) nJ	0.6%

Questions

Can the state-of-the-art laser technology provide what are needed in advanced accelerator R&D? such as,

- Future Light Sources,
- High-current ERL, and
- SNS (H- Laser stripping)?
- ……

Which one is preferred in the near term?

What is the key issue and the path forward?

Report of the BESAC Subcommittee on Future X-ray Light Sources

- Report provided to the Office of Science on March 21, 2013, BESAC made the clear statement:

  "the BESAC urges DOE to aggressively pursue a new future light source with unprecedented beam characteristics and thus unprecedented opportunities for world-leading science".

- Executive Summary

  The world leadership that the U.S. has provided in accelerator-based x-ray … In spite of the present intensely competitive environment, an exciting window of opportunity exists for the U.S. to provide a revolutionary advance in x-ray science by developing and constructing an unprecedented x-ray light source. **This new light source** should provide ***high repetition rate, ultra-bright, transform limited, femtosecond x-ray pulses*** over a ***broad photon energy range*** with ***full spatial and temporal coherence. Stability and precision timing*** will be critical characteristics of the new light source.

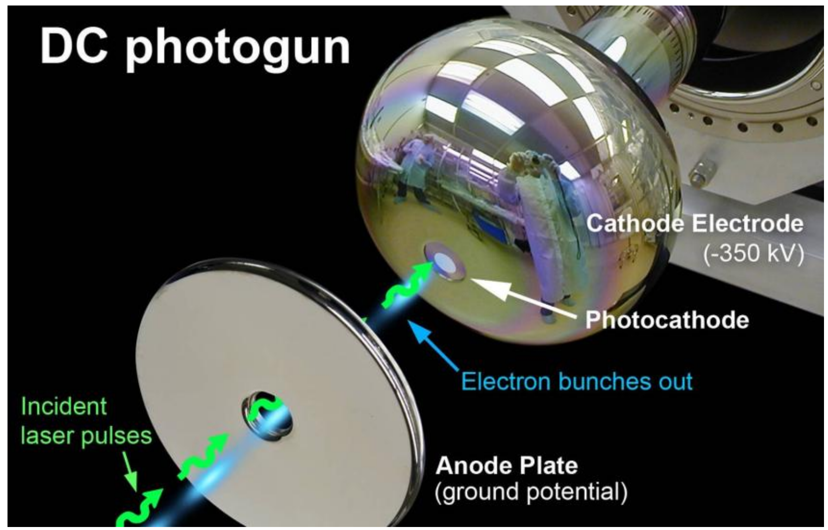
What Lasers Do for Beam/Accelerators

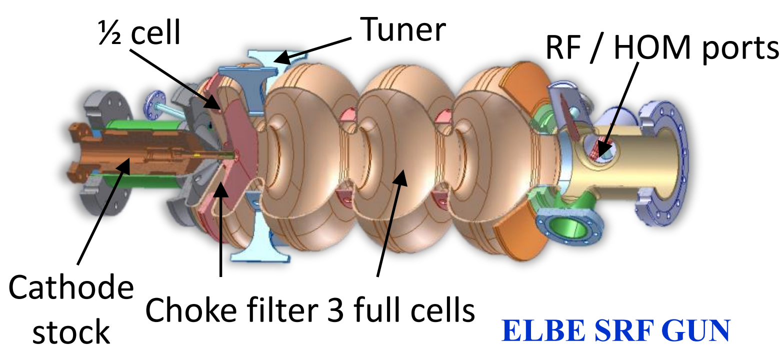
- Generation of High-power High Brightness short-pulse e-beam
  - Short pulse e-bunch, special e-beam requirements/low emittance
- Seed Lasers for future light sources
- Laser plasma acceleration
- Diagnostics
  - Non destructive E-bunch temporal and spatial measurement (EO)
  - Laser wires/scanner, Laser mapping
  - Compton scattering devices (diagnostics, Gamma ray)
- Laser stripping/notching/Chopping
- High precision synchronization (Optical vs RF)
- Application in Super conducting cavity
  - SRF cavity inspection
  - Laser heating, Surface repair/treatment
- More ……

Drive Laser for Photo-Cathode

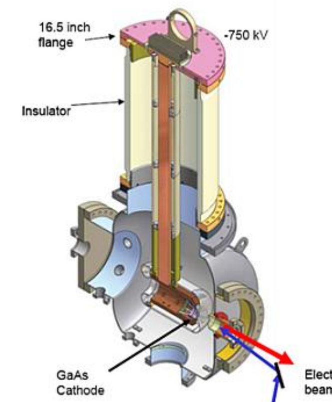
- GUN/Injector technology identified as the key for future light sources,
- JLAB FEL ERL 10mA, Cornell DC GUN 60mA reported,
- Under development: JAEA 500kV GUN, ELBE, BNL, LANL, LBNL,...

- A high performance drive laser is crucial to generate high quality e-beam
- Stringent e-beam requirement also pushes up laser development

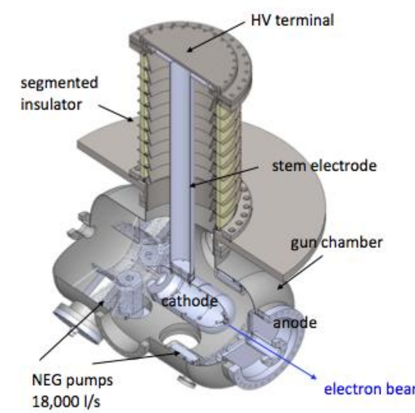




ELBE SRF GUN



Cornell GUN



JAEA 500kV DC GUN

Example: Laser Power for HP e-Beam

$$QE = \frac{124 * \text{Current (mA)}}{\text{Laser power (W)} * \text{Wavelength (nm)}}$$

For GaAs and 532nm Laser, 135 pC, 2% cathode QE,

- ✓ 10mA current needs ~ 2W laser power@75MHz
- ✓ 1000mA current needs ~ 200W laser power@75MHz

- Cathode lifetime,
  - ✓ 100W power & 10,000C charge lifetime, continuously run at 100mA and deliver <40kC until QE falls from 10% to ~0.2% (<5 days of operation).

- Not even to mention *the loss along the transport*. Power consuming!

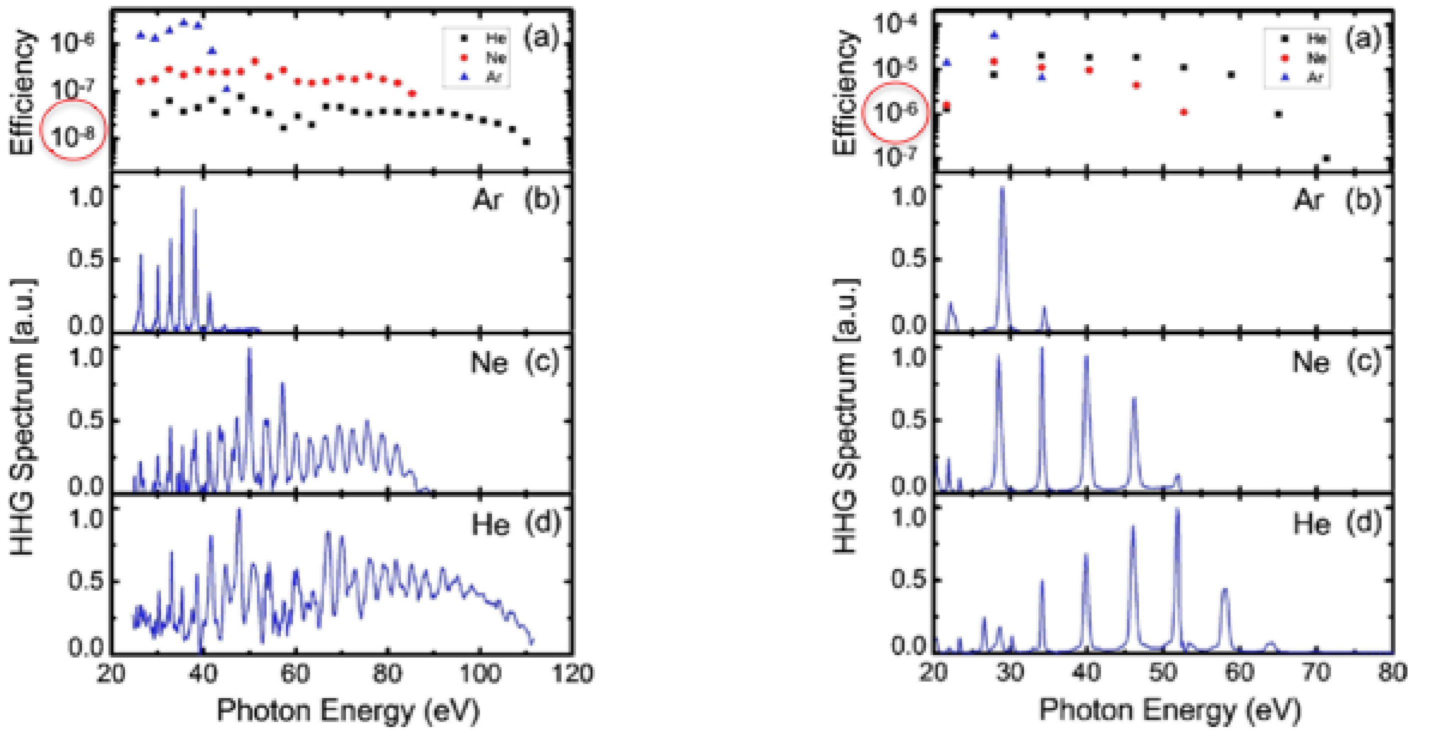
Cathode	QE (%)	Laser λ(nm)	Laser power W/mA	Laser power @ 1um
Ce:GaAs	2.5	532	0.1	0.2
CsTe	0.5	266	1	5
Cu	1.e-5	266	500	2500
Mg	5.e-5	266	100	500

Laser Parameters for H- beam

Parameter / Facility	SNS LS	CERN LS	FNAL LS	FNAL Notching	Chopper	H- beam laser Diagnostics
Time Frame/status	Current / R&D	Future	Future	Current/ R&D	Conceptual	Current
H- beam energy	1 GeV	4 GeV	8 GeV	750 KeV	Few MeV	varies
Wavelength	0.355 um	1 um	1um / 2 um	1 um	1 um	typically 1 um
Micropulse Frequency	402.5 MHz	352 MHz	162.5 MHz	201.25 MHz	325 MHz	few hundred
Micropulse duration	~50 ps	90 ps	~30 ps	1.5 ns	1 -2 ns	fs (longi.) ns (trans.)
Micropulse energy	~300uJ(IR) 50 uJ (UV)	450 uJ	400 uJ(1um) 80 uJ (2um)	2 mJ	260 uJ	10's uJ ~ 10's mJ
Micropulse Peak power	1 MW	5 MW	5.5 / 1.1 MW	1.6 MW	210 kW	1 -10 MW
Burst Frequency (rep rate)	60 Hz	1 Hz	10 Hz	458 kHz	~ CW	10's Hz ~ MHz
Macropulse width	1 ms	2.4 ms	4.3 ms	~9 * 60 ns	NA	NA
Macropulse energy	120 J (IR) 20 J (UV)	300 J	~250 J ~50J	267 mJ	NA	NA
Average power	7.2 kW (IR) 1.2 kW (UV)	10 kW	65 kW (IR) 13 kW (UV)	15 kW	NA	10 W ~ 1 kW

Challenges from Seeded XFEL

- High peak power/Energy X-rap pulse needed to seed the FEL amplifier
- Low HHG conversion efficiency requires high peak/energy pump laser



800nm, 35fs, 2.3×10^{15} Wcm^{-2}

400nm, 26fs, 2.7×10^{15} Wcm^{-2}

Need more pulse energy and high rep rate from Ti:S lasers (now few mJ / 10s of kHz)!

High Average Power ps/fs Lasers

- *Fiber laser*
  - 321W/20 ps/1 GHz Yb fiber MOPA (1060 nm) (2006)
  - 110 W IR / 65 W green/1.3GHz/ sub-ps fiber amplifier Opt. Express 20(5) 4850 (2012)
  - 135 W/520 nm fs pulses, fiber laser Opt. Lett. 36(3), 316 (2011).
  - 130-W ps green laser/frequency-doubled hybrid cryogenic Yb:YAG amplifier," Opt. Express 17(19), 16911 (2009),
  - 830 W fs fiber CPA system, Opt. Lett. 35(2), 94 (2010).

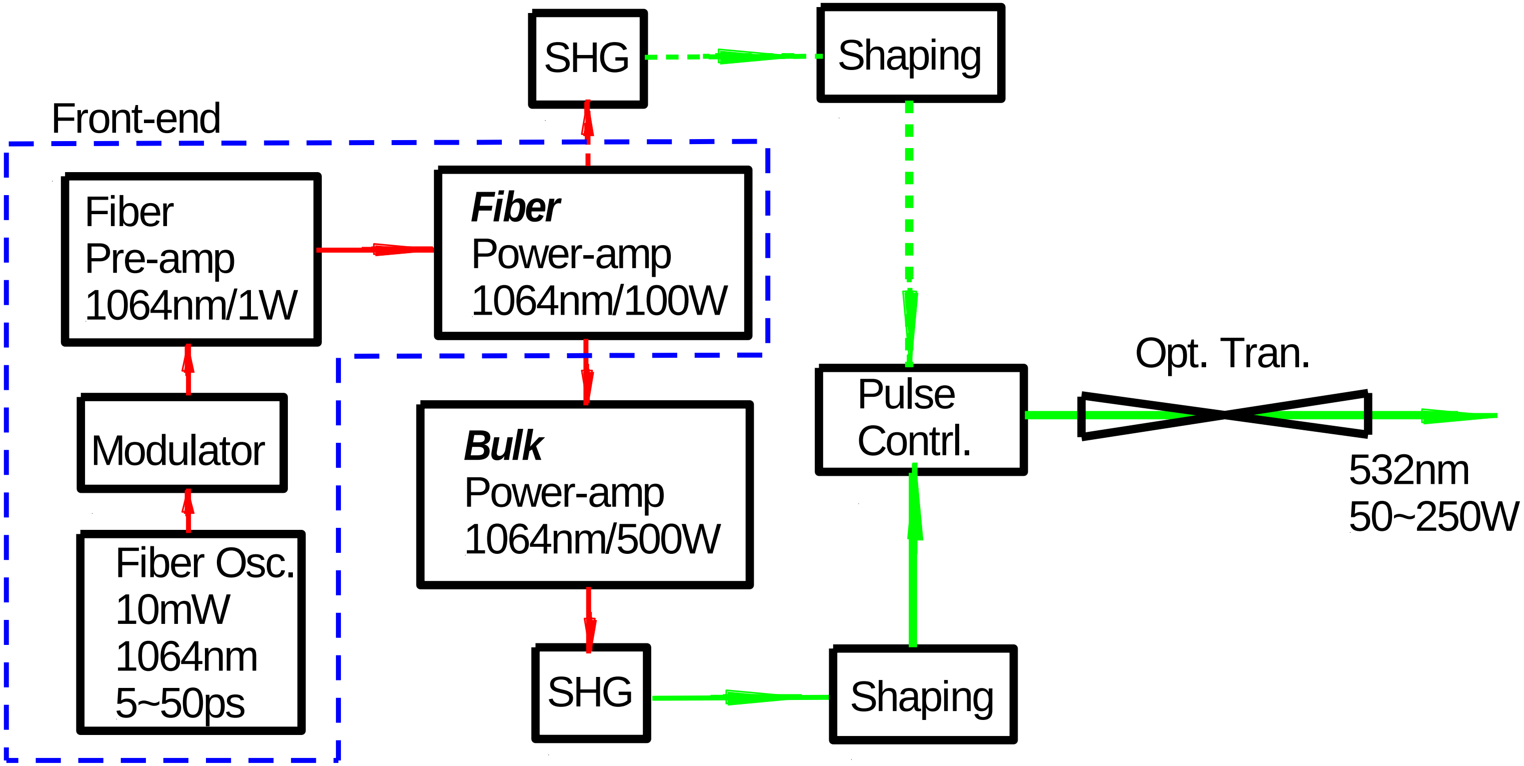
- *Bulk material*
  - 400 W / 680 fs /76 MHz room temperature, without CPA ,Yb:YAG Innoslab MOPA, Nearly transform and diffraction limited
  - 287W 1030nm/5.5ps /78 MHz ,cryogenically cooled Yb:YAG amplifier seeded by a fiber CPA system (*Lincoln Lab)*
  - 600W 1030nm/ 200W green/ 12ps /50 MHz ,cryogenically cooled Yb:YAG amplifier (SCL)

Technologies Behind Powerful Lasers

- *Technical path: **MOPA***
  - Stable ML oscillator (DPSSL, fiber)
  - Despite great progress in SESAM fs/ps laser oscillator technology, MOPA will likely be dominant for multi-hundreds/kW watts system.
- *Amplifiers*
  - Fiber
  - Bulk materials, including thin-disk amplifier
- *Mixed/hybrid configuration preferred:*
  - **Fiber front-end (Oscillator, preamplifiers)**
  - **Bulk material power amplifiers**
- *Other possible routes*
  - Coherent Beam Combing
  - Enhanced cavity

Hybrid Configuration

- ML Fiber or Gain-switched seed oscillator, pulse control by fiber modulator
- Fiber front-end: Oscillator, fiber-preamplifiers, fiber power amplifiers.
- Bulk power amplifier: Cryogenically-cooled Yb material.
- Shaping and pulse control

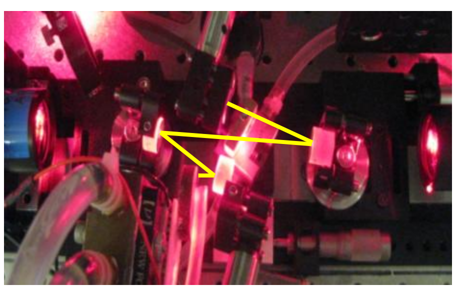


Laser Oscillator Determines System Stability

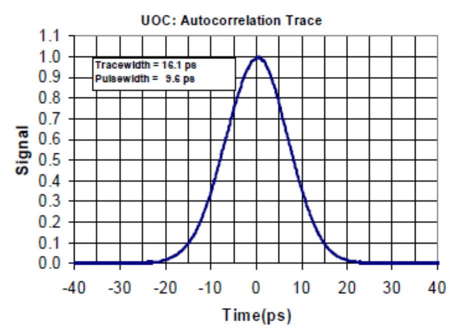
What do we need from oscillator,

- Power is not important
- Stability upmost
- Short pulse, variable preferred
- Good beam quality, near DL
- Robust, Long life-time

Yb-fiber Oscillator:
Actively ML ,thermally stabilized
5~10ps (up to > 60ps),
compressed < 2ps.
Very robust and reliable
Meets industry standard.
Can be master clock for synch. system
Disadvantage: low power 10~30mW



1 GHz diode pumped ML CrLiSAF Laser
timing jitter [1kHz – 10 MHz] < 200as

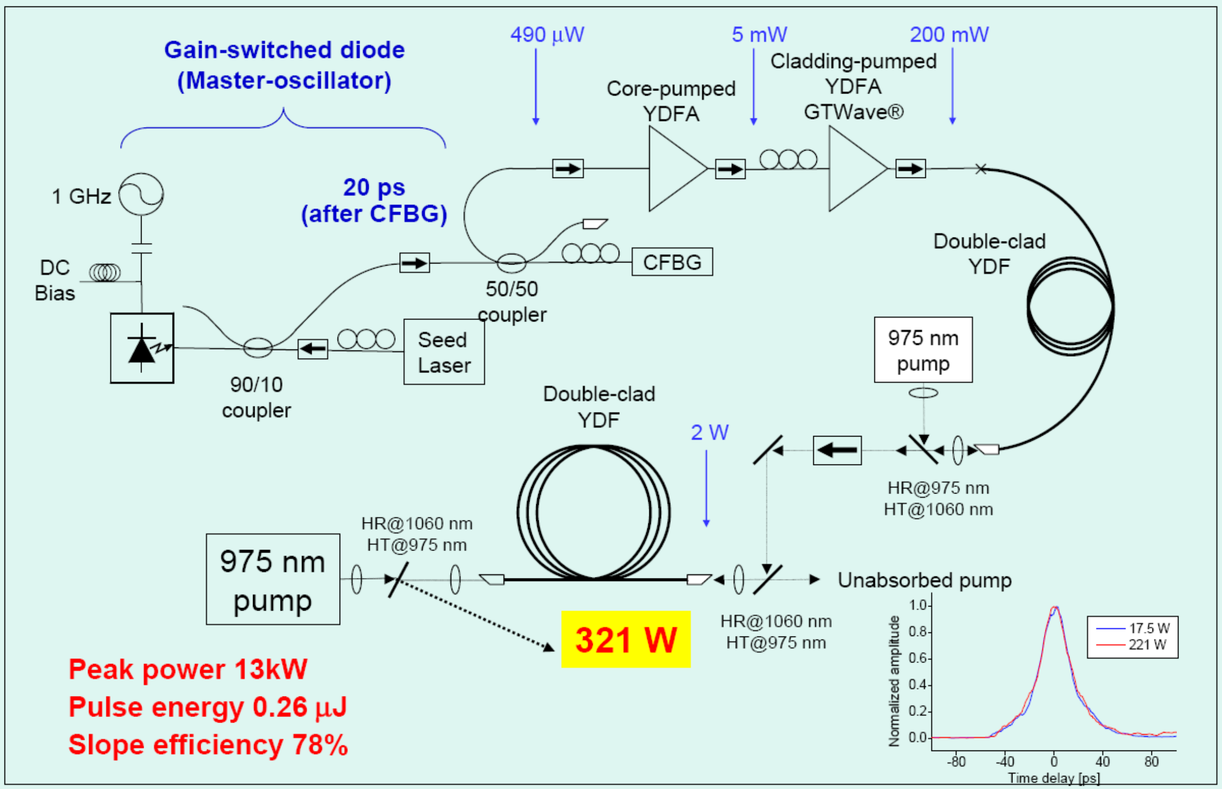


1060-nm Ultrafast Optical Clocks

PriTel, Calmar

High Power ps Fiber Laser

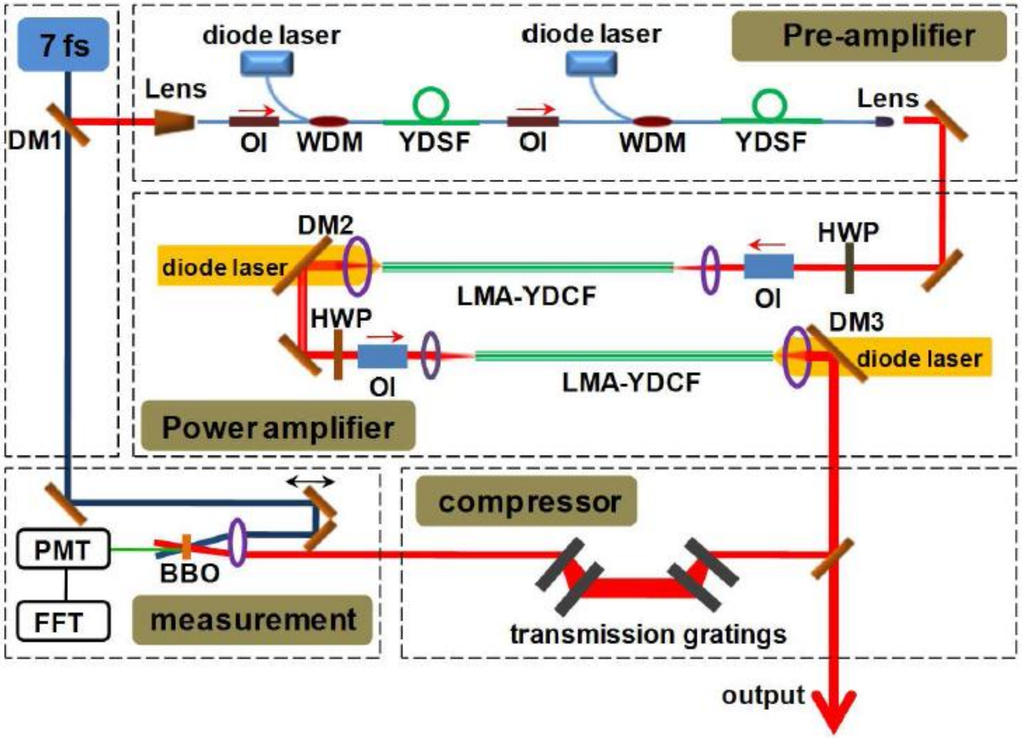
- Gain-switched seed, Double-clad FA s as power amplifiers, 43um core/600um clad
- 321 W/1GHz/20ps, slope efficiency of 78% , M^2~2.4, Contrast ~ 20 dB
- Peak intensity~ 1GW/cm^2 < SRS threshold, Beam load <100MW/cm^2
- **Power-scaling up to >500 W should not lead to significant degradation in specs**



IEEE PHOTONICS TECHNOLOGY LETTERS, ***18***, NO. 9, 1013(2006)

Fiber fs CPA System

- LMA PC (Photonic Crystal) fibers as power amplifiers, 40um core/200um clad



260W/80MHz/2.3ps,

Compressed to 240fs

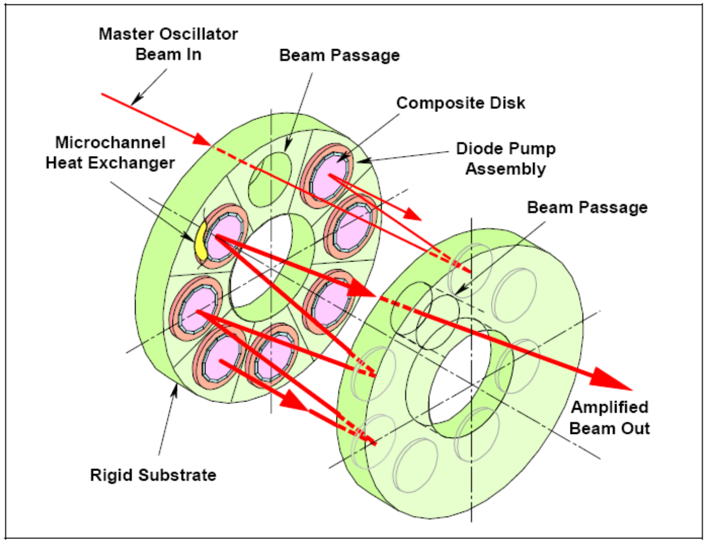
60% efficiency

OPT EXP. 17, 5815 (2009)

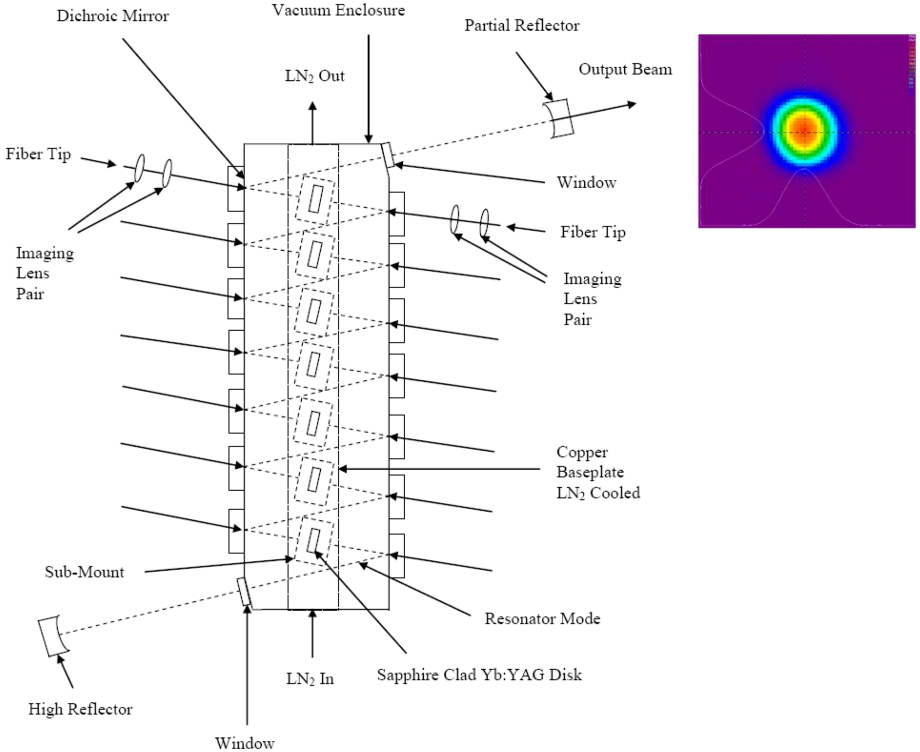
- The peak intensity inside LMA-YDCF ~1MW, extraction effi ~70% and 130W/m
- Scalable to 500W with 2 more power amplifiers & doubled rep rate to 160MHz
- Beam load in fiber ~65MW/cm^2 still below the GW/cm^2 threshold for FS core
- But peak pulse intensity ~ 100GW/cm^2 > SRS threshold?

Bulk/Disk Amplifiers

- **The risk of damaging fibers can be greatly reduced by using bulk material power amplifiers!**
- There are choices for kW bulk amplifiers.



J. Vetrovec, Laser&EO Systems, Boeing Company



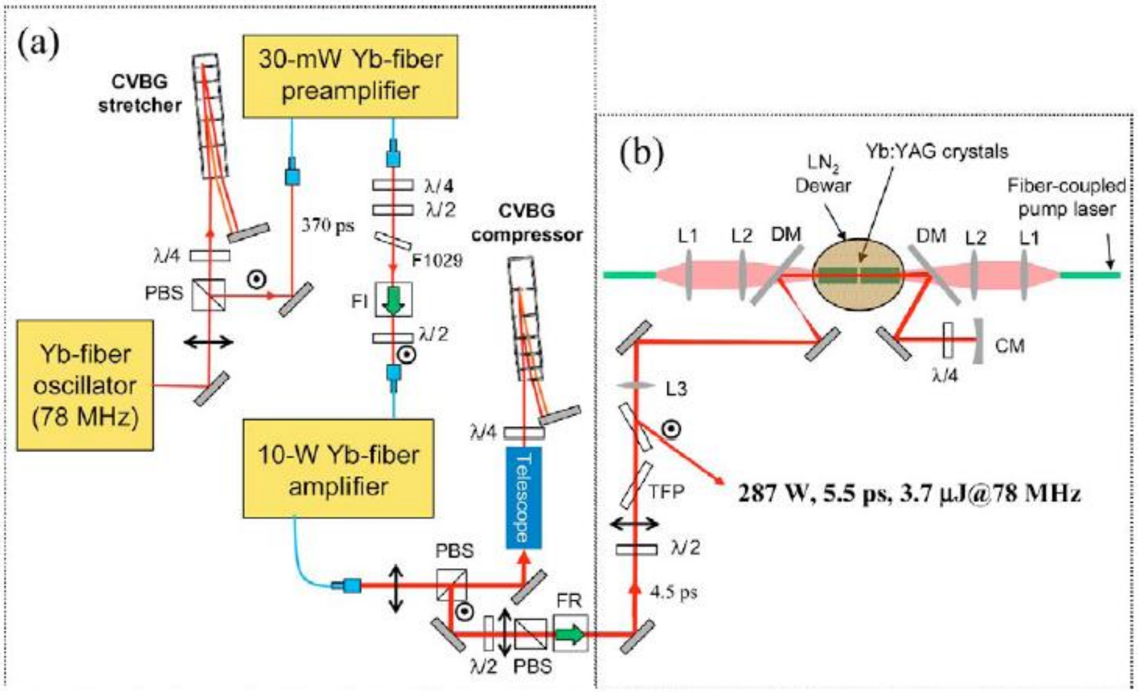
Schematic Diagram of the CW Diode pumped Yb:YAG Cryogenic Laser.

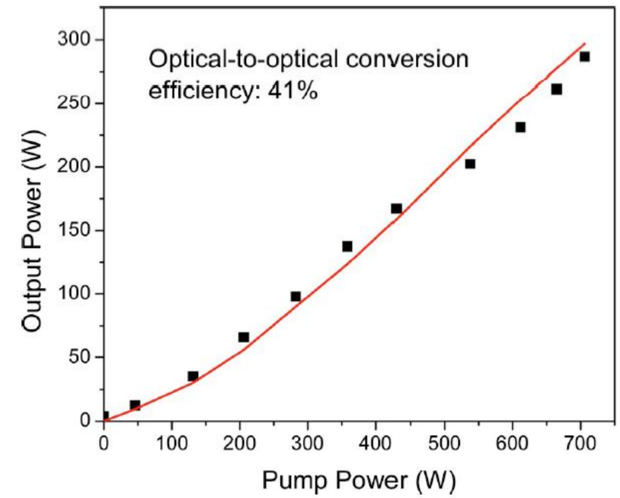
D.C.Brown, SCL, PA

- To take the full advantage, a front-end of 10s watts is needed.

Cryogenically-cooled Yb:YAG Amplifier

- Scale up to ~kW possible!



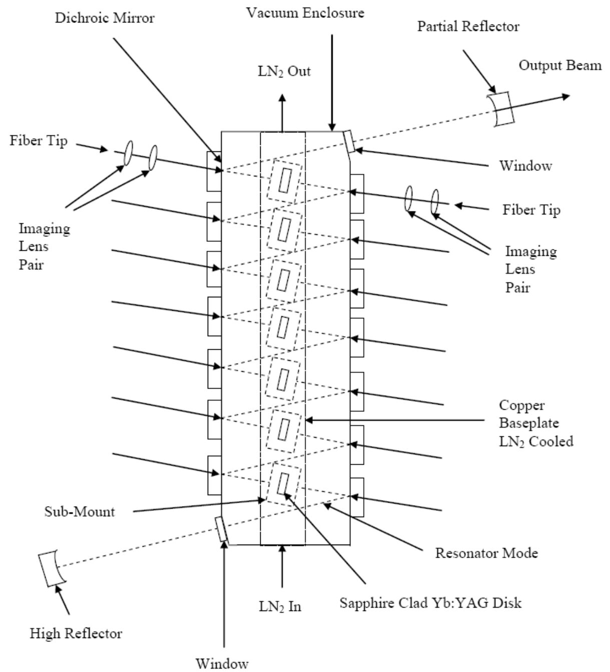


Estimated *B-integral* 5.1×10^{-3}, average power potentially scaled to 10 kW without being limited by SPM

- The pulse intensity far below the NL and optical damage threshold!

OPTICS LETTERS Vol. 33, No. 21 **2475 (2007)**

Green Cryo Yb:YAG Lasers



Schematic Diagram of the CW Diode pumped Yb:YAG Cryogenic Laser.

D.C.Brown, SCL, PA

201 W picosecond green laser using a mode-locked fiber laser driven cryogenic Yb:YAG amplifier system

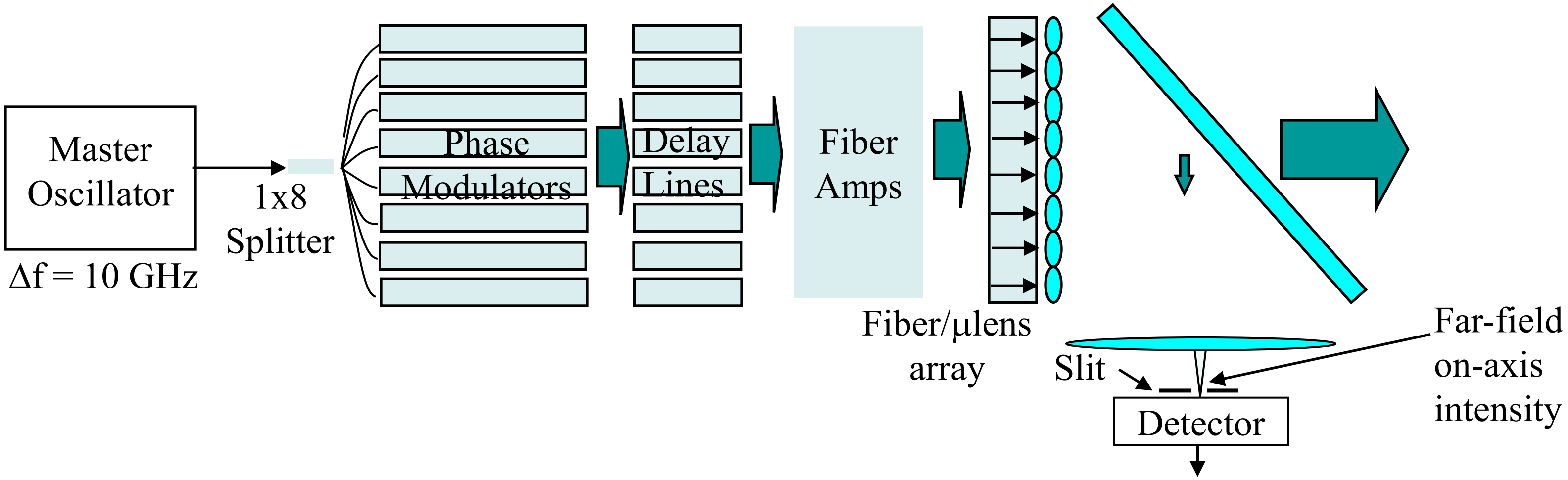
Katie Kowalewski, Optics Letters, Vol. 37, Issue 22, pp. 4633-4635 (2012)

Abstract: We have generated 201 W of green (514.5 nm) average power from a frequency-doubled picosecond cryogenic Yb:YAG laser system driven by a 50 MHz, 12.4 ps mode-locked Yb fiber laser producing 430 W of average power at 1029 nm, using direct pulse amplification. The fundamental beam produced was near-diffraction-limited ***(M2<1.3). Second-harmonic-generation is achieved using a 20 mm long noncritically phase-matched Lithium triborate (LiB3O5) crystal; conversion efficiencies as high as 58% have been observed. At 100 W of 514.5 nm output power, the averageM2value was 1.35. To the best of our knowledge, this is the highest average power picosecond green pulsed laser.***

- YLF can be a better option!

Coherent-beam-combing

- All eight 0.5-kW IPG PM fiber amplifiers are coherently combined to achieve 4-kW with 70% fill-factor mlens (T.Y.Fan, Lincoln Lab/MIT)

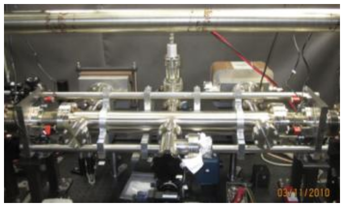


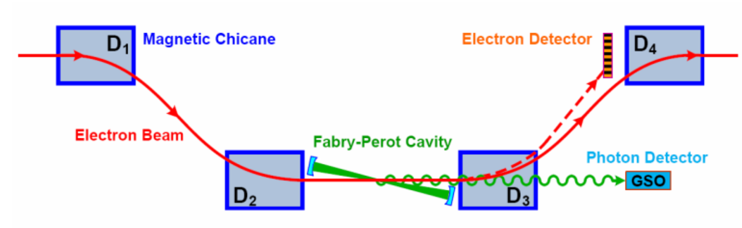
Year	Lab	# of Beam	Laser power (kW)	Ref
2011	LL/MIT	8	4	[1]
2012	LL/MIT	5	1.9	[2]
2011	AFRL	16	1.4	[3]
2012	NUDT	9	1.8	[4]

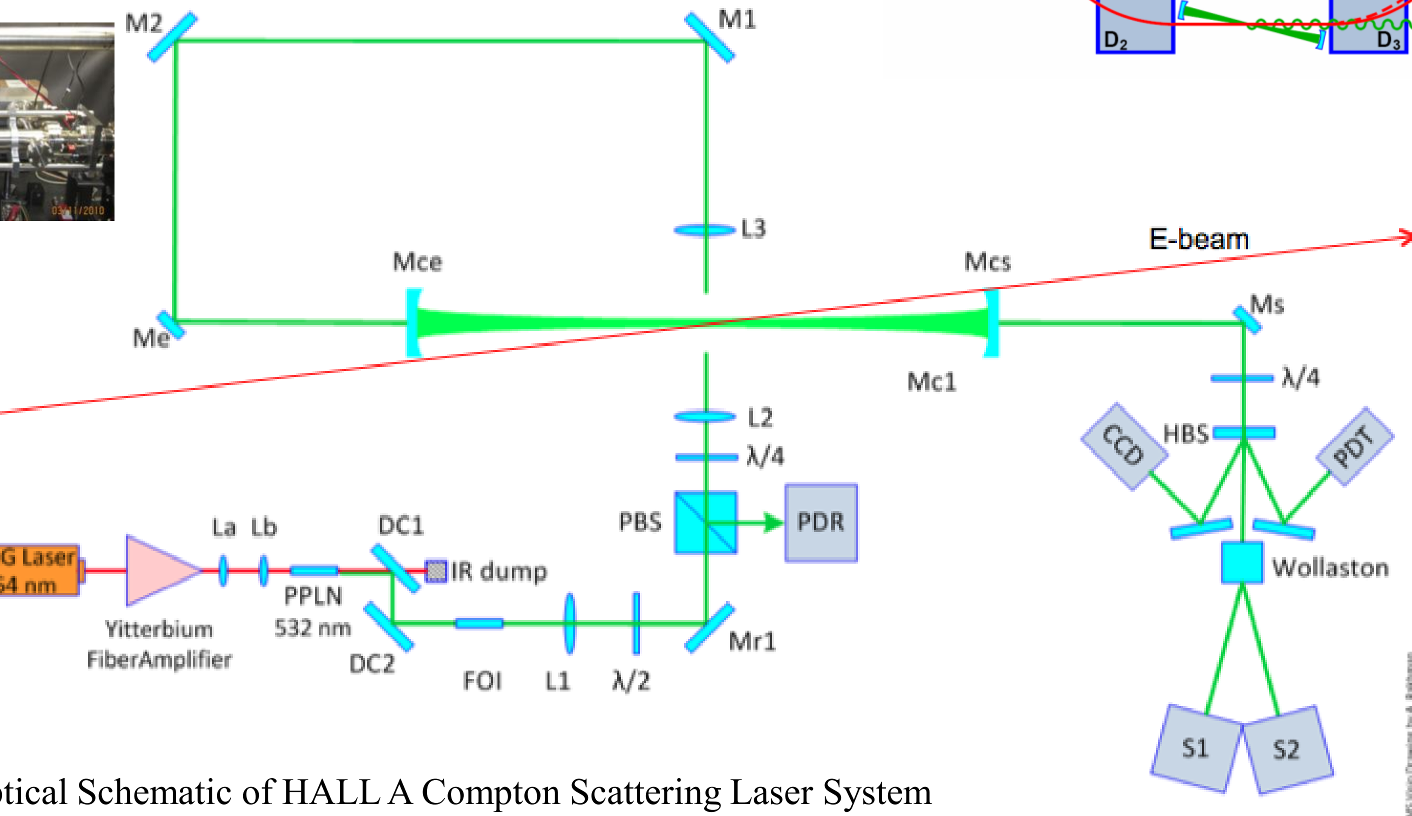
- Need to demonstrate performance with short pulses!

Power Enhancement by External Cavity

- Design goal, 1.5kW/532nm/TEM00
- Achieved 3.5kW intra-cavity power







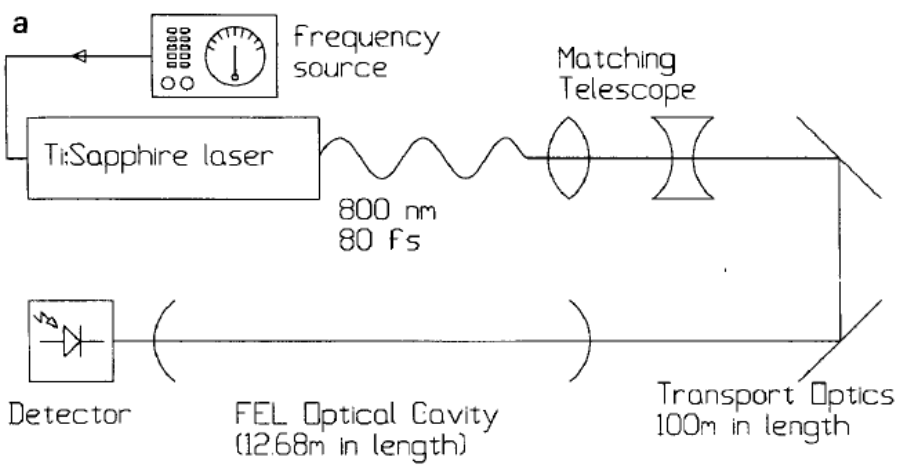
Optical Schematic of HALL A Compton Scattering Laser System

- More efficient interaction expected with pulse lasers!

Courtesy: S. Nanda, A. Rakhman

Enhanced (FP) Cavity-Pulse Laser

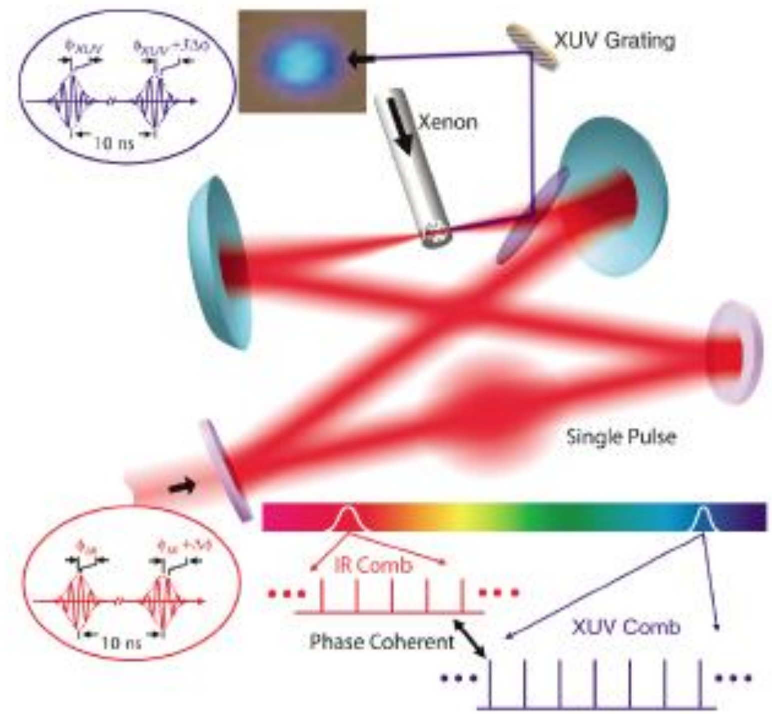
- Old idea found new applications
- Demonstrated with FEL and fs Ti:S laser



FEL cavity length measurement with an external laser

K.W. Berryman *, P. Haar, B.A. Richman

NIMA (1995)



x600 enhancement, 50fs
PRL 94, 193201 (2005)

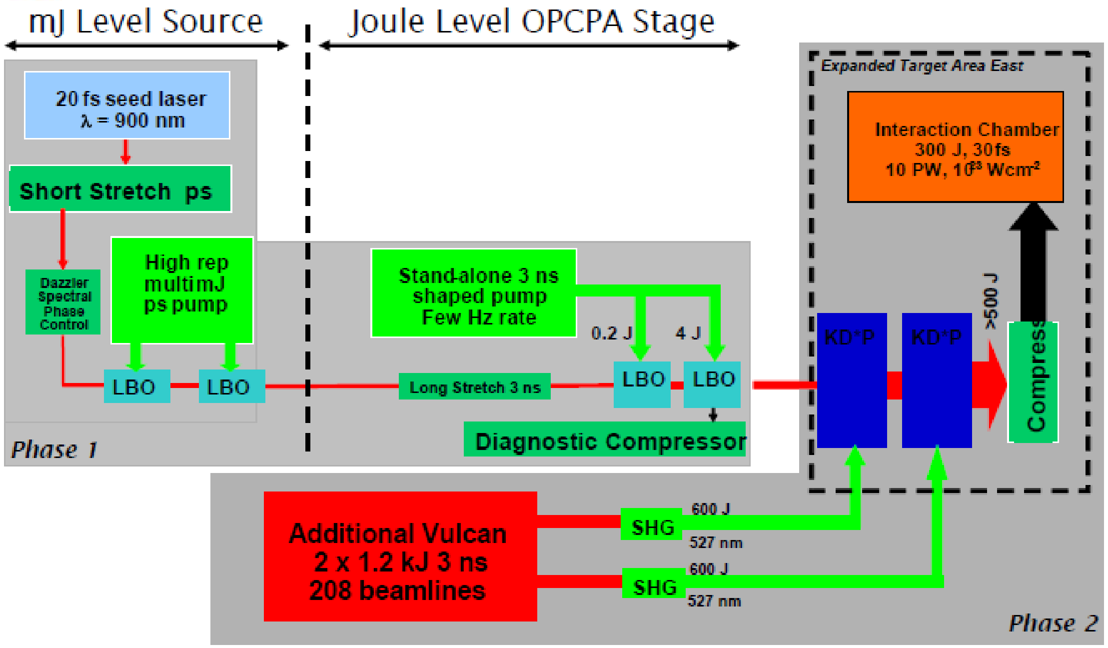
- Also refer to Francois's talk.

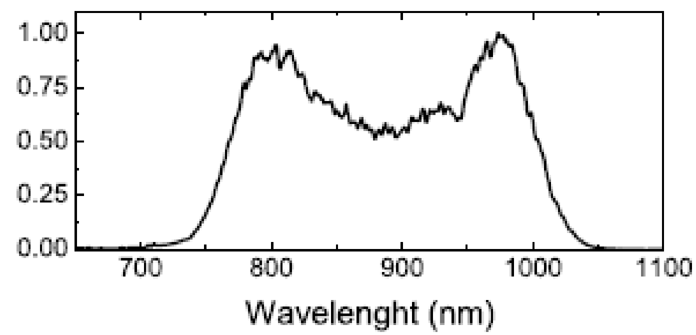
OPCPA: Alternative to Ti:Sapphire Lasers

- Optical Parametric Chirped-Pulse-Amplification (OPCPA)
  - Large, low loss, Boradband NL crystals available
  - Very high gain (1e12), Efficiency >50%, Near DL, No thermal loading
  - Potentially sub-10fs HAP and HE (J level)

Limited by pump source (Spatial &Temporal flat-top, ps)!

High Energy 10 PW OPCPA on Vulcan



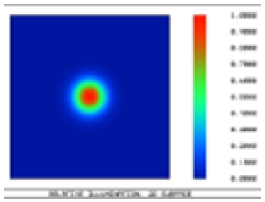


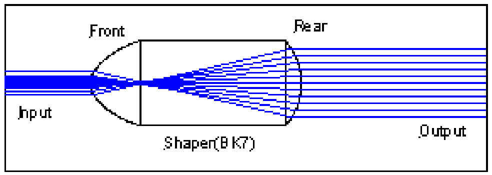
5mm BBO Ampl. Spectral gain

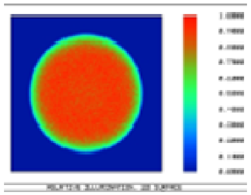
- Will be based on a combination of LBO and KD*P

Beam Shaping

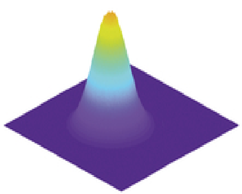
- Lasers are intrinsically Gaussian, both T and L,

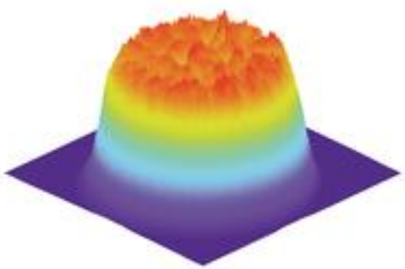






- Refractive shaping, high efficiency. Needs ***perfect*** input beam: shape, size and collimation





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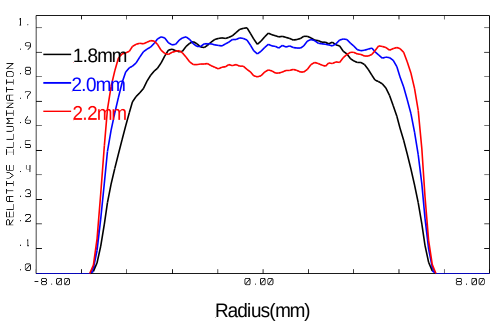
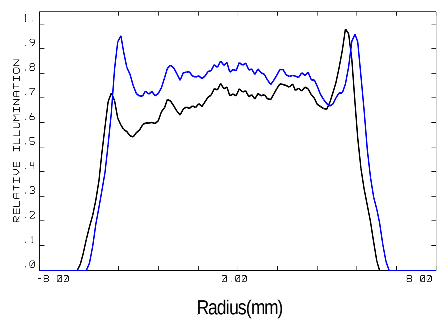
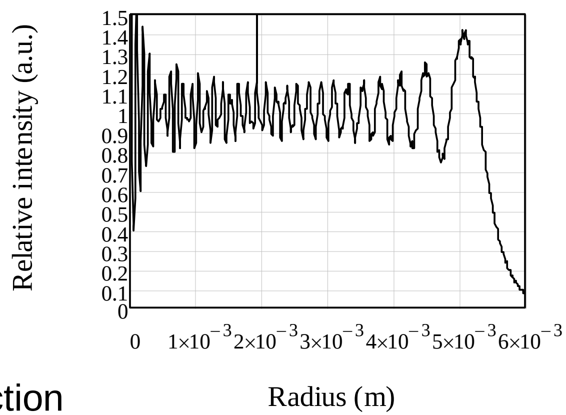


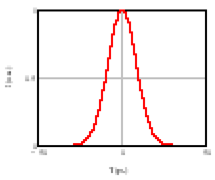


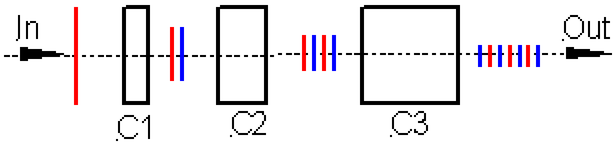


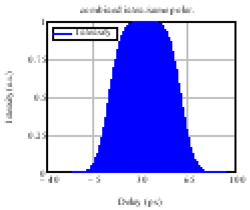
Left: Size mismatch. Center: de-centering Right: diffraction

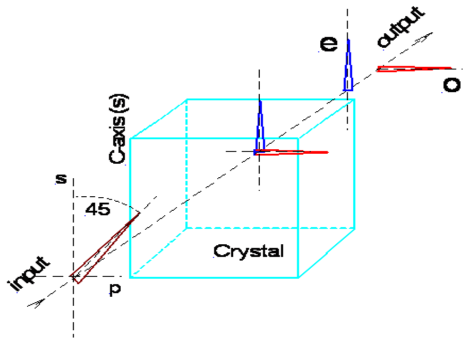
Temporal Shaping Technique

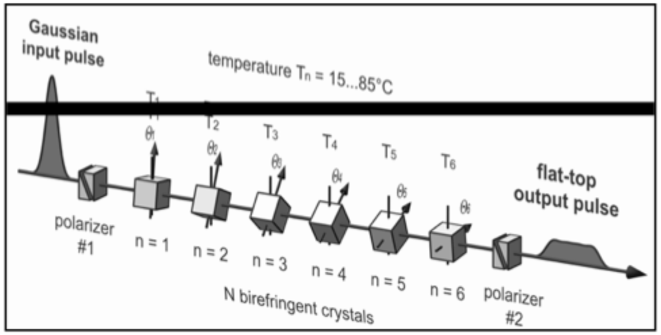
- Temporal shaping by pulse stacker.











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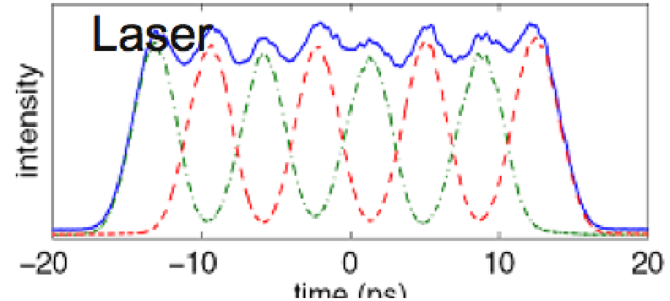

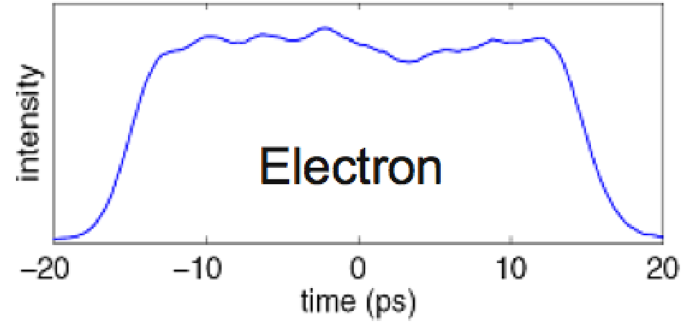

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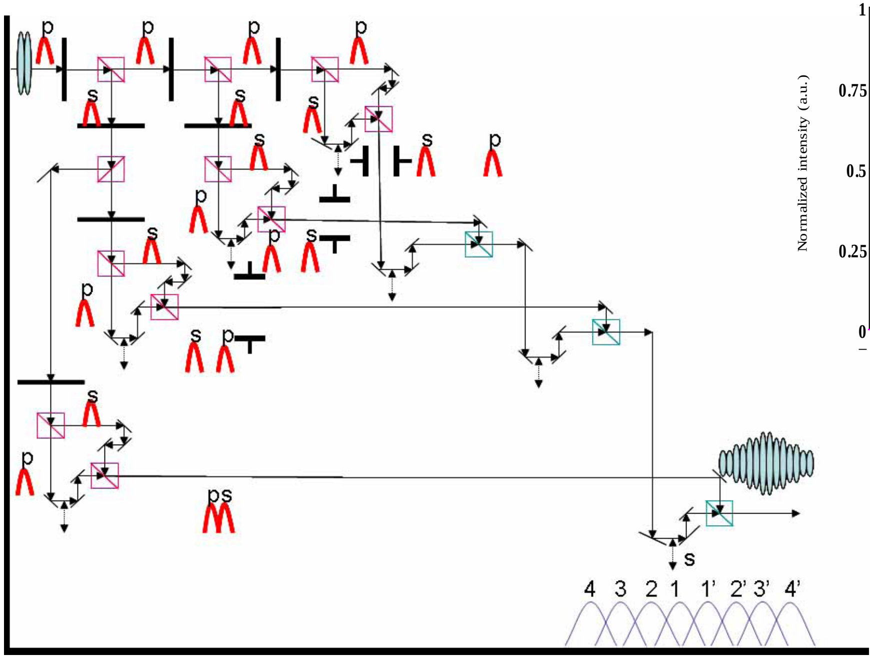
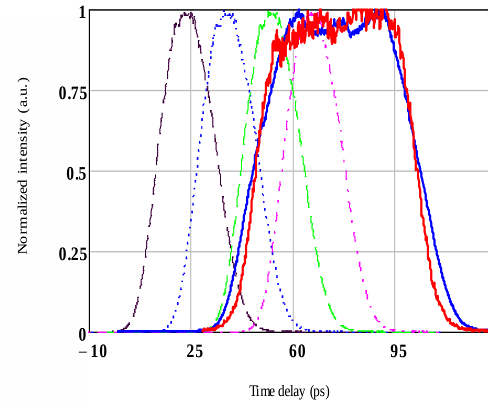
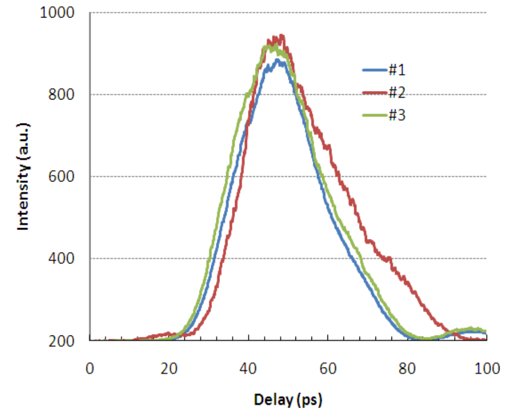
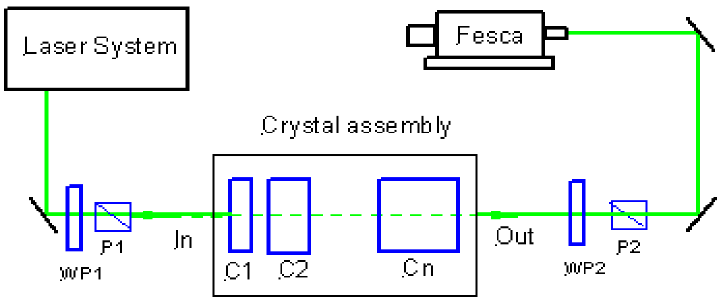
Go Arbitrary?









- **Complicated and can be lossy,**

It is possible to generate unusual shape with a pulse stacker. /S. Zhang, FEL 2010

Z.He et al. Proc of PAC2011

Demand and challenge

Higher pulse energy/Power
Higher rep rate (10s~100s MHz)
Shorter pulse (ps,10s of fs)
Robust beam & pulse shapers
Flexible pulse structure/contrast
Better stability
(Higher opt. damage threshold)

A Brief Check-list for Laser Specs

- Wavelength/Spectral bandwidth (IR/Green/UV, TLD)
- Beam (spatial) shape and quality
- Power/pulse energy
- Rep rate and pulse structure
- Pulse shape/width, and contrast
- Polarization
- Synchronization control and Protection
- Stability
  - ➢Amplitude stability, Phase stability
  - ➢Pointing stability, Frequency stability
- Scalability/upgradability
- Radiation resistive
- Beam transport

Robustness
easiness of maintenance
Weight/Volume/Cooling
/Diagnostics
Cost

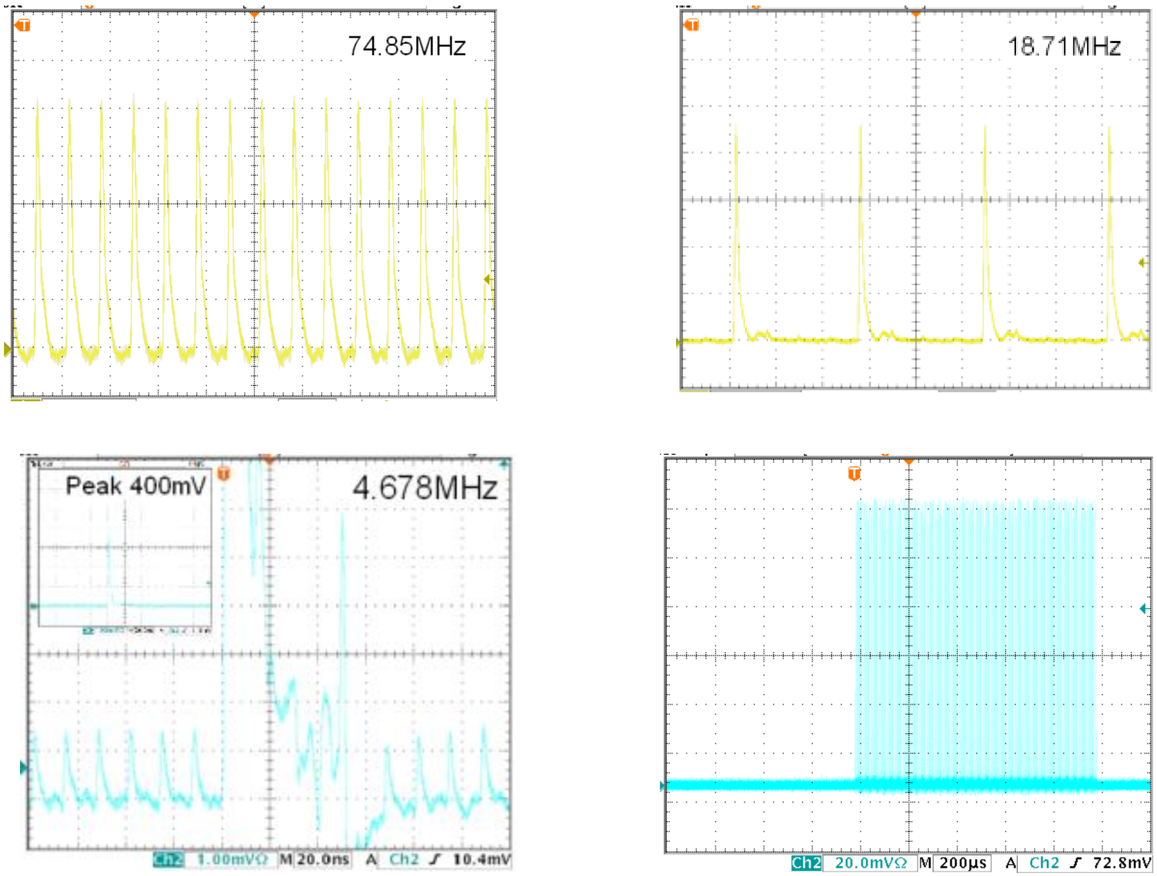
Summary

- Significant advancement is seen in laser applications in accelerator R&D.
- Although lasers have become an important part in accelerator systems, the gap exists between the state-of-the-art technology and that needed.
- Further effort on laser R&D has to be made in order to meet the challenges from accelerators.

Acknowledgement: Thanks to all whose work was cited in this talk and apology to those whose name are inadvertently neglected.

Pulse Contrast

- The ghost pulse will severely interfere with the initial machine setup. Pulse contrast of at least 10^4 is needed.

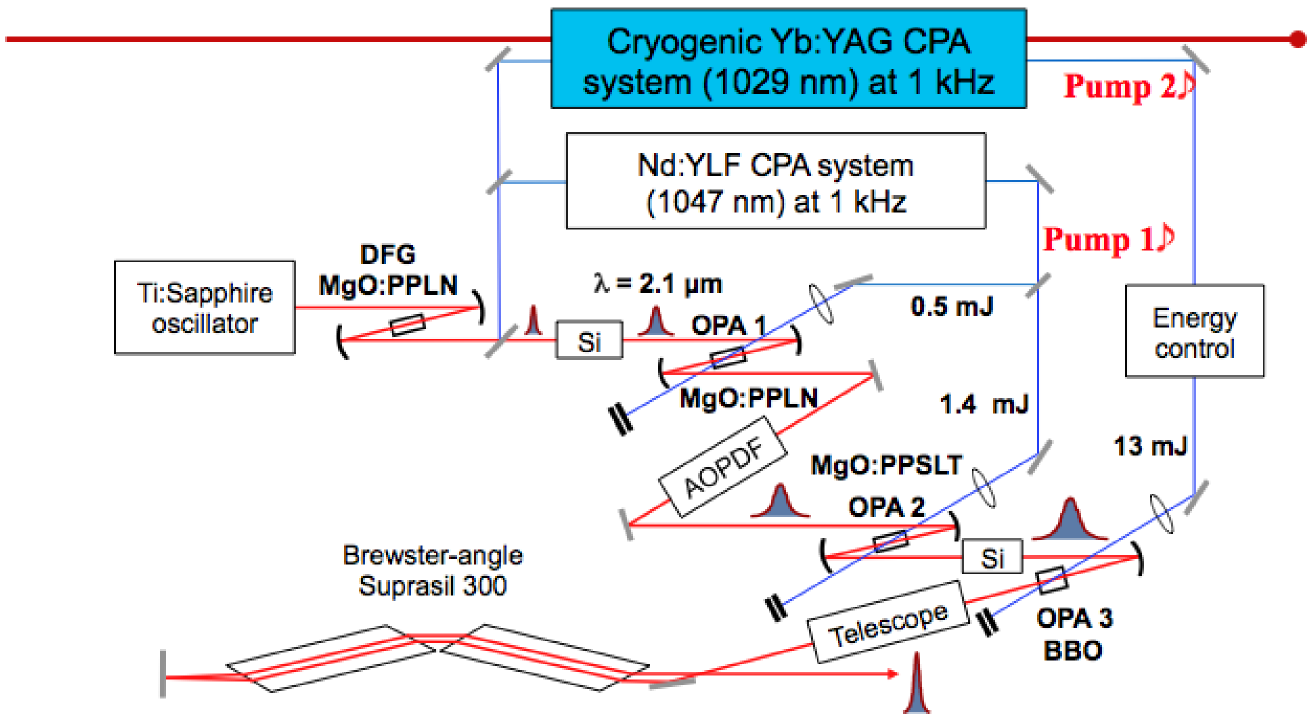


Examples: Pulse waveforms at different repetition rates. Top-right, 74.85 MHz pulse train. Top-left, 74.85/4 MHz pulses. Bottom-left, pulse peak and residual pulses. Bottom-right, a macro-pulse.

Another One

- OPCPA promising for High energy, kW average power, picosecond pulses

Cryo Yb:Yag pumped 2.1-μm OPCPA



- BBO: 4-mm long, type I, θ=21.4 deg
- Beam size: ~1.4 mm (dia.)
- Pump peak power: ~50 GW/cm²
- Suprasil 300: Brewster angle, 62 cm total path length

SLAC NATIONAL ACCELERATOR LABORATORY

K.-H. Hong *et al.*, Opt. Express **19**, 15538-15548 (2011).