Overview Of New Laser Technologies For Applications In Beam Instrumentation

Shukui Zhang
Thomas Jefferson National Accelerator Facility

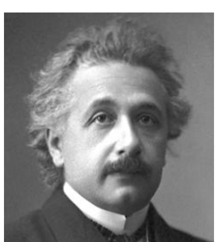
BIW'2012, April 16, 2012, Newport News, Virginia, USA

Outline Of Talk

- A bit of history
- What has been achieved
- Application in accelerators
- What are needed and expected
- Summary

52 Years of Laser Innovation

- LASER: "Light Amplification by Stimulated Emission of Radiation",
- Einstein's (1917): Stimulated Emission,
- Charles Townes at Columbia U., Arthur Schawlow at Bell Laboratories, published paper (1958)/ 1st laser Patent (1960),
- The first working laser, Theodore Maiman, Hughes Research Lab (1960),
  - 1964, **Townes, Prokhorov and Basov**, for "fundamental work in the field of quantum electronics which has led to the construction of oscillators and amplifiers based on the maser-laser principle."
  - 1981, **Arthur Schawlow and Nicolaas Bloembergen**, one half of the Nobel Prize in Physics for "contribution to the development of laser spectroscopy."
- *Laser Patent War,* Gordon Gould, graduate student at Columbia University




Charles Hard Townes


Basov


Prokhorov


Nicolaas Bloembergen


Arthur Leonard Schawlow

Laser Revolutionized the Way We Live

- Laser, one of the greatest inventions of the 20th century,
- 50^{th} anniversary widely celebrated around the world in 2010

"Today, lasers are everywhere: from research laboratories at the cutting edge of quantum physics to medical clinics, supermarket checkouts and the telephone network." C. Townes

- 1971, invention of the laser printer,
- 1974, bar code scanners, The first widely recognized application,
- Now, from DVD players to eye surgery, from toys to weapons…
- Almost every day, a new laser application is reported.
- >55,000 patents involving the laser granted in US

Where We Are Today

The rapid growing ***Diode Laser/Fiber*** technology brought in revolutionary advancement to other lasers,

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

May 16, 1960

Ted Maiman demonstrates the first ruby laser.

Hughes Research Laboratory

Where Lasers Stand Today - Powerful

- We don't know how much power Theodore made, maybe <mW
- 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

TiTAN Series

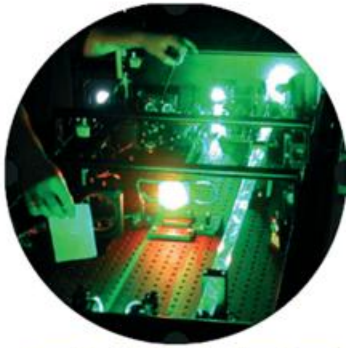
Laser Photonics Unveils First Ever 10-Kilowatt Laser Cutting System

Lake Mary, FL., December 2, 2008

Where Lasers Stand Today - 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. Ti:sapphire PW laser

Off the shelf!



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

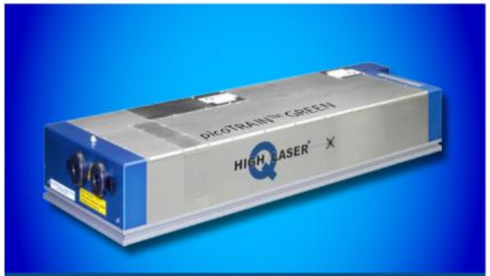
LUMERA LASER

1064 nm <15 ps
>45 W @ 1000 kHz

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}; $M^2 \le 1.2$						

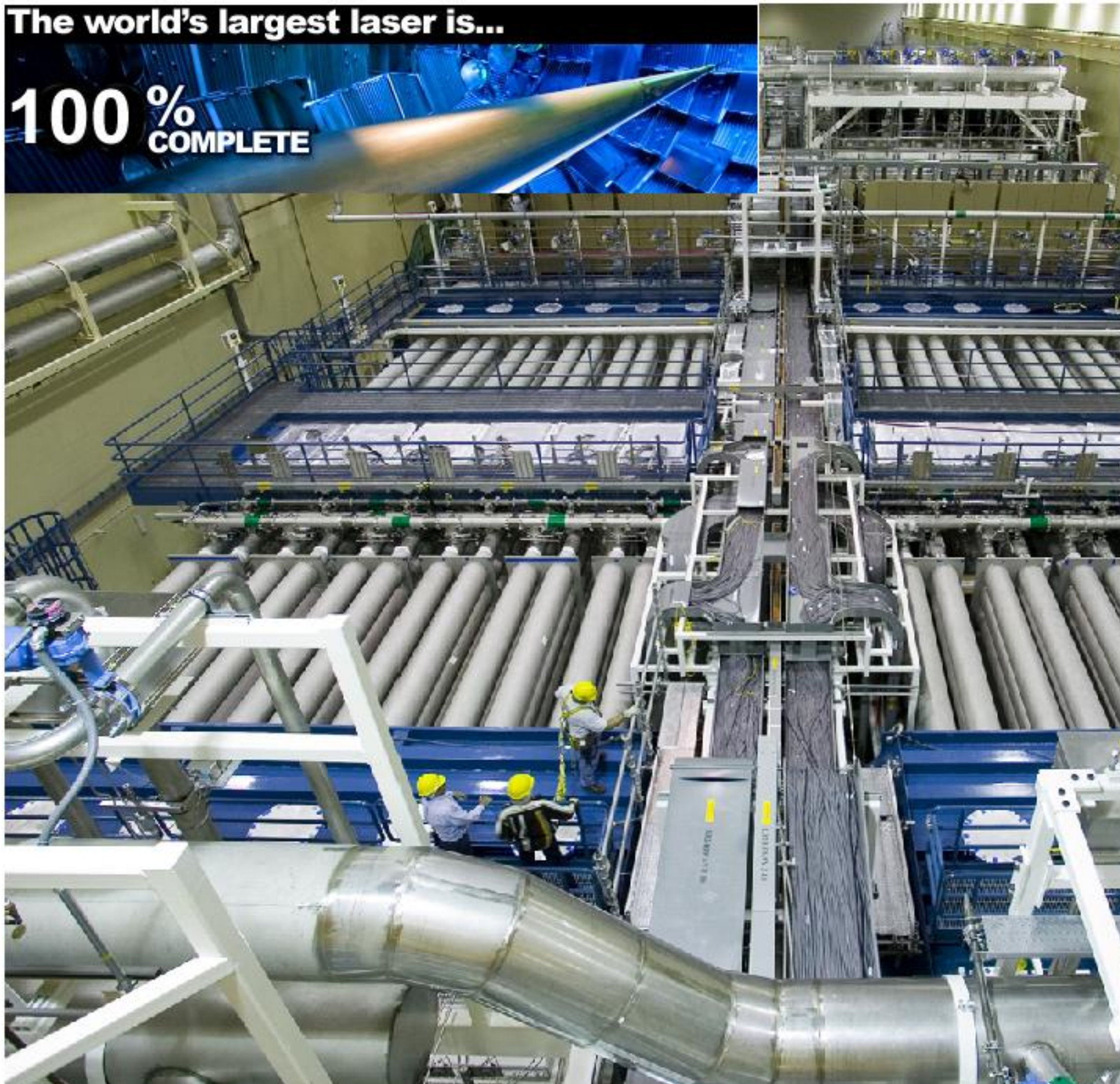
ARGOS™

High-Power Picosecond Laser

SESAM® Technology
Customizable

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

Real Big Laser for Great Science



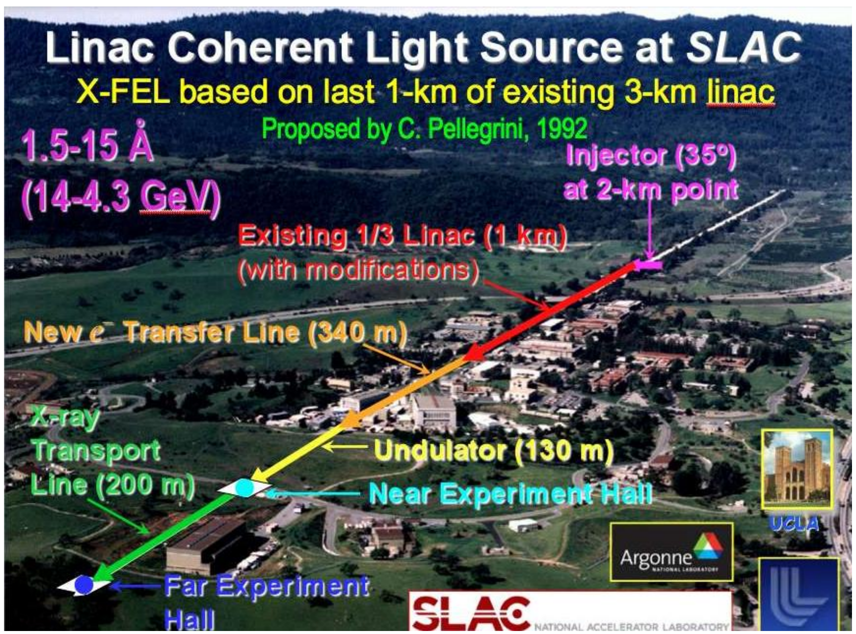
Mar.15, 2012, LIVERMORE, Calif. -- NIF, the world's most energetic laser, surpassed a critical milestone in its efforts to meet one of modern science's greatest challenges: achieving fusion ignition and energy gain in a laboratory setting. NIF's 192 lasers fired in perfect unison, delivering a record 1.875 MJ of ultraviolet laser light to the facility's target chamber center.

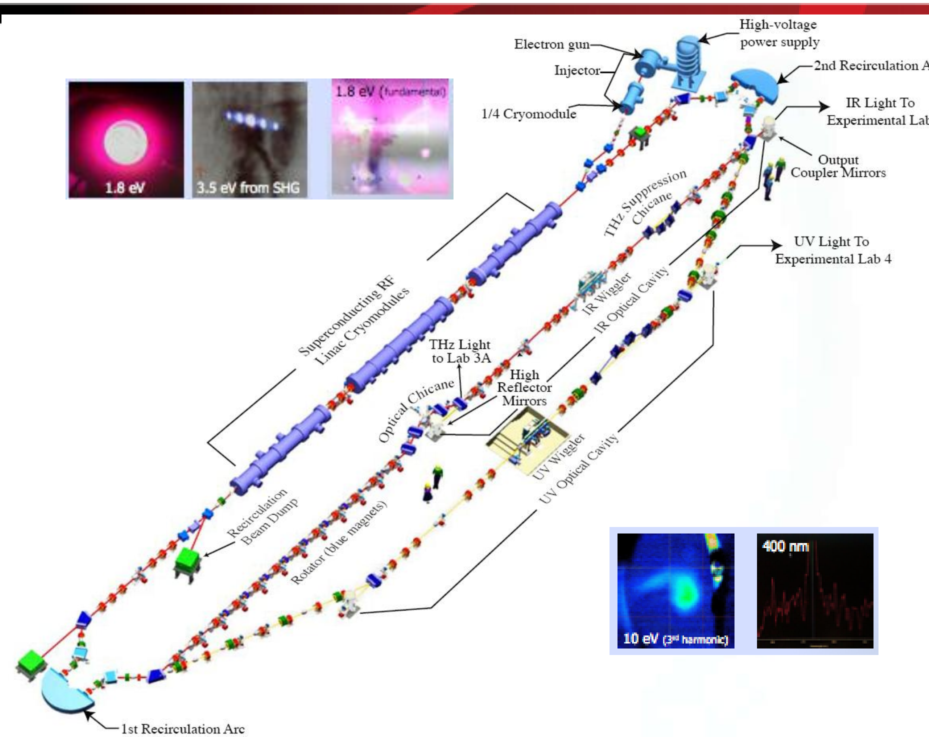
Lasers Built on Accelerator Technology

❑ SLAC LCLS

✓ 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 (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%

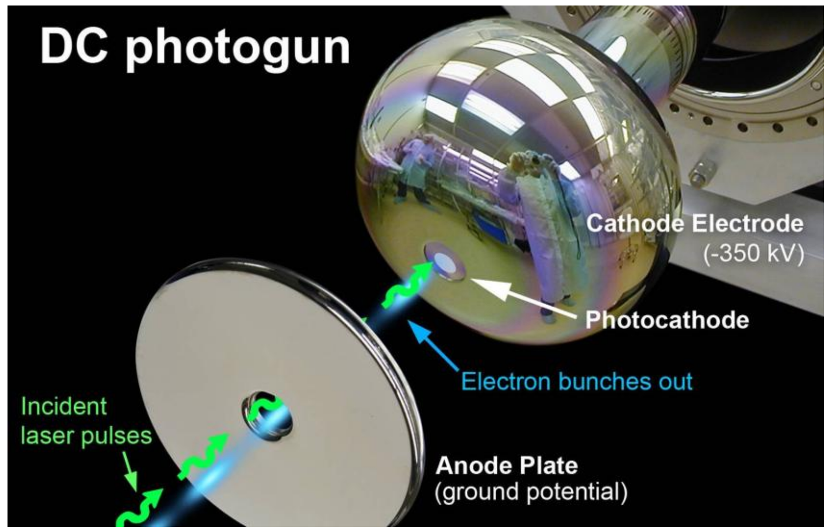
What Lasers Do for Beam/Accelerators

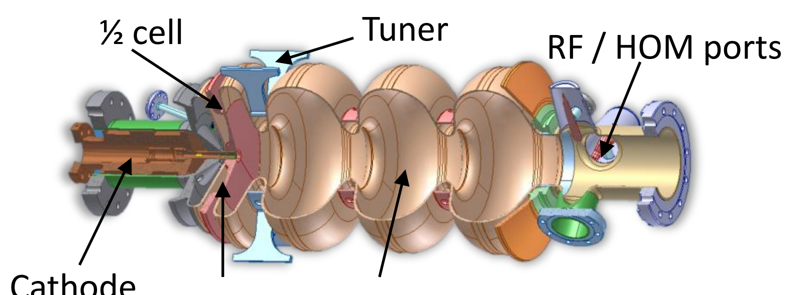
- Generation of High-power High Intensity High Brightness short-pulse e-beam
  - Short pulse e-bunch, Special e-beam requirements.
- Diagnostics
  - Non destructive E-bunch temporal and spatial measurement (EO)
  - Laser mapping, Laser stripping, Laser wires/scanner,
  - Compton scattering devices (external cavity)
- High precision synchronization
- Application in SC cavity
  - Laser heating,
  - SRF Cavity inspection
  - Surface repair/treatment
- Seed Lasers for future light sources

Generation of HPHIHB short e-bunch

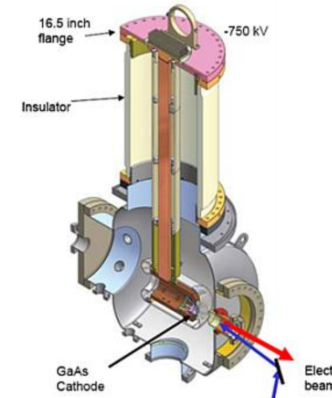
- GUN/Injector technology identified as the key for future light sources,
- JLAB FEL ERL 10mA, Cornell DC GUN 50mA reported,
- Under development: JAEA 500kV GUN, ELBE, BNL, LANL, LBNL,...

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

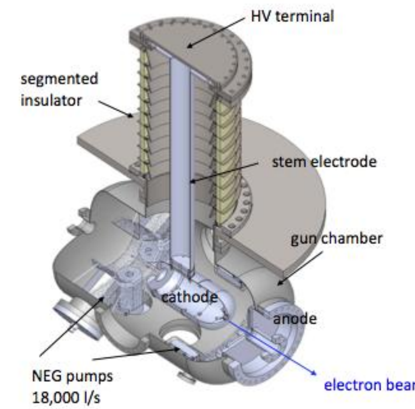




ELBE SRF GUN



Cornell GUN



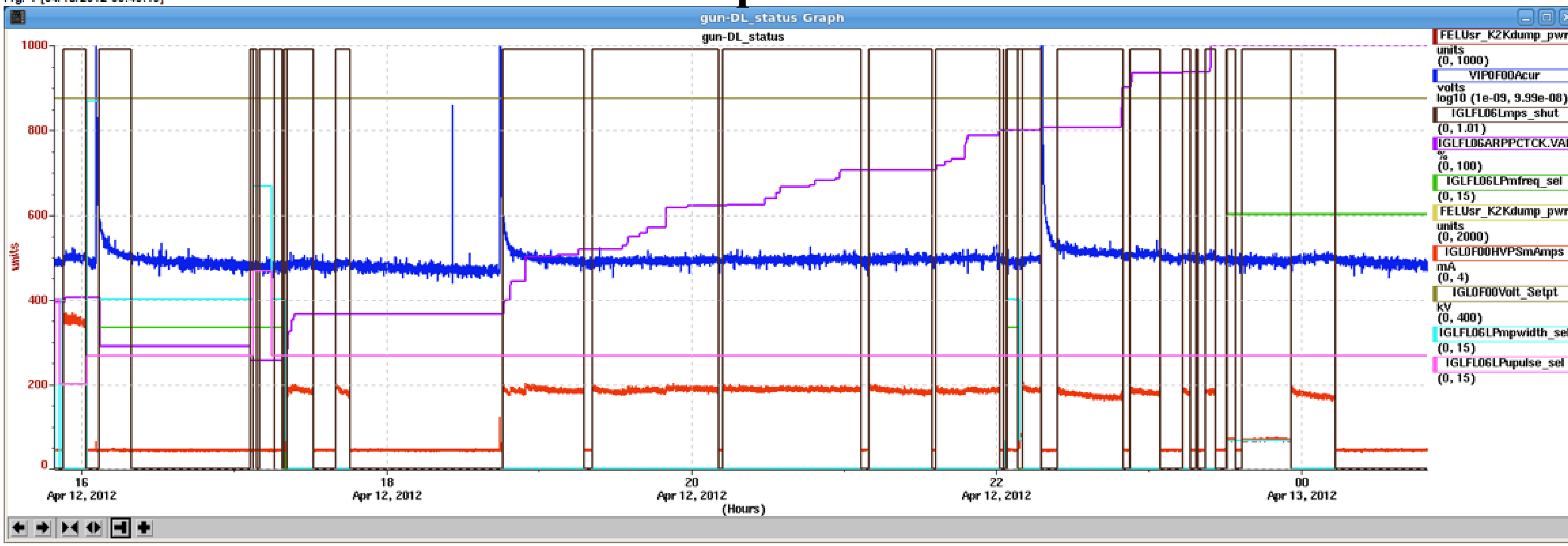
JAEA 500kV DC GUN

Needs lots of Laser Power

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

JLAB FEL Beam operation record

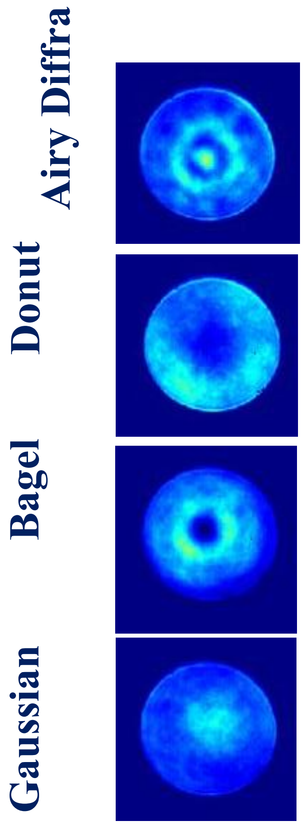
Fig. 1 [04/13/2012 00:49:19]

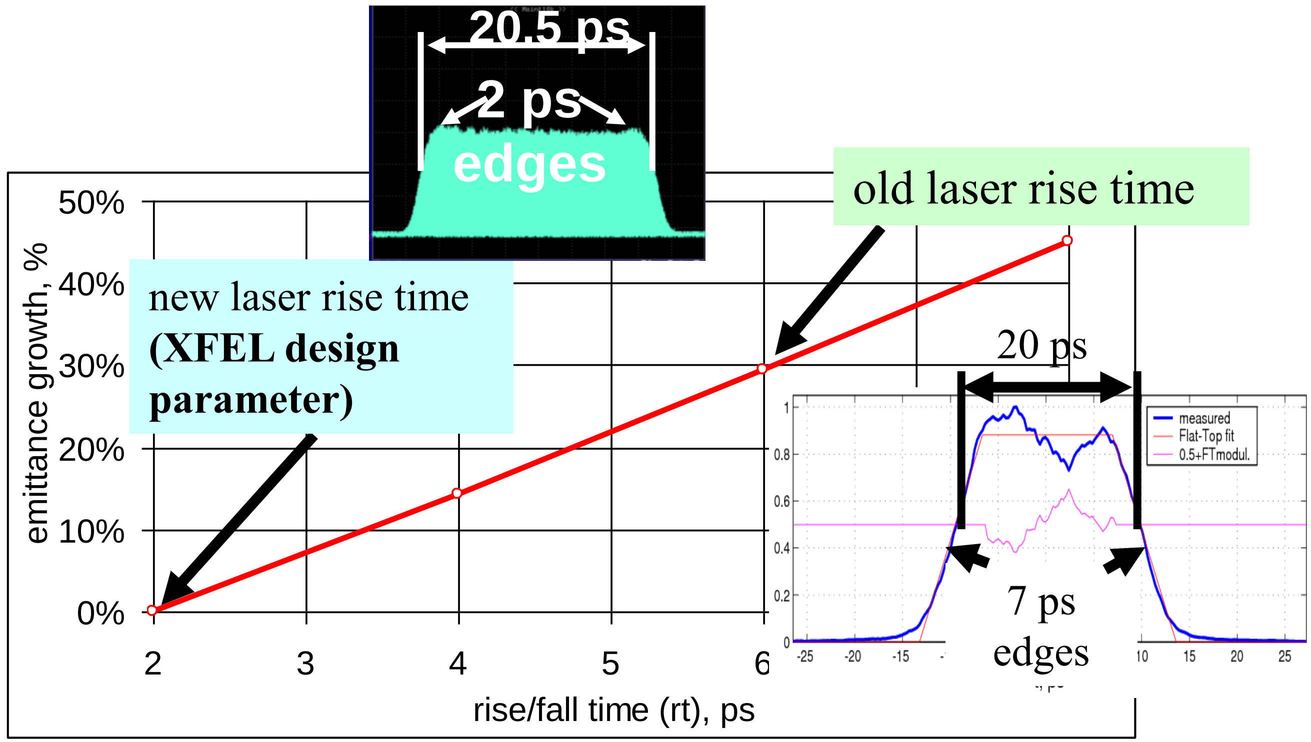


Improving e-beam Brightness

- Transversely, uniform laser beam leads to smaller emittance growth (D. Dowell, FEL'09)

Measure for Each Shape: Projected & Slice Emittance, Gain Length, FEL Extraction





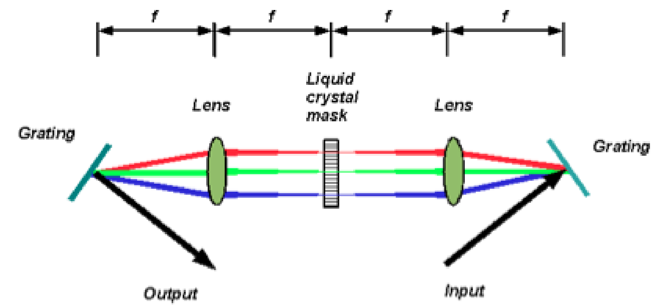
Longitudinally, Shape/Rise/Fall Edges affect emittance (*C. Boulware, FEL'08*)

Laser helps Improve Beam Brightness

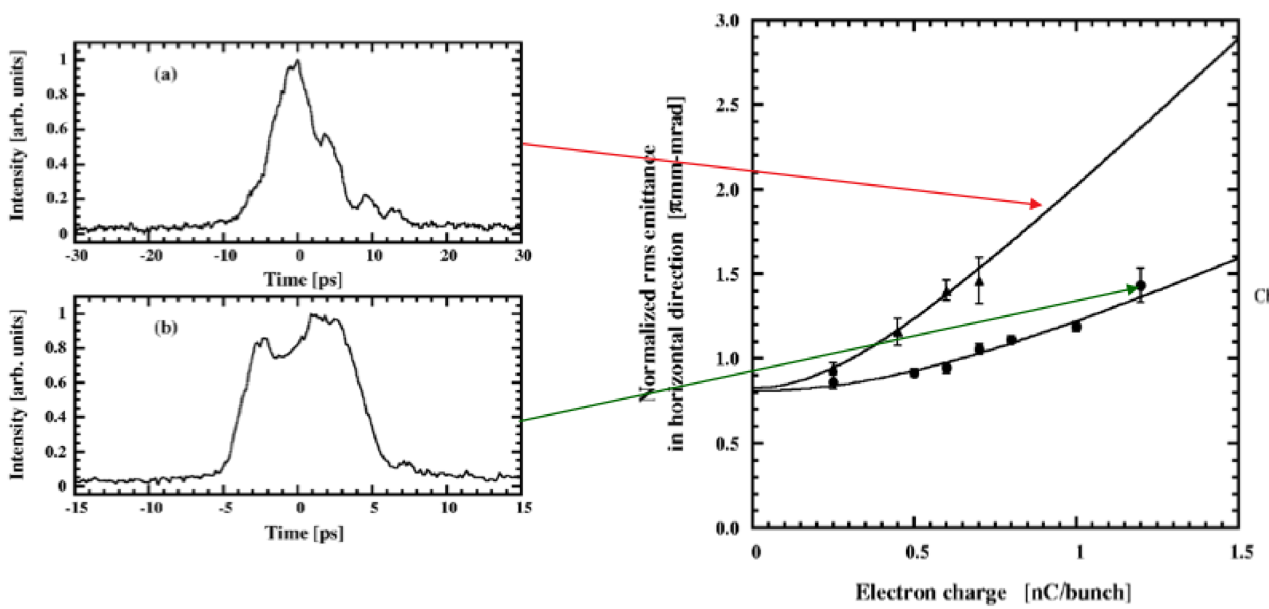
Pulse shaping by liquid crystal spatial light modulator (LC SLM) phase modulation driven by a genetic algorithm significantly reduced emittance,

- Beam: 14 MeV, 1 nC, 8 ps pulse
- LC SLM works well only with low power laser,

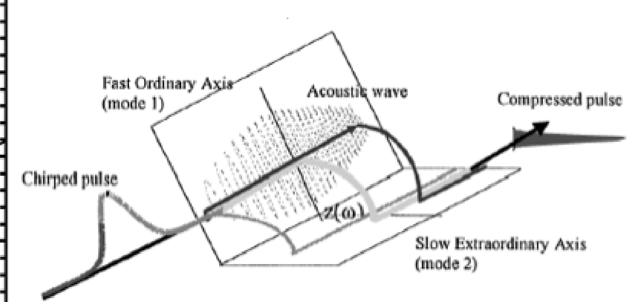
difficult to align, with limitation on tunability

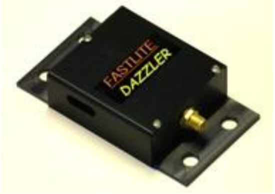


A. M. Weiner, Rev. Sci. Instrum. 71, 1929 (2000).



Yang et al., J. Appl. Phys 92, 1608 (2002)



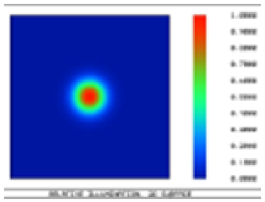


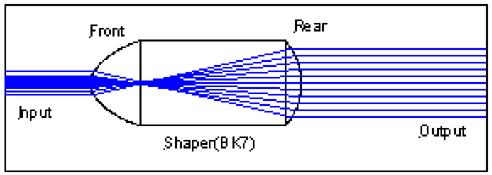
fastlite.com

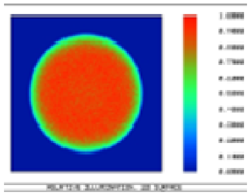
[Ultraviolet acousto-optic programmable dispersive filter laser pulse shaping in KDP S.Coudreau et al.O.L. Vol.31, p.1899-1901] (2006)

Transforming the Gaussian Shape

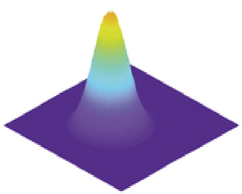
- Lasers are intrinsically Gaussian, both T and L,

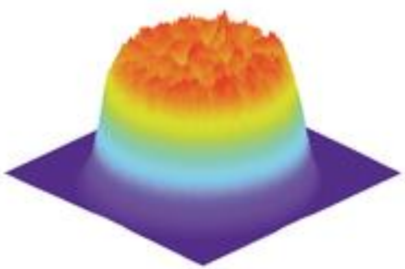




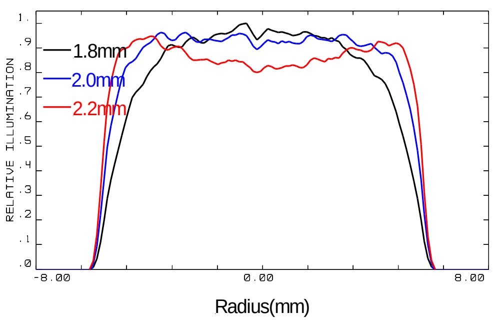


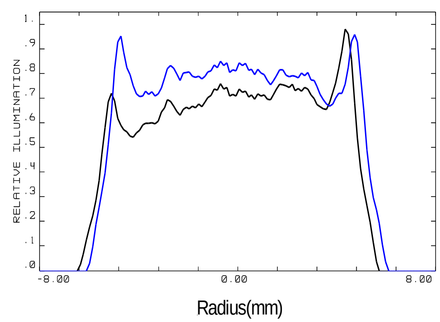
- Refractive shaping, high efficiency. Needs ***perfect*** input beam: shape, size and collimation

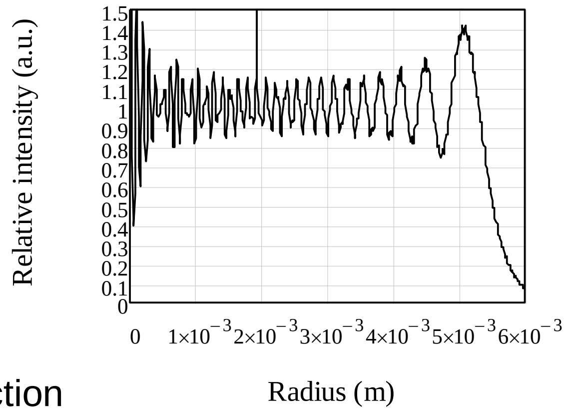




J. A. Hoffnagle et al., *Appl. Opt.* **39**, 5488–5499 (2000).
S. Zhang, *J. Opt. A: Pure Appl. Opt.* **9** 945-950.
C. Liu and S. Zhang, Opt. Express **16**, 6675-6682 (2008)
S. Zhang, et al.,*Opt. Express* **14**, 1942-1948 (2003).
S. Zhou, et al., Appl. Opt. **46**, 8488-8492 (2007).



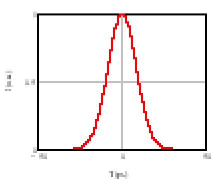


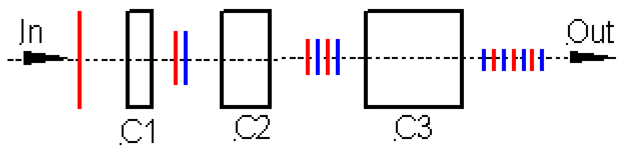


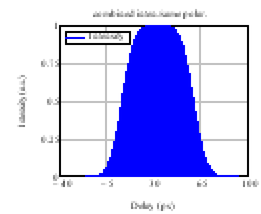
Left: Size mismatch. Center: de-centering Right: diffraction

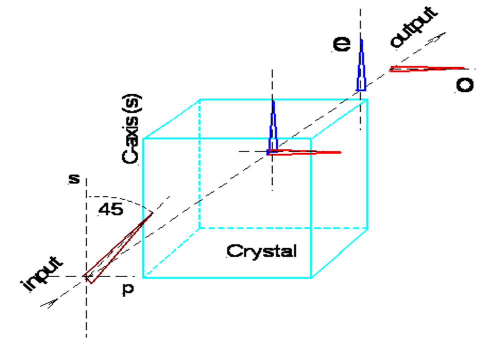
Temporal Shaping Technique

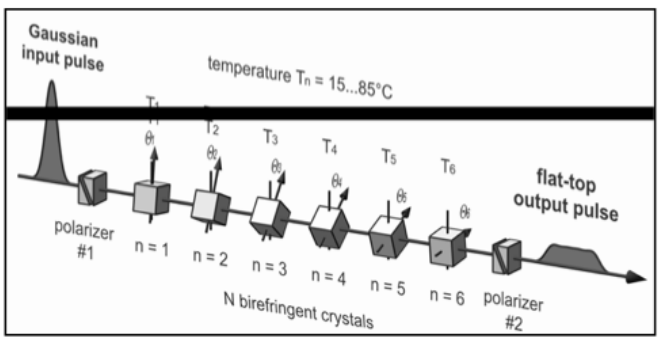
- Temporal shaping by pulse stacker.



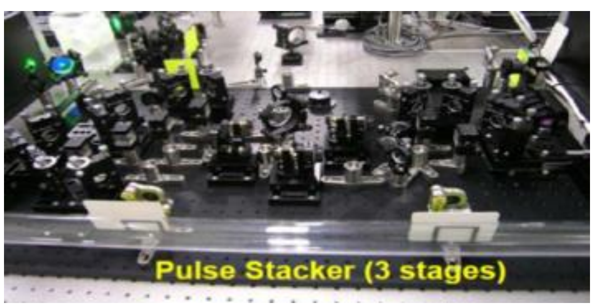




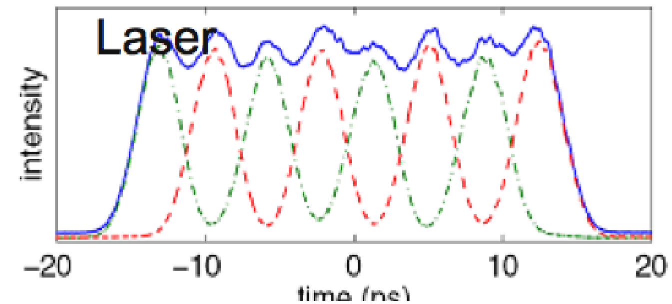


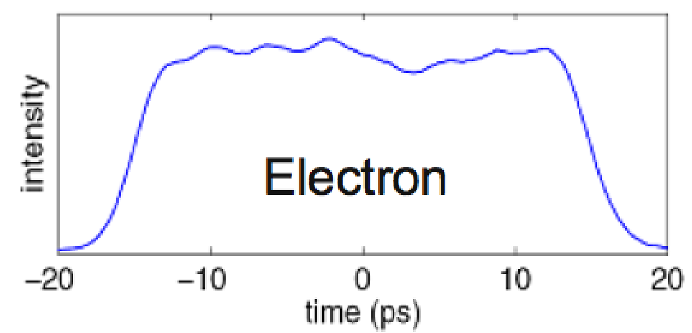


I. Will et al.; Optics Express 16 (2008) 14922



Tomizawa, Quantum Electronics 37, 697 (2007)

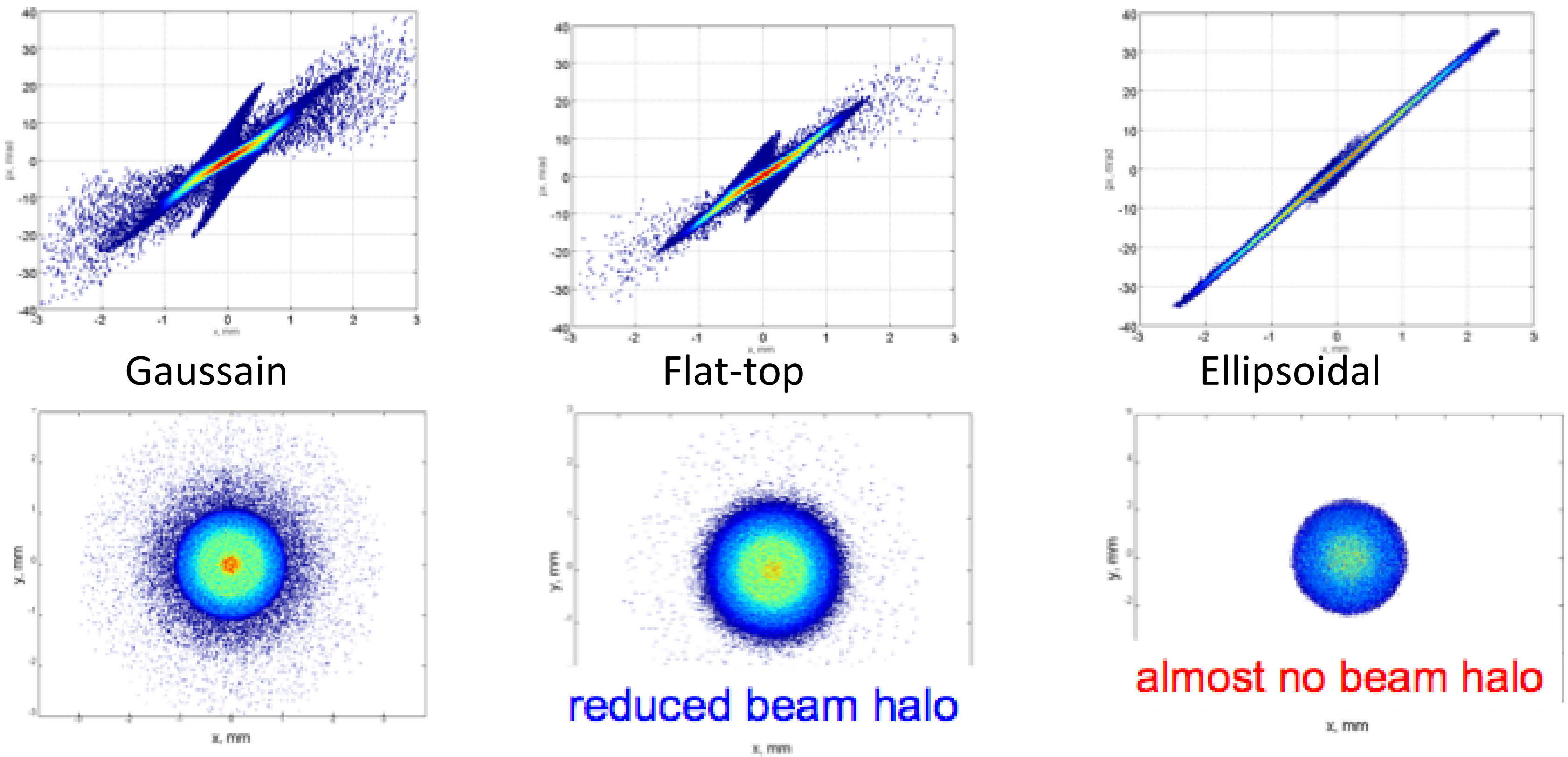




H. E. Bates et al., Appl. Opt. 18, 947 (1979)
I.V. Bazarov et al, Phys. Rev. ST AB 11, 040702 (2008).

Is there an Ideal Bunch Distribution

- **Ellipsoidal shape, linear phase space for complete emittance compensation,**
- **May only be possible with laser optical approach.**



Top: Transverse phase space. Bottom: e-beam transverse distribution. 1nC/ z=5.74m

Courtesy: M. Kraslinkov. Simulation for PITZ

Racing for “egg”

- Starting with a pancake laser, the electron beam “blow out”, evolves to ideal ellipsoid,
- Demonstrated <50 pC charge, distortion at higher charge.

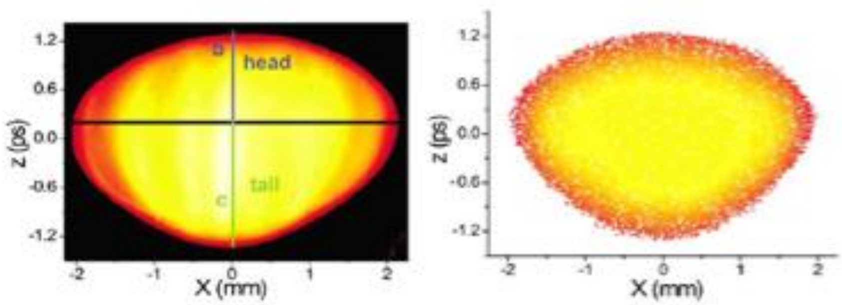
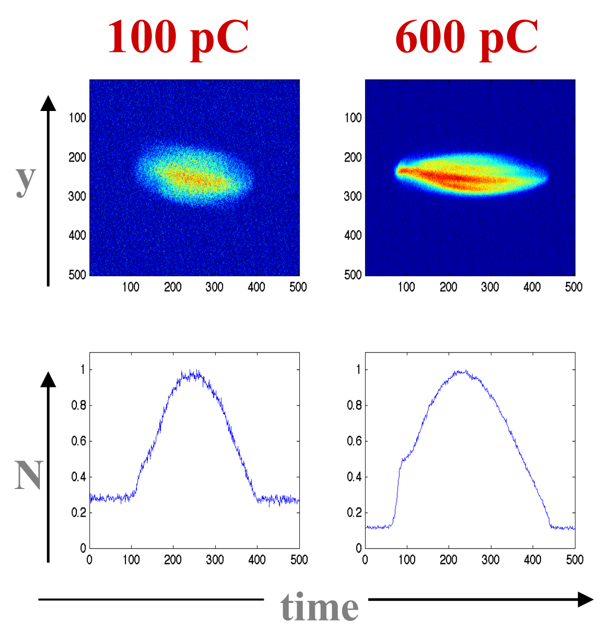


FIG. 5 (color online). Measured (left) and simulated (right) asymmetric beam distribution for $Q = 50$ pC.

P. Musumeci, et al., PRL. 100, 244801 (2008).

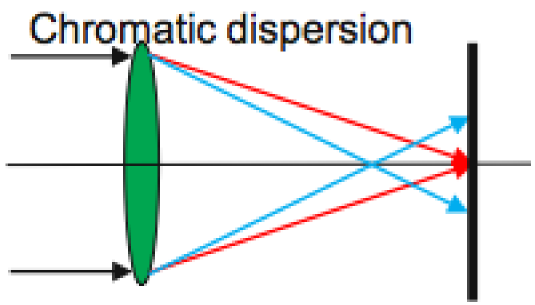
L. Serafini, AIP Conf. Proc. 413, 321 (1997).
O. J. Luiten et al, PRL. 93, 094802 (2004).
B. J. Claessens, PRL. 95, 164801 (2005).
J. B. Rosenzweig et al., MINA 557, 87 (2006).
Measurement at PITZ, O’Shea et al, 2009 ICFA



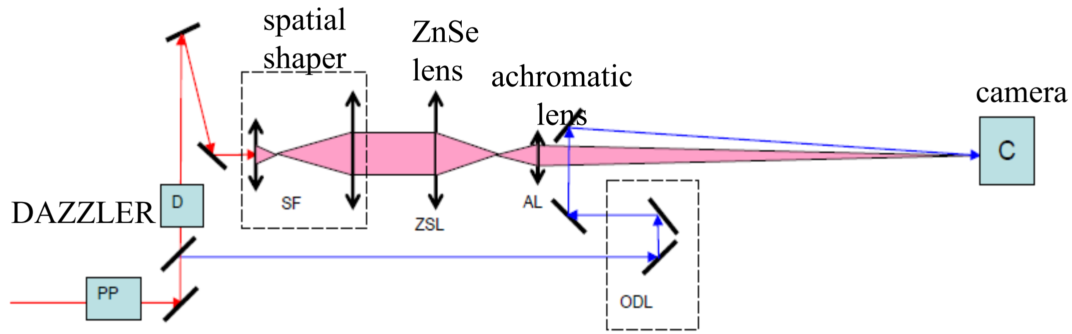
- P. Piot, Generation of uniformly-filled 3D ellipsoidal bunch from
- Cs_2Te photocathode (preliminary)

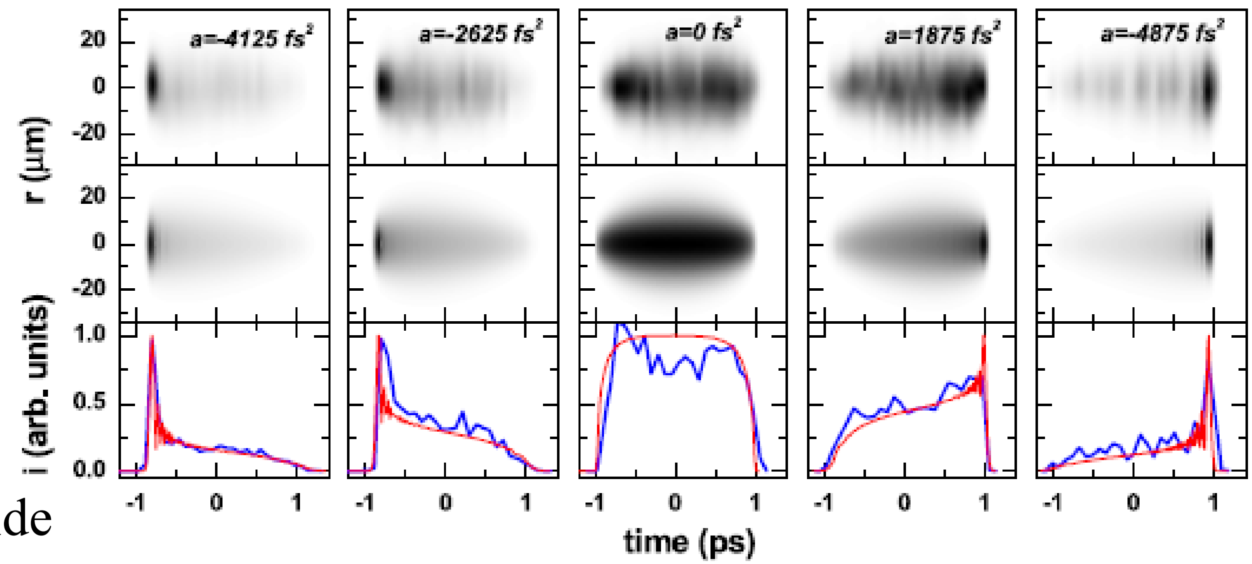
An Alternative

- Time and space interplay via chromatic dispersion



$$\frac{1}{f(\omega)} = [n(\omega) - 1]\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

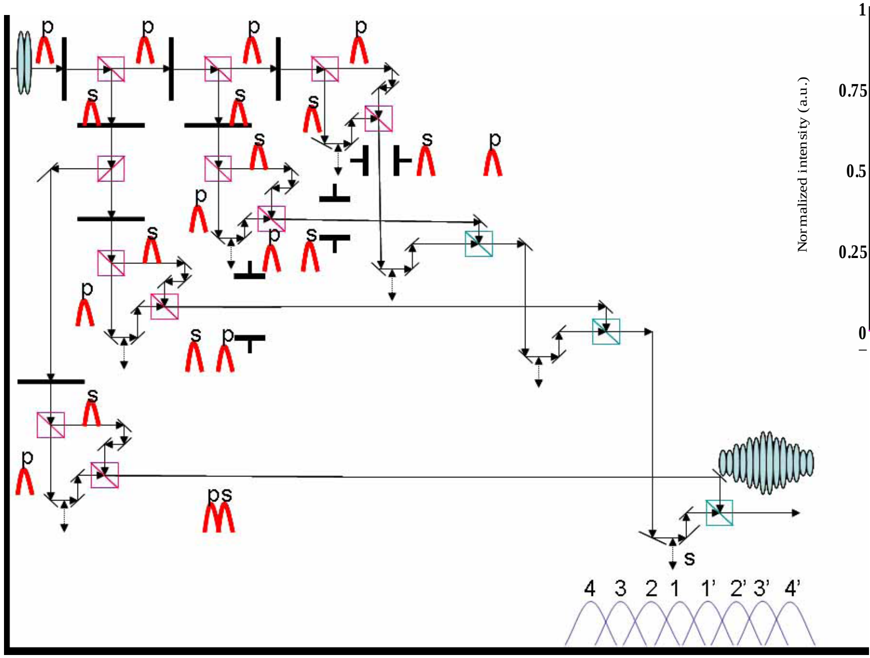


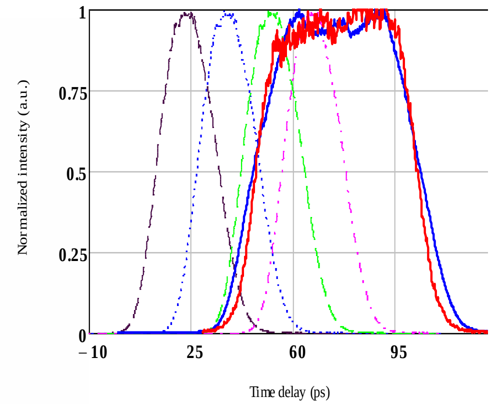


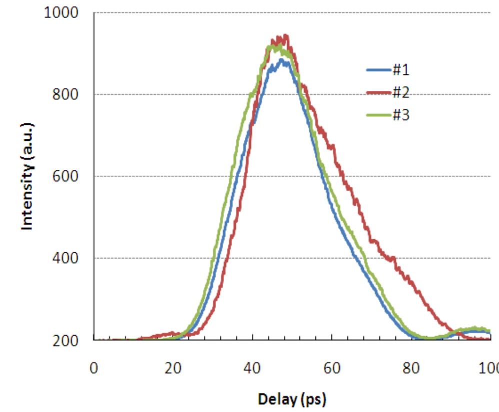
- Need short pulse to provide enough bandwidth

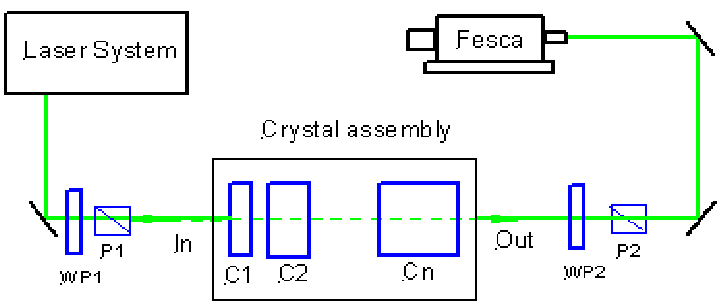
Y. Li et al. PRSTAB 12, 020702 (2009)

Go Arbitrary?









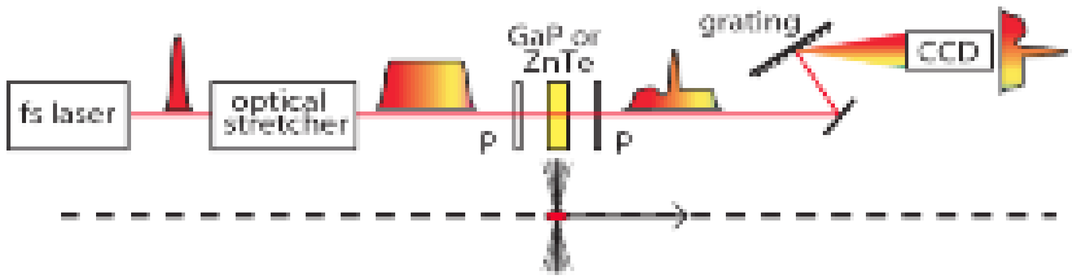
- **Complicated and can be very lossy,**

Vicario, FLS2010,. Z.He et al. Proc of PAC2011

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

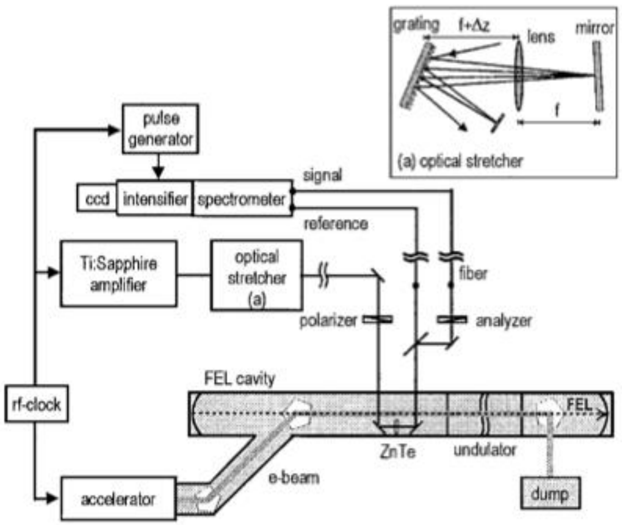
Non-invasive Diagnostics: EO Sampling

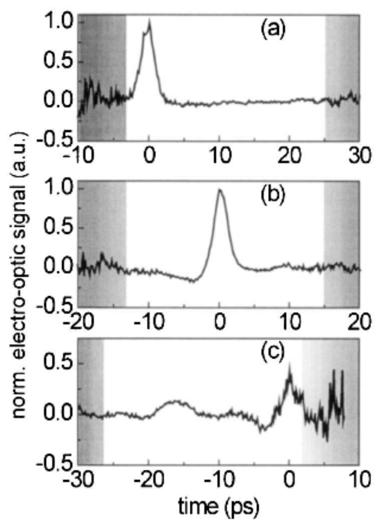
- Non-invasive, bunch temporal measurement
- Need very short laser pulses. Limited by optical materials.



Spectral decoding: Stamp time info on spectra with a chirped pulse

1. Z. Jiang and X.-C. Zhang, IEEE J. Quantum Electron. **36,1214 (2000).**
2. Z. Jiang, and X.-C. Zhang, APL. 74, 1191–1193 (1999).





Demonstration of picosecond optical sampling, Valadmanis et al, APL 41, 212, (1982)

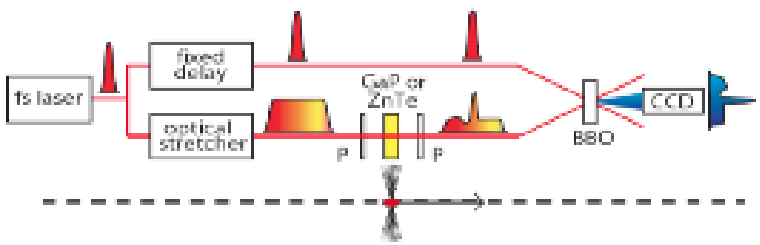
Application in beam measurement, 1998-
FNAL and BNL: 100 ps- ns temporal resolution
FELIX: Yan et al., PRL 85, 3404 (2000);
FELIX: Wilke et al., PRL 88, 124801 (2002), 2 ps
FELIX: Berden et al., PRL 93, 114802 (2004), 300 fs
SLAC/SPPS: Cavalieri., PRL 94, 114801 (2005), 300 fs

More Configurations for EOS

- It's all about smart **gating** techniques!

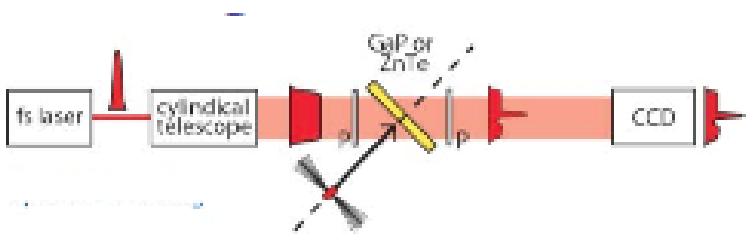
Temporal Decoding

Spectral decoding: relatively simple, lower cost. Lower laser pulse energy.

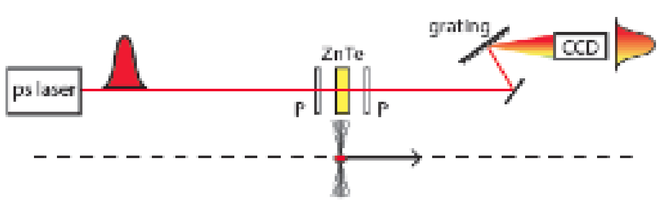


Temporal decoding:

Higher Resolution, also high laser pulse energy.



Spatial decoding, similar to cross-correlator. Lower laser pulse energy.



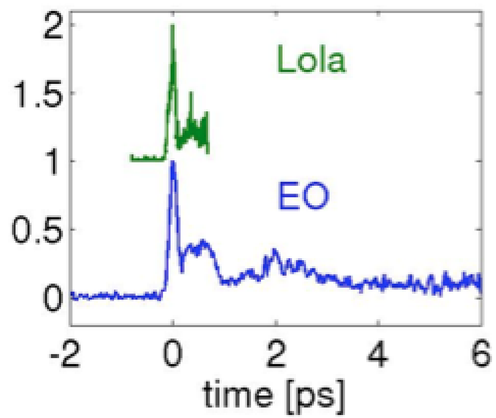
Spectral up-conversion:Long/CW laser and monochromator. Potentially simple, robust laser diagnostic

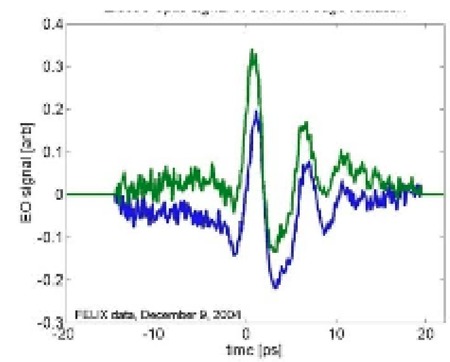
Courtesy: S. Jamison

EOS Device and Test

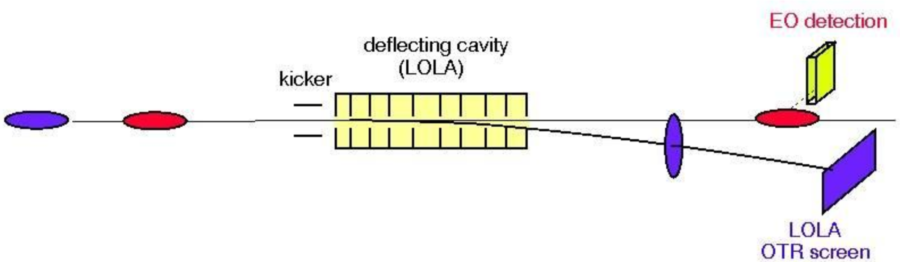
- Implemented at many labs, Beam *Bunch length/profile - FLASH, FELIX, SLAC, SLS, ALICE, FERMI, BNL,…*
- Good comparison with kicker cavity, ~50fs resolution.

FLASH/Temporal Decoding

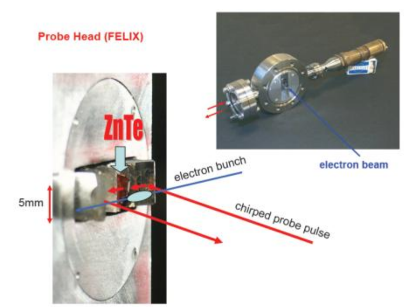




FELIX/CSR

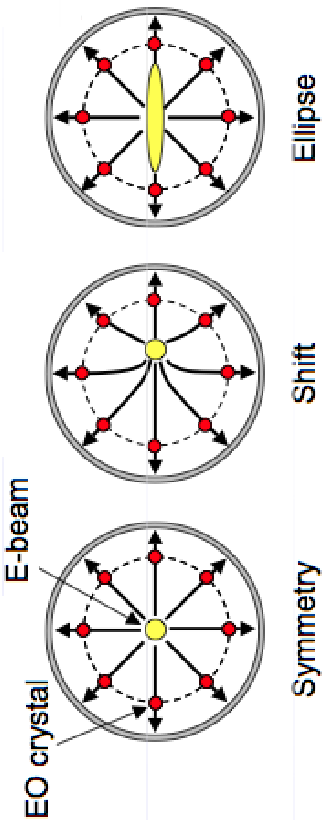


Courtesy: S. Jamison



EOS Beam Profile Diagnostic

- Beam position and 3D Profile, Transverse + longitudinal



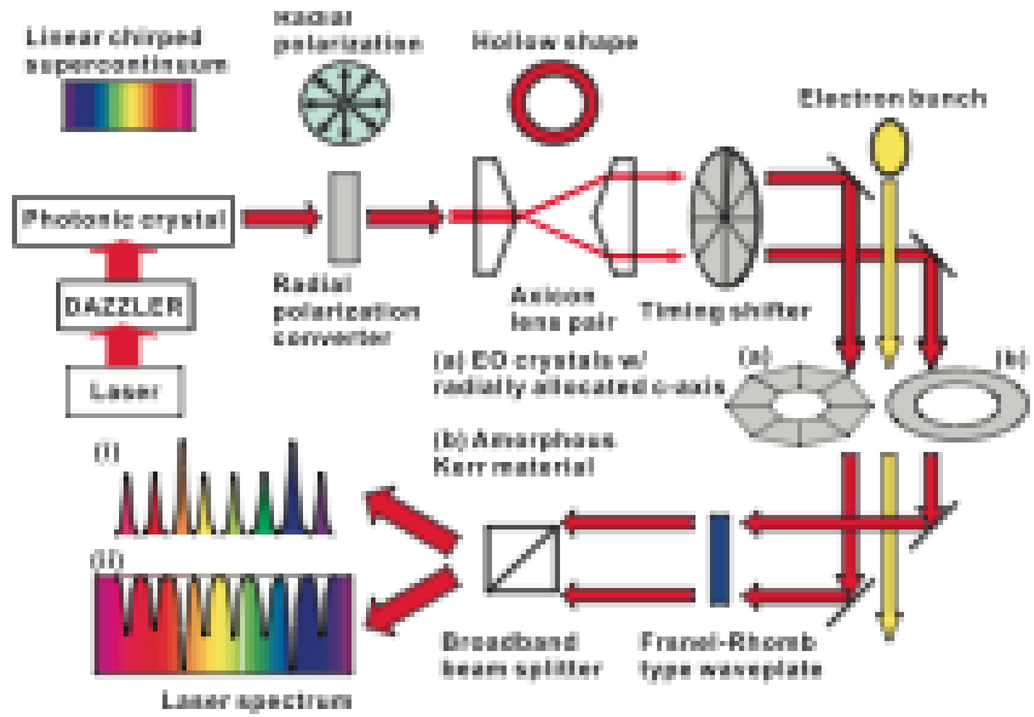
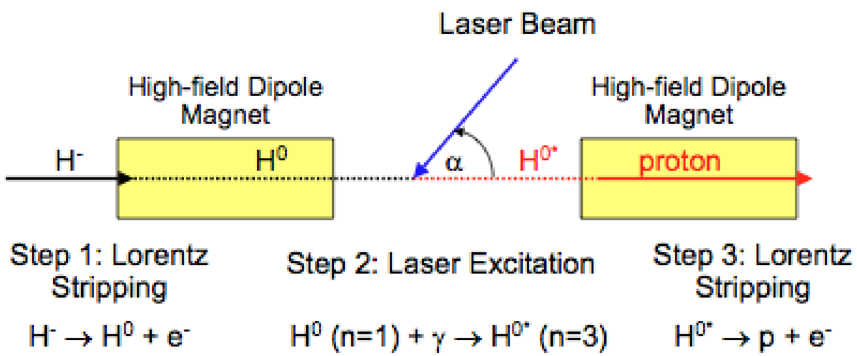


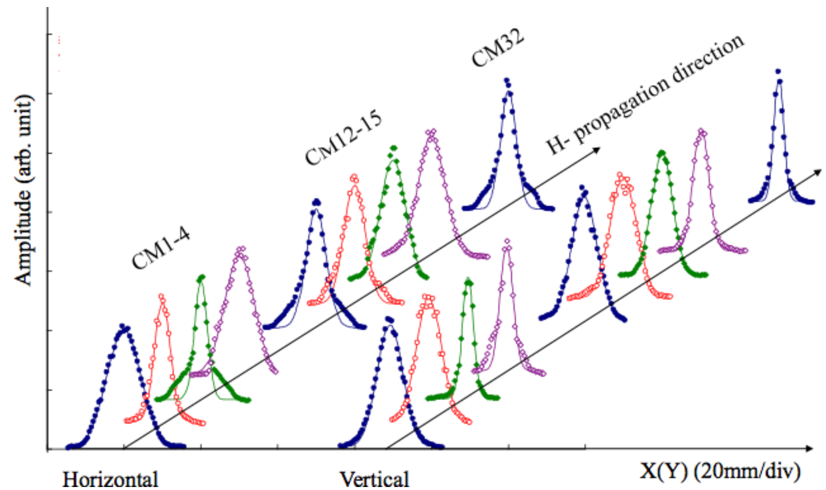
Figure 1: A schematic view of the 3D-BSM configuration.

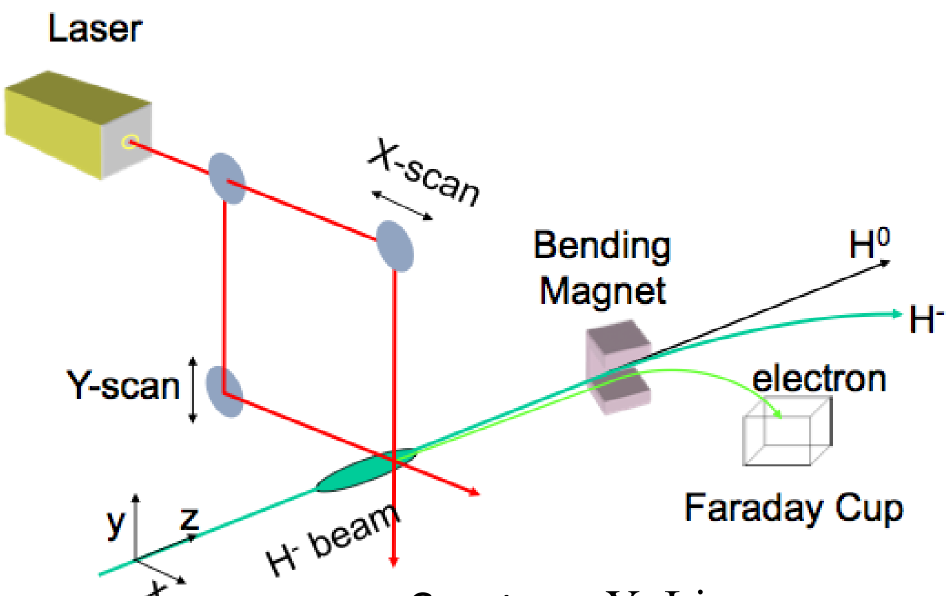
H. Tomizawa, TUPD68, Proceedings of DIPAC2011

Diagnostics by Laser-particle Interaction

- Laser Wire, **1-MW H- profiles measured at SCL. Non-invasive, but limited dynamic range ~100?**







Courtesy: Y. Liu

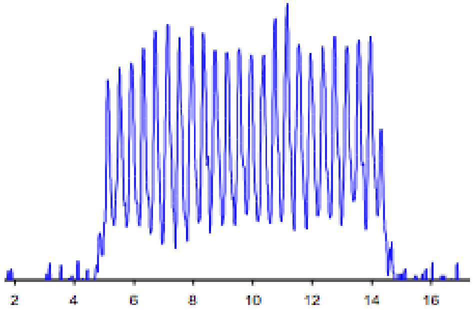
A conventional carbon wire scanner

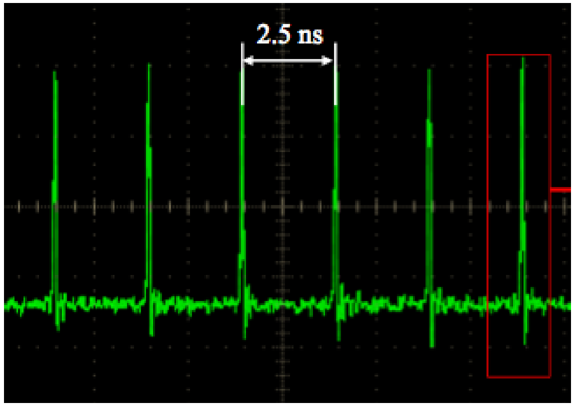
SCL Laser Wire

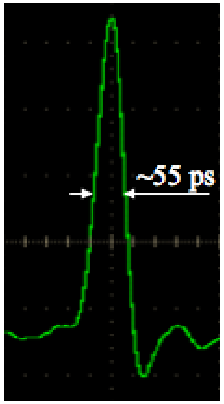
- Laser for the Laser stripping,

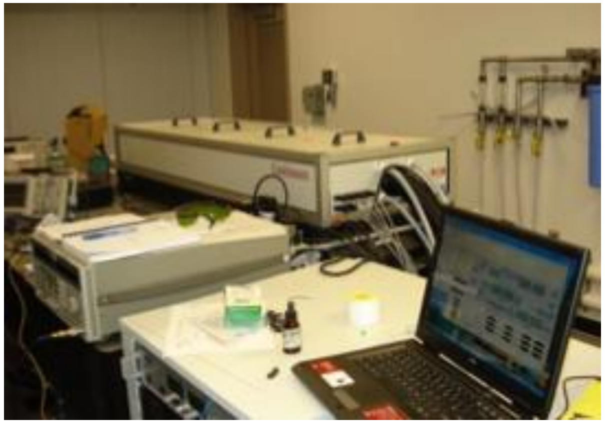
  SESAM ML Oscillator + **Continuum burst-mode laser amplifie**

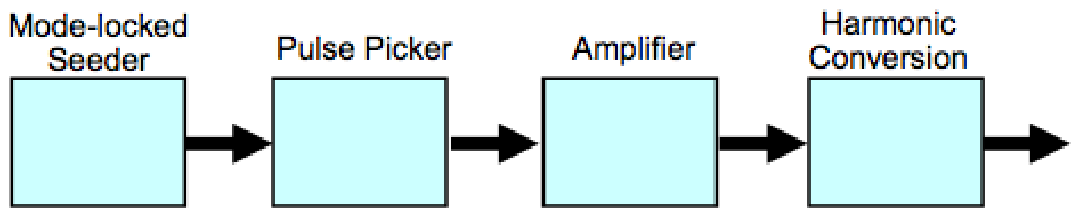
  355nm/50 ps/402.5 MHz/50 uJ10 us @ 10 Hz20 KW2W
- Wish list: 1 ms @60Hz, 20 KW/peak, **1.2 KW**/average







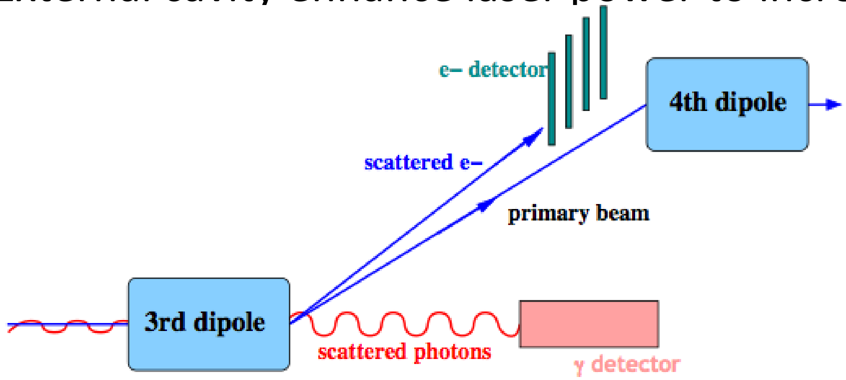


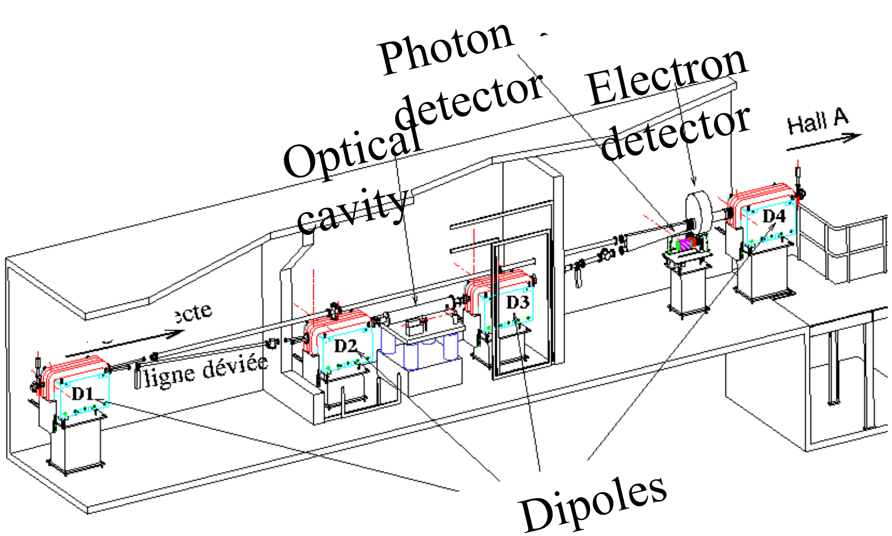


Courtesy: Y. Liu

Diagnostics by Laser Scattering

- Hall A Compton detects scattered electron and backscattered photon simultaneously
- External cavity enhance laser power to increase luminosity.





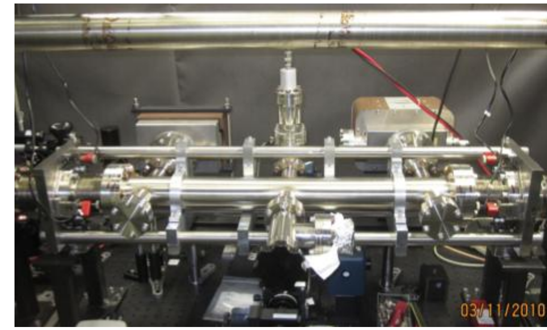
Upgrade Parameters

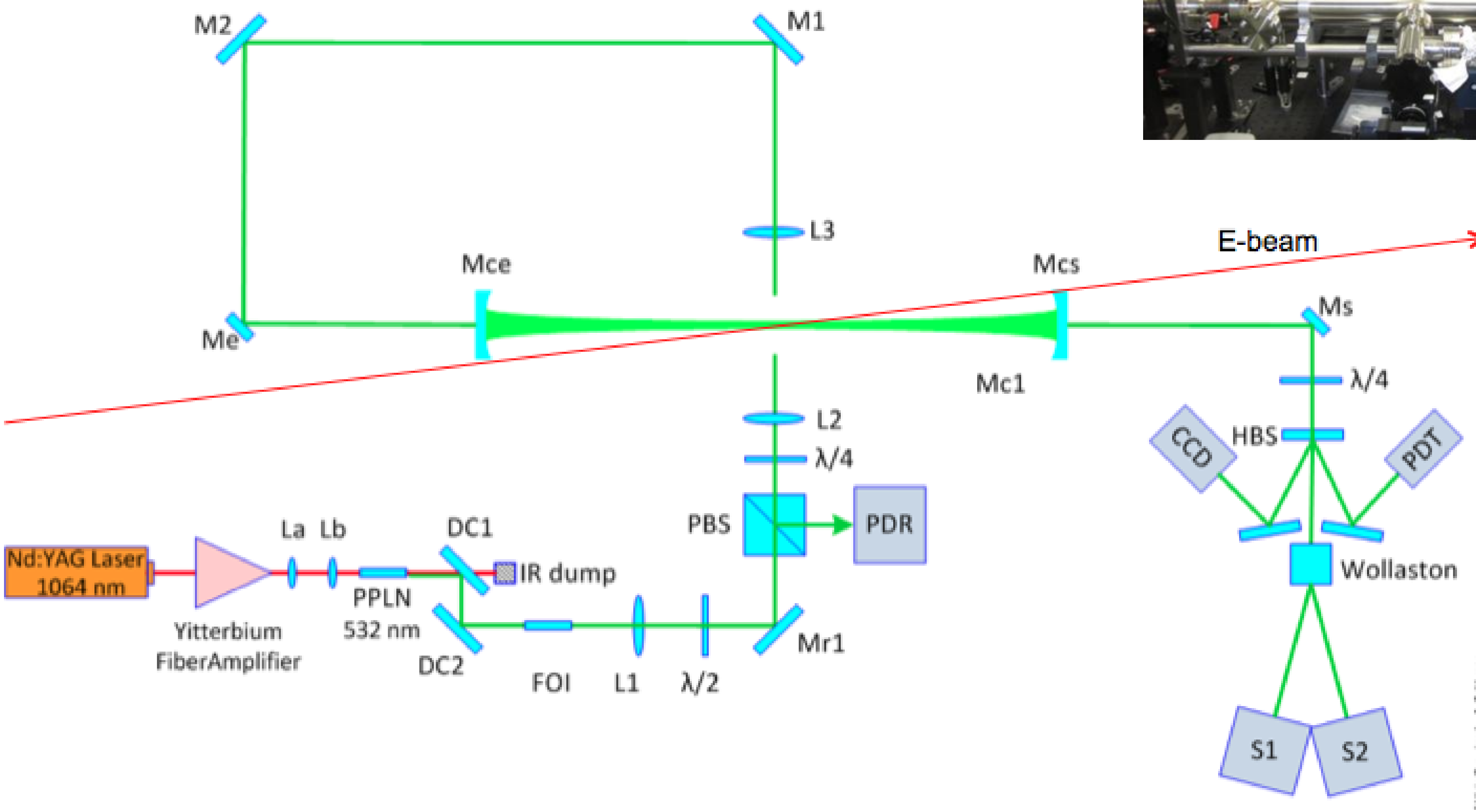
	Present	Upgrade
Wavelength (nm)	1064	532
Cavity Power (W)	1500	3000
Cavity Q	1.0×10^{11}	1.8×10^{11}
Luminosity @50μA $(\mu b.s)^{-1}$	0.26	0.26
FOM (σ.A^2) @.85Gev	0.57	2.2
Energy Range (GeV)	2 - 6	0.8 - 6
$\delta P_e/P_e$ @.85Gev	?	1%

JLAB Hall A Compton Polarimeter

Power Enhancement by External Cavity

- Design goal, 1.5kW/532nm/TEM00
- Achieved 5kW intra-cavity power





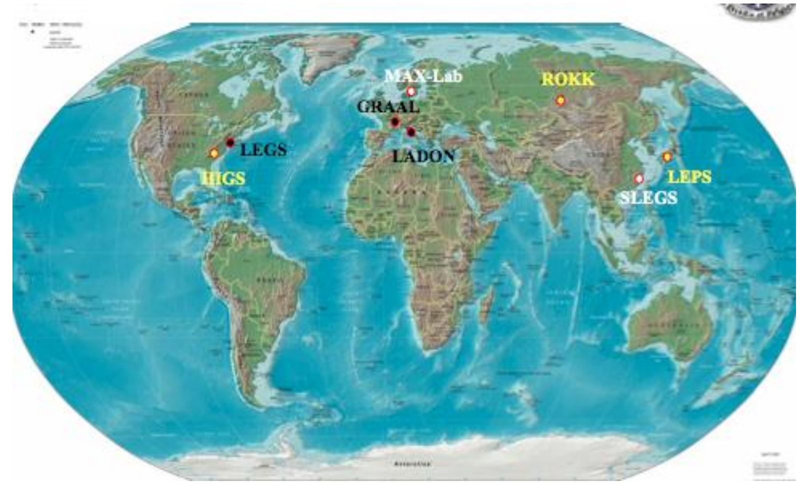
Optical Schematic of HALL A Compton Scattering Laser System

Courtesy: S. Nanda

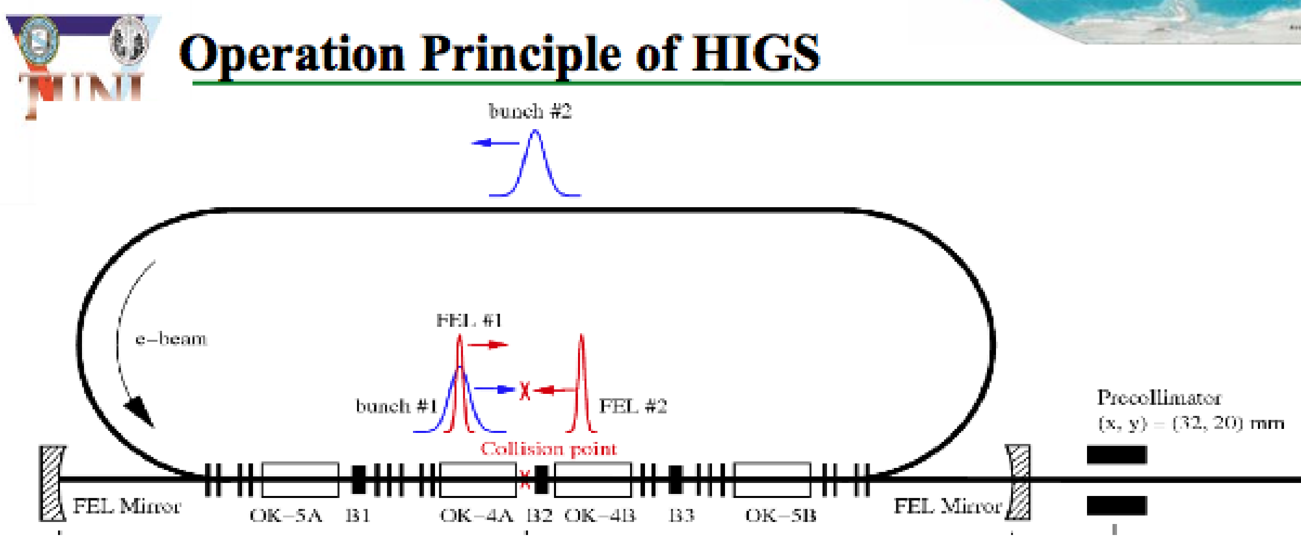
Jefferson Lab

Compton Scattering Sources

- High current e-beam and powerful laser
- Generate high energy hihg flux MeV Gamma-ray



Intra-cavity-FEL beam used



High Intensity Gamma-ray Source (HIGS) at Duke University

Courtesy: Y. WU

Old Concept Find New Application

- External cavity enhancement

Nuclear Instruments and Methods in Physics Research A 358 (1995) 260–263

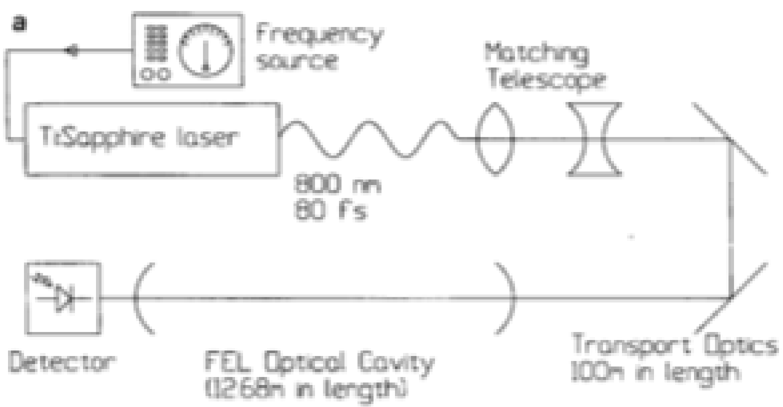
ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

FEL cavity length measurement with an external laser ☆

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

Stanford Picosecond FEL Center, W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085, USA



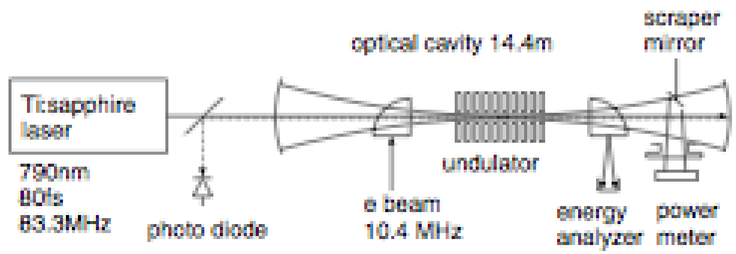
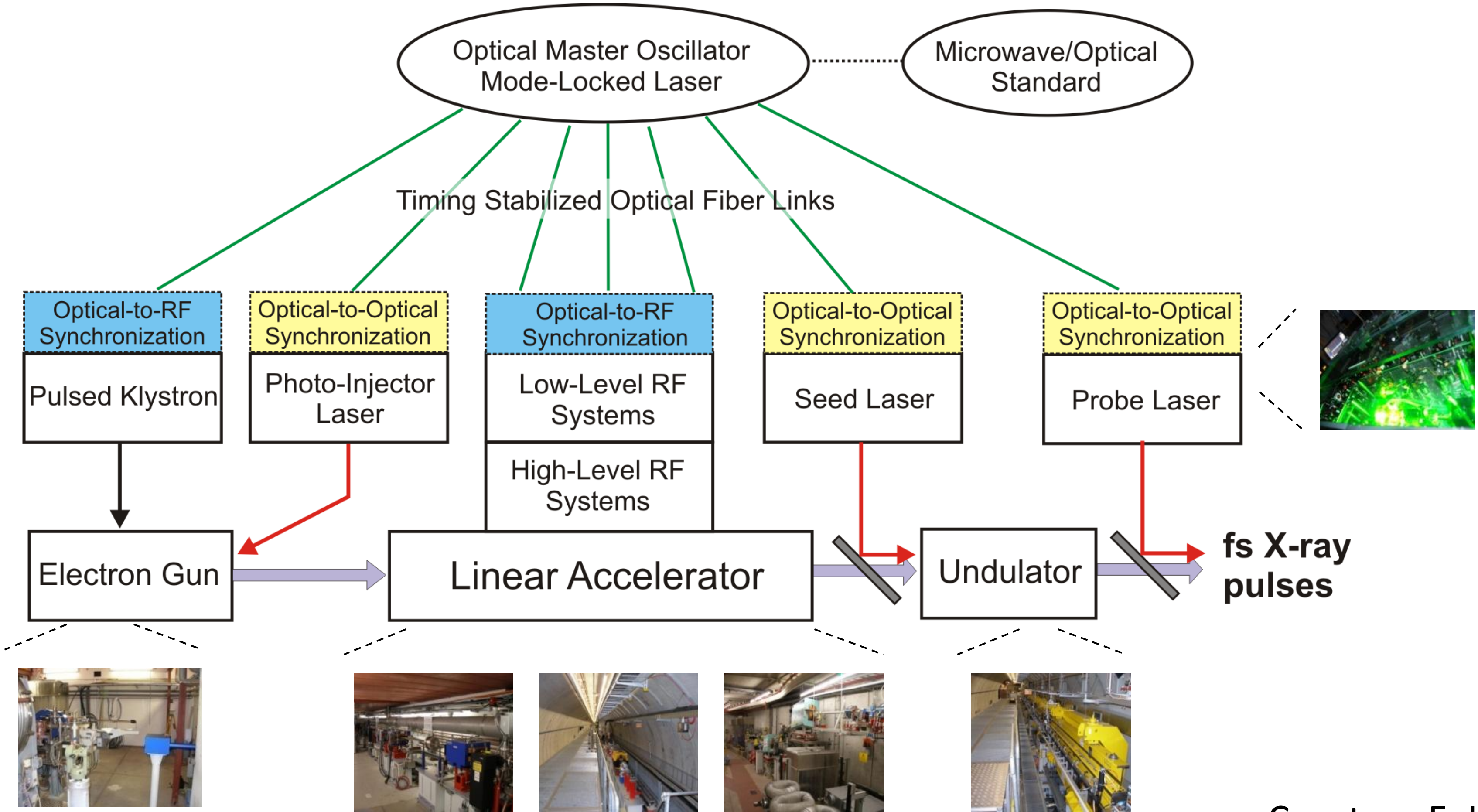


FIG. 2. An experimental setup for a simultaneous measurement of FEL power and absolute cavity length.

N. Nishimori, PRL, 86(25), 2001

Laser and Synchronization

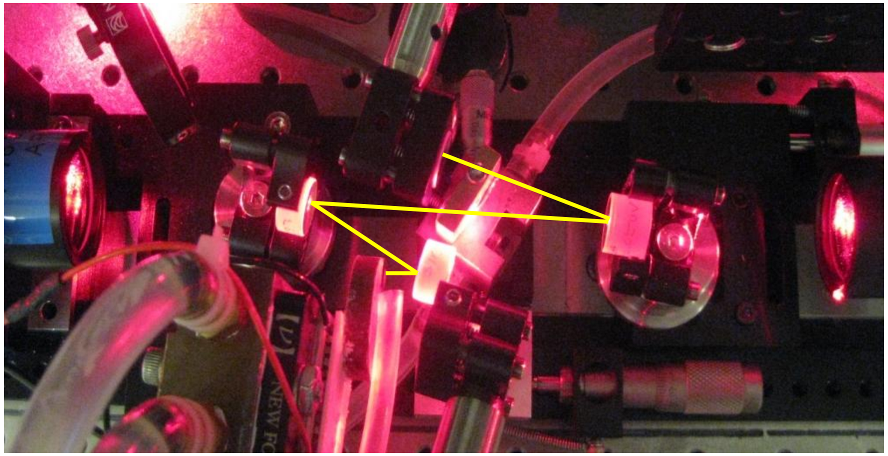
- High precision timing and sych. with lasers/optical technique
- Achieved <20fs jitter on 100s meter scale

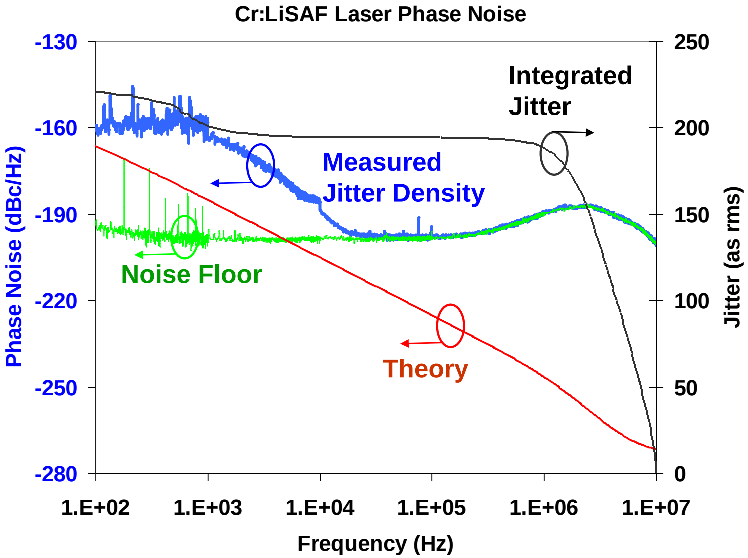


Courtesy F. Kartner

Laser and Synchronization

- Solid-State Lasers show timing jitter [1kHz – 10 MHz] < 200as
- 300 m Fiber Links, < 5 fs over 10h
- Optical-to-Optical Synchronization, < 1fs over 12h
- Optical-to-Microwave Synch., < 7fs over 10h





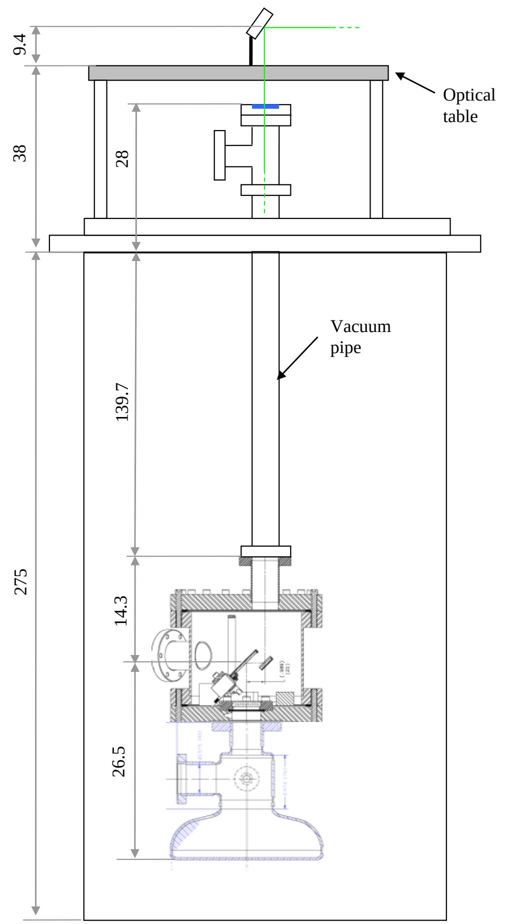
Optical clock out-performs RF clock

Courtesy F. Kartner

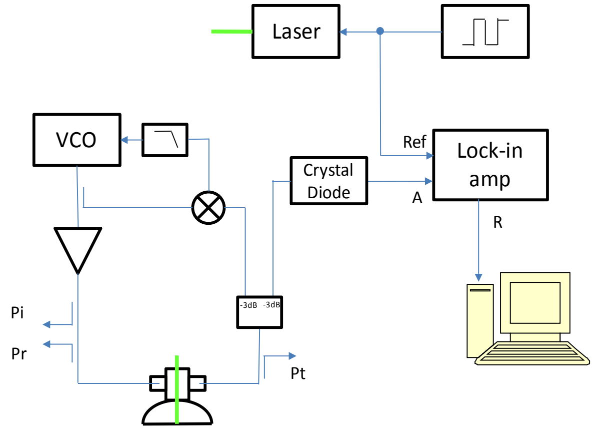
Berkley developed a fs timing system based on CW laser!

Laser In SC Cavity R&D

- **Low temperature laser scanning microscopy of a superconducting RF cavity, JLAB**



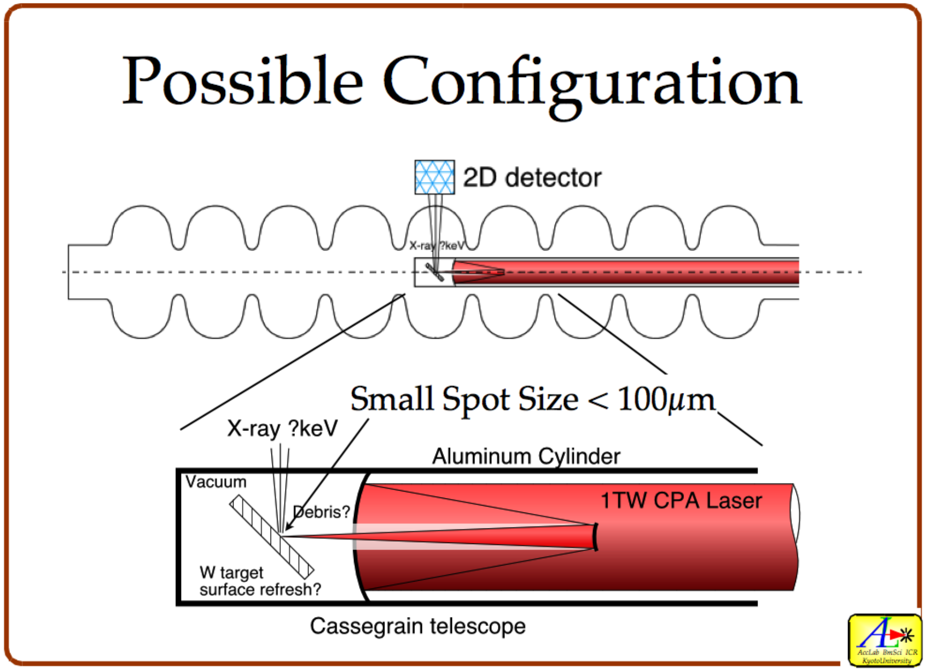
An apparatus was developed to obtain, for the first time, 2D maps of the surface resistance of the inner surface of a superconducting radio-frequency niobium cavity by a low-temperature laser scanning microscopy technique. This allows identifying non-uniformities of the surface resistance with a spatial accuracy of about one order of magnitude better than with earlier methods.

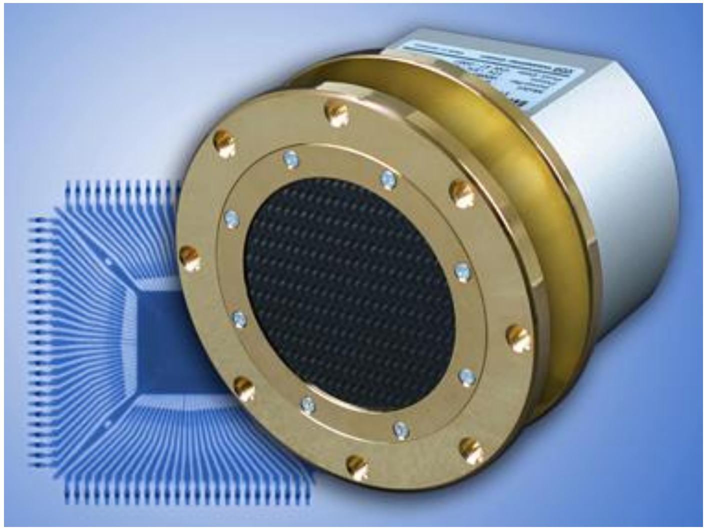


G. Ciovati et al., Riview Sci. Instru., 2012

Laser In SC Cavity R&D

- **Laser generated X-ray radiography for Nb 9-cell cavity, KEK**





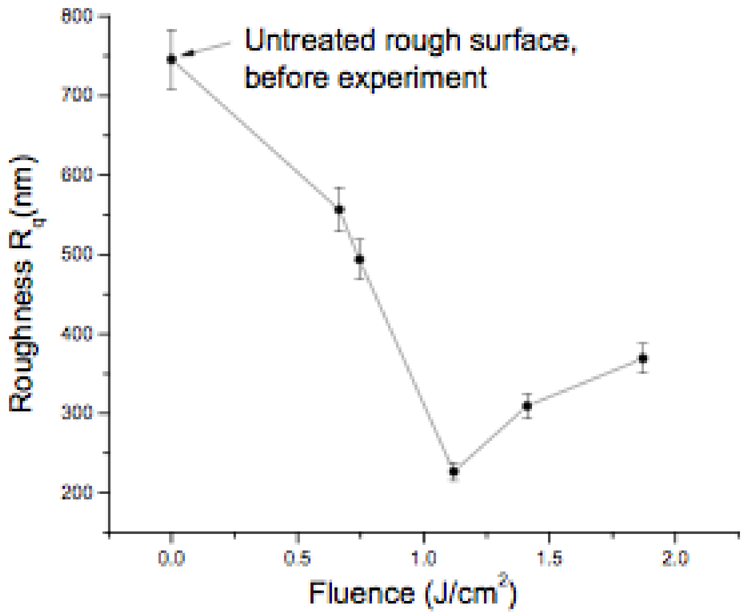
High resolution X-ray camera

Courtesy R. Geng

従来の高品位シンチレータ　　Scint-X シンチレータ

Laser In SC Cavity R&D

- LASER POLISHING OF NIOBIUM FOR APPLICATION TO SRF ACCELERATOR CAVITIES
- LASER NITRIDING OF NIOBIUM FOR APPLICATION TO SRF ACCELERATOR CAVITIES
- PULSED LASER DEPOSITION OF NbN THIN FILMS



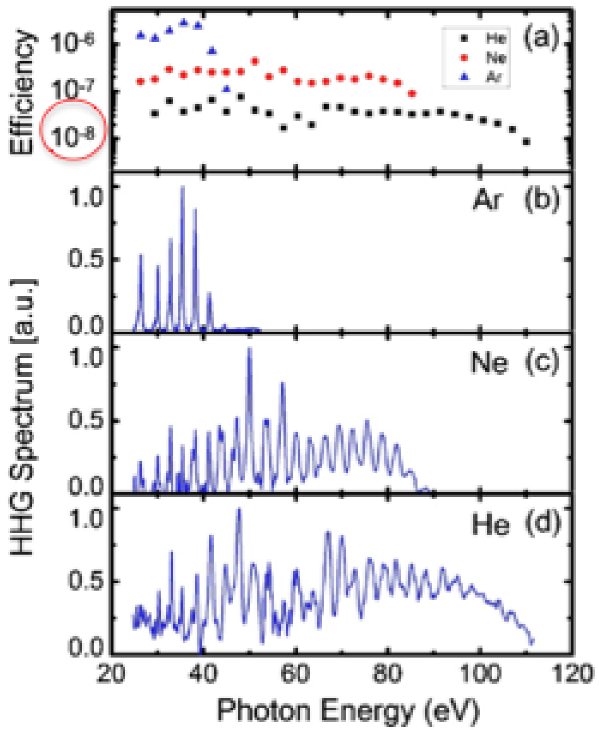
when the fluence was just above the melting temperature, the roughened surface melted and Rq decreased from 745 nm to 202 nm.

"LASER PROCESSING OF METALS AND POLYMERS", R. Singaravelu, JLAB/ODU, 2012

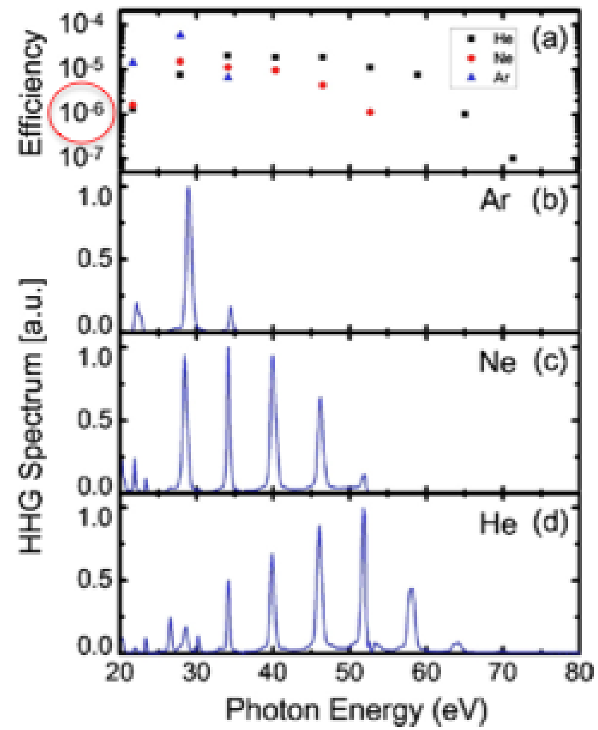
JLAB FEL PLD Lab

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



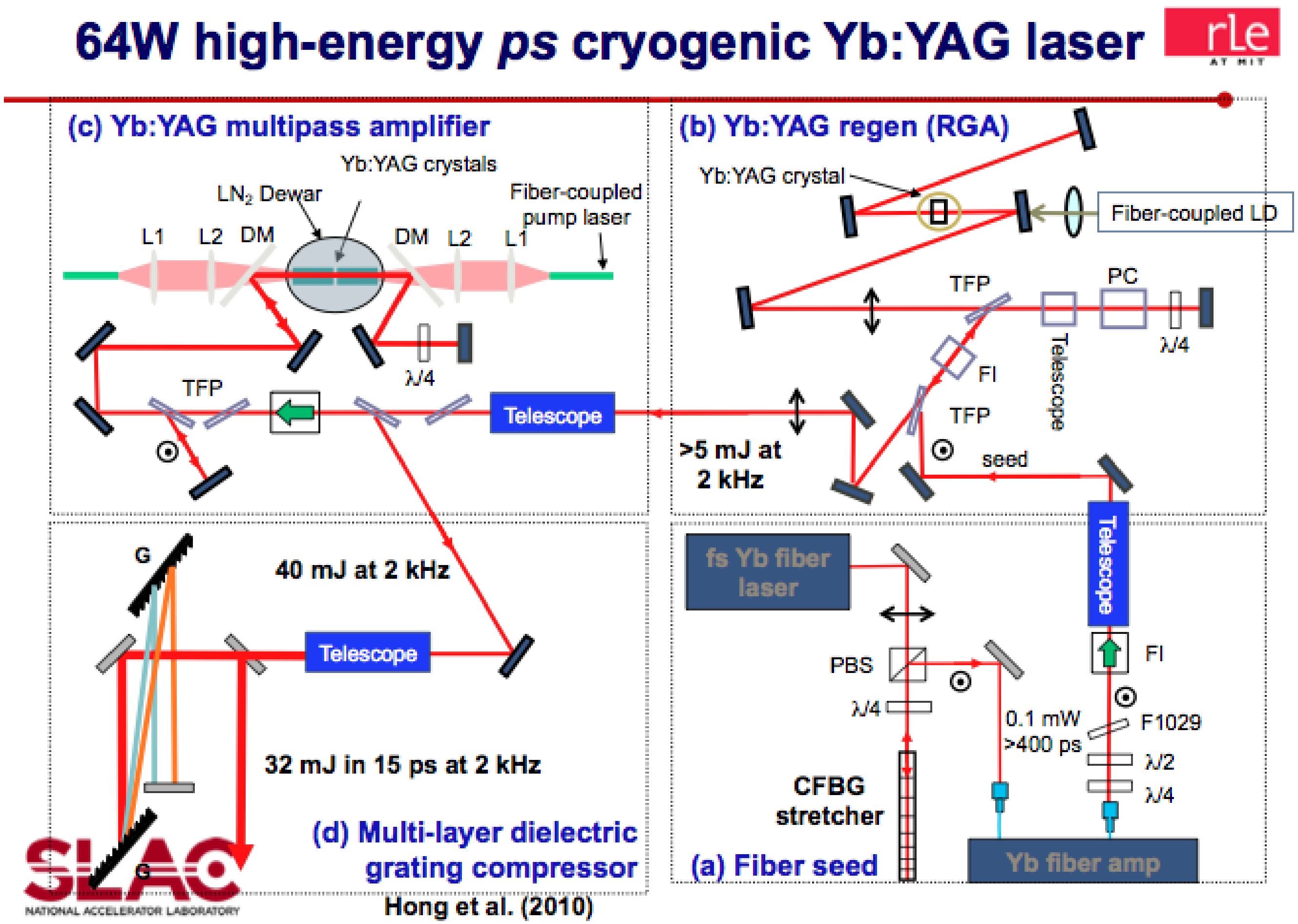
800nm, 35fs, 2.3×10^{15} Wcm^{-2}



400nm, 26fs, 2.7×10^{15} Wcm^{-2}

Technical approach

- High energy, kW average power, picosecond pulses

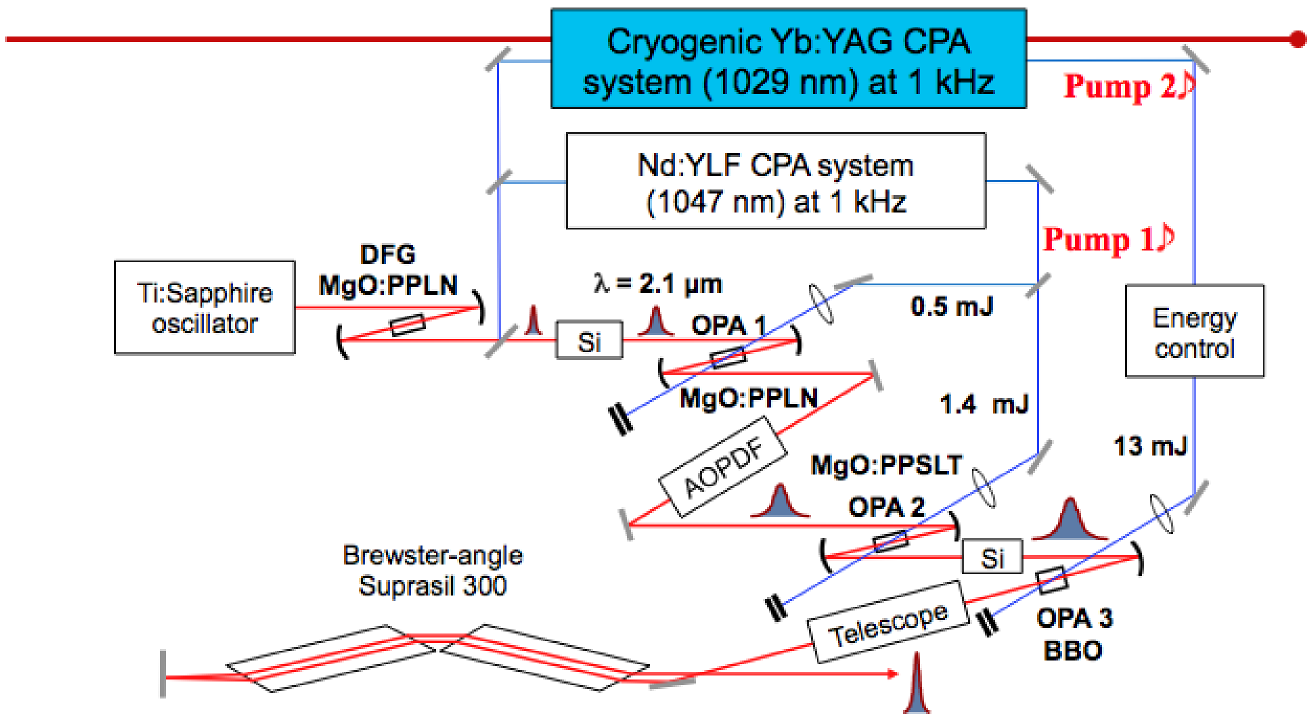


Hong et al. (2010)

Another One

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

Cryo Yb:Yag pumped 2.1-μm OPCPA



Compressed pulse, 0.85 mJ, 32fs

- 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).

What Are Needed

- Stability (high power system)
- Robustness
- More power (peak/average) & energy
- High contrast
- Shorter pulse
- Wavelength longer than 1um
- Radiation resistive
- Better optic/laser diagnostics for Accelerators

Summary

- Reviewed some latest lasers development and their applications in accelerator,
- Lasers have become an important part of accelerators,
- Lasers will continue to advance due to challenging demands from accelerators.

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