LASER TECHNOLOGY FOR ACCELERATOR

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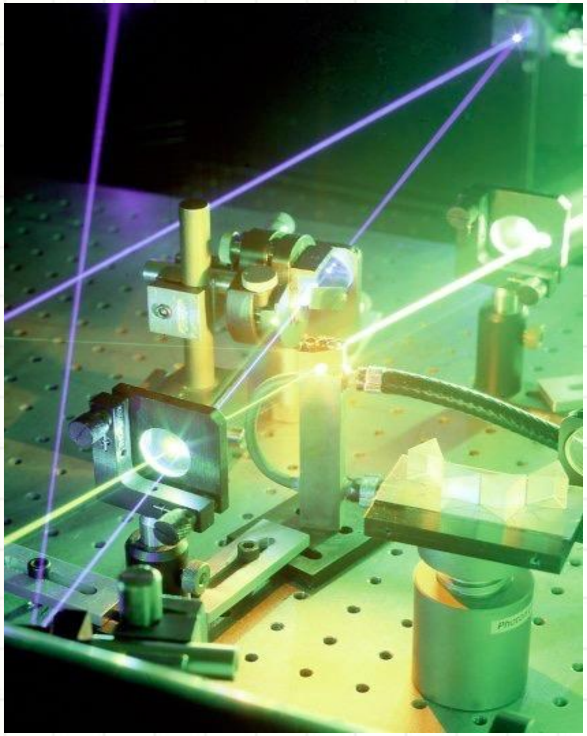
高エネルギー加速器セミナーOHO’20,
8 – 11 September 2020

LASER

Light Amplification by Stimulated Emission of Radiation



courtesy Dr. L. Corner, University of Liverpool

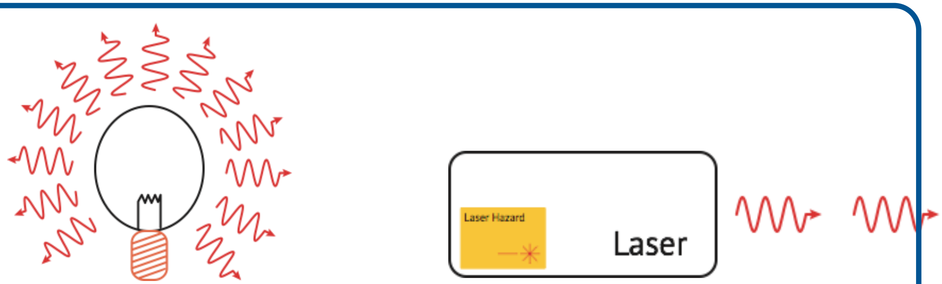
Laser types

Lasers come in many different styles:

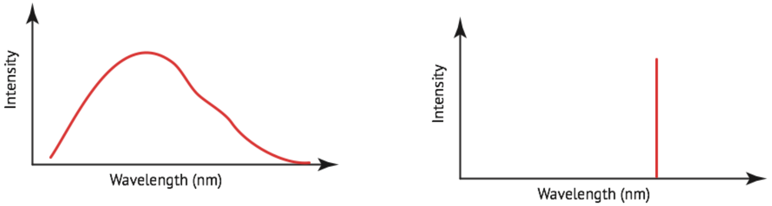
- Temporal structure - continuous wave (cw) or pulsed (down to femtoseconds).
- Wavelength - X-ray free electron lasers through visible to near infrared fibre and solid state systems, mid infrared quantum cascade lasers to 10.6μm CO_2 lasers.
- Low power (barcode scanners, laser pointers).
- High peak power (100s TW, PW systems available commercially).
- Need to consider what it is required for your application.
- Overspec – makes it very expensive!

Laser properties

- They produce highly directional beams.



- They have a "narrow" spectrum (bandwidth).



- They are spatially and temporally coherent.

Diagram courtesy Prof. S. Hooker, Oxford

Laser applications in accelerator physics

- **Many applications of laser technology.**

- **Broadly 2 categories:**

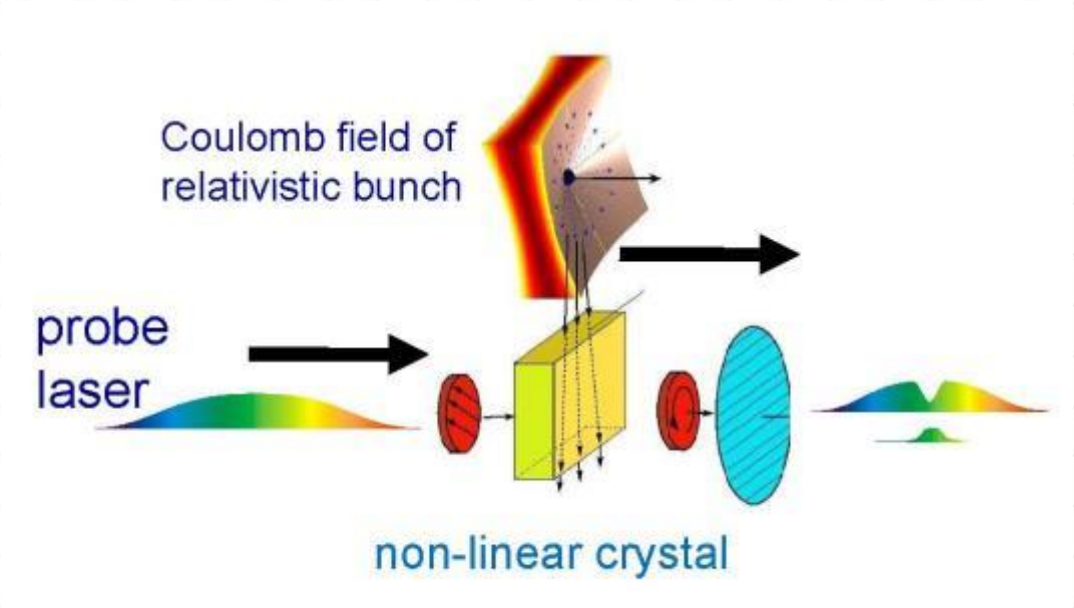
- **Improving standard accelerators – diagnostics, timing, photocathodes.**

- **Driving new accelerators – laser driven plasma accelerators, dielectric laser acceleration, direct laser acceleration in vacuum.**

- **Laser-based particle sources**
- **Laser-driven particle beam acceleration**
- **Lasers for beam diagnostics**
- **System integration**
- **Laser and photon detector technology**

Lasers for particle beam diagnostics

- Electro-optic methods for bunch length measurement.



- Coulomb field of the particle bunch alters the optical properties of the nonlinear crysta
- Changes polarisation state of laser propagating through crystal.
- Laser is chirped so spectral features directly relate to time.
- Particle bunch length measured single shot and non-destructively.

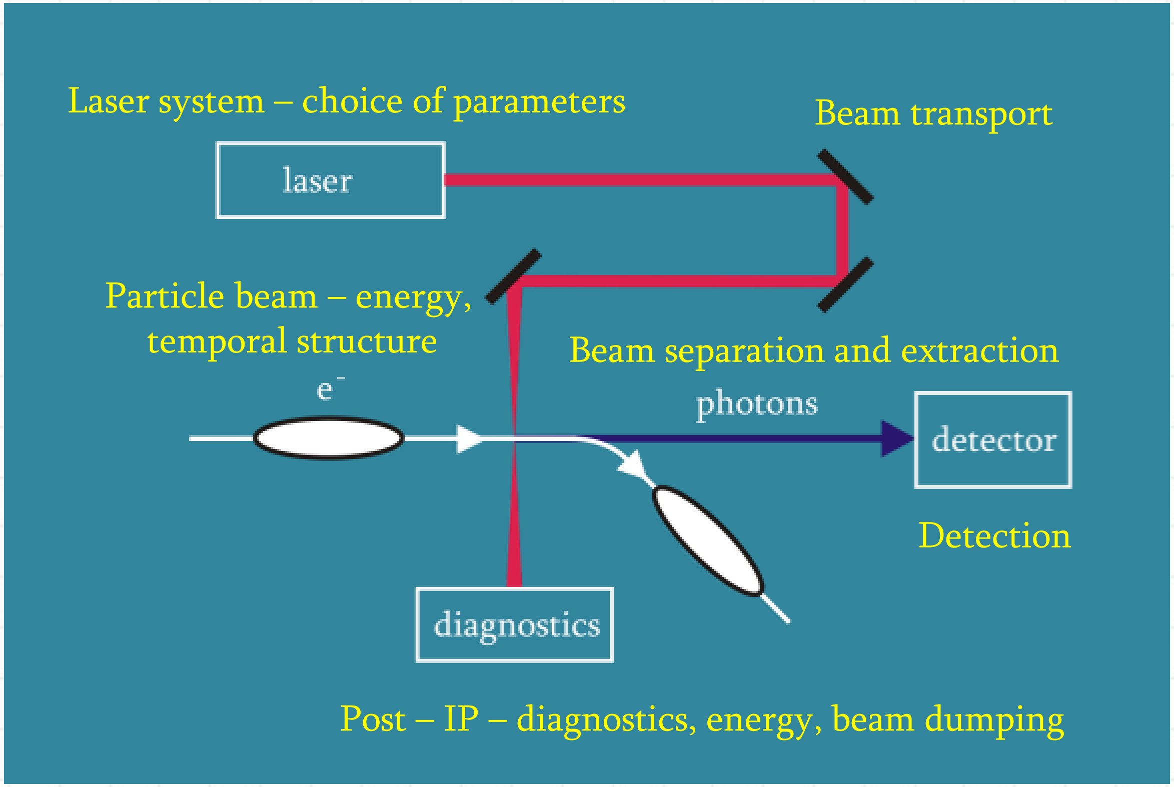
See for example:

- Pan et. al., MOPME077, IPAC 2013.

courtesy Dr. L. Corner, University of Liverpool

Lasers for particle beam diagnostics

- Laser based beam size measurement.



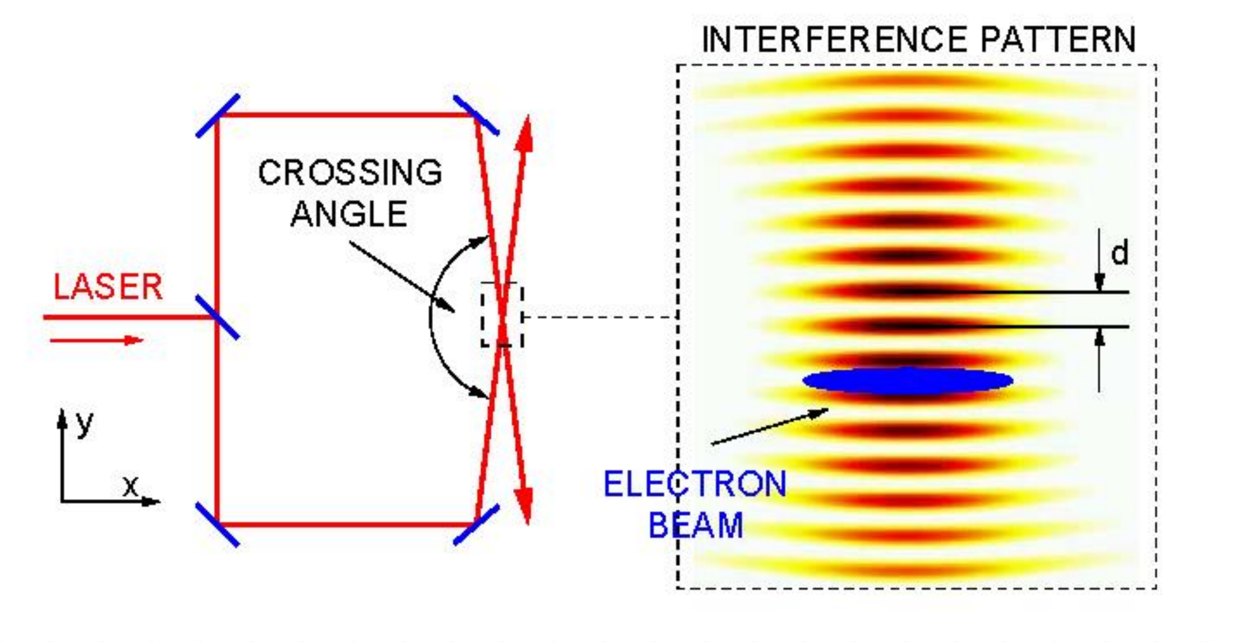
- Measure electron beams (Compton scattering) - SLC, ATF2.
- Also ion beams (photo-neutralisation) - H$^-$ laserwire at Linac 4, CERN.

See for example:

- Nevay et. al., Phys. Rev. ST Accel. Beams 17, 072802 (2014).
- Kruchinin et. al., MOPWI003, IPAC 2015.

Lasers for particle beam diagnostics

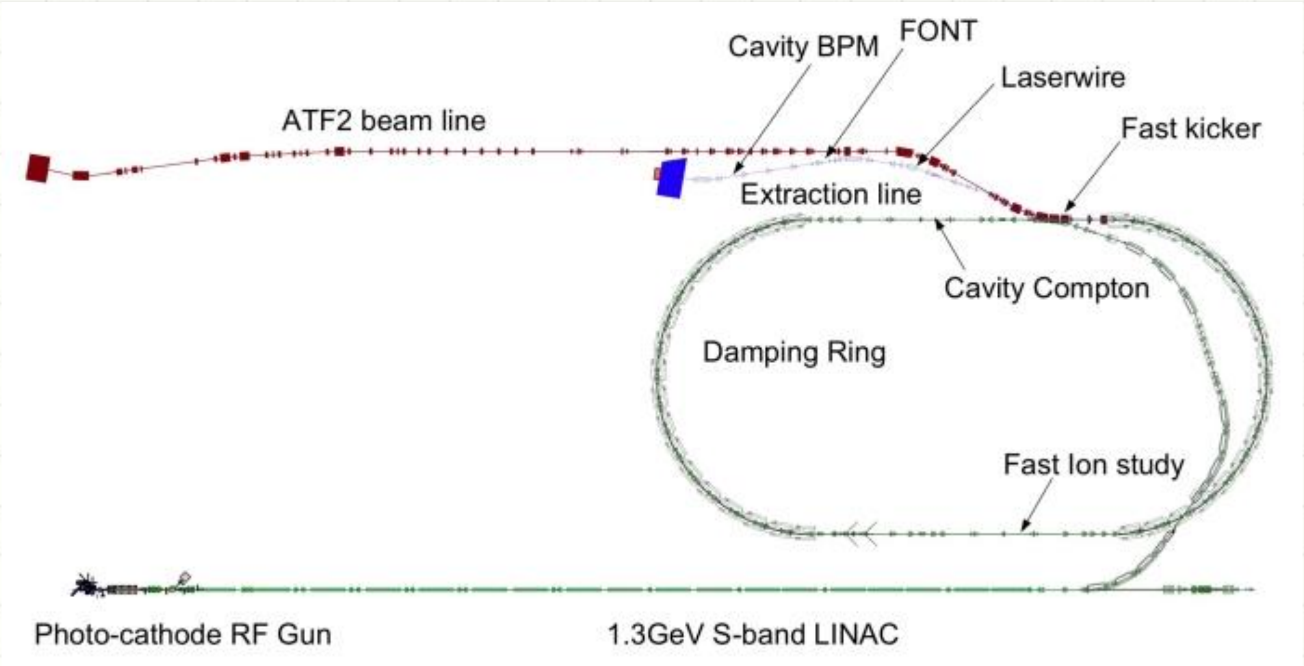
- Measuring really small beam sizes



- For < 1μm beams need something different – can't focus laser spot to much less than this.
- Cross 2 laser beams at large angle to make very narrow interference fringe pattern.
- Scan interference fringes across beam and look for modulation in Compton signal.
- This monitor is *really* hard to align and make work well. Requires very stable laser source.

  See for example:
  - White et. al., Phys. Rev. Letts. 112, 034802 (2014).
  - Yan et. al., 261, TIPP 2014.

ATF2 laser-wire

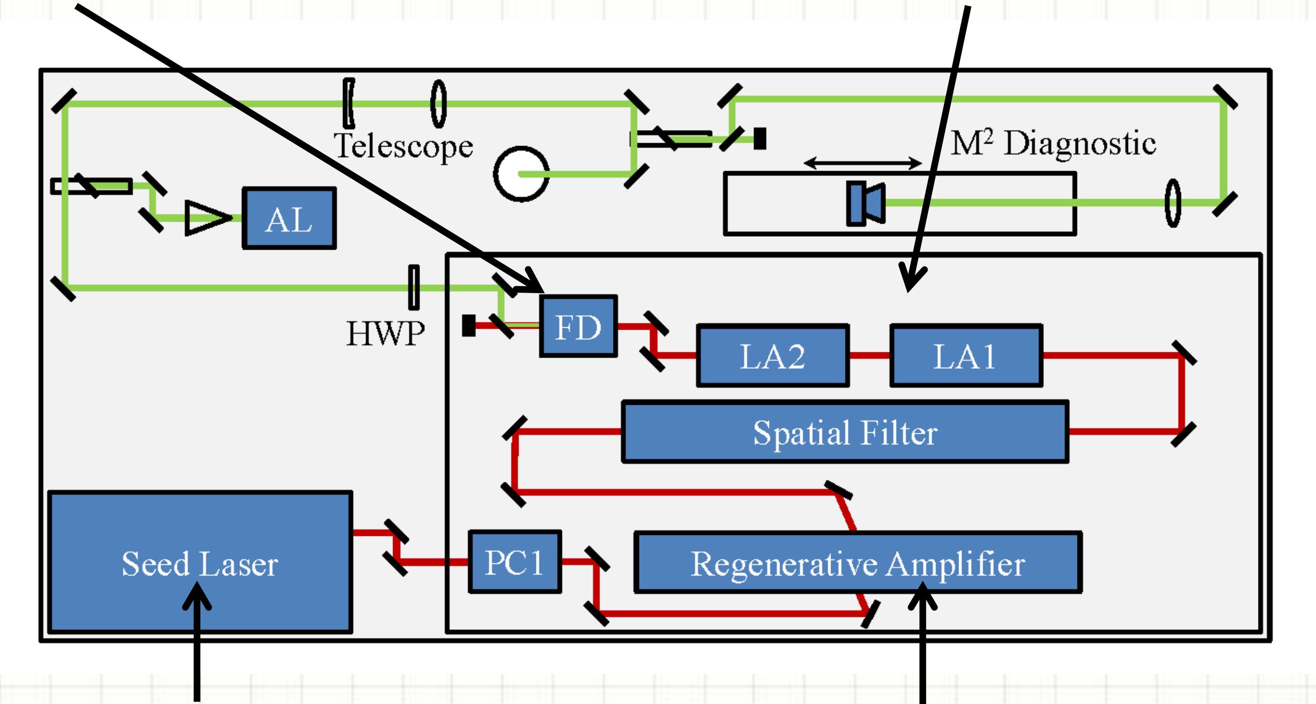


- ATF2 major international collaboration – scaled test of ILC optics.
- Aim – electron beam size < 40nm.
- Major test of new diagnostics – high resolution (< 5nm) bpms, fast feedback etc.
- Laser-wire designed for highest resolution – measurement ~ 1μm.

ATF2 laser system

SHG – 532nm, 100mJ

Linear amps up to 500mJ



Seed laser @ 357MHz locked to sub-multiple of accelerator frequency

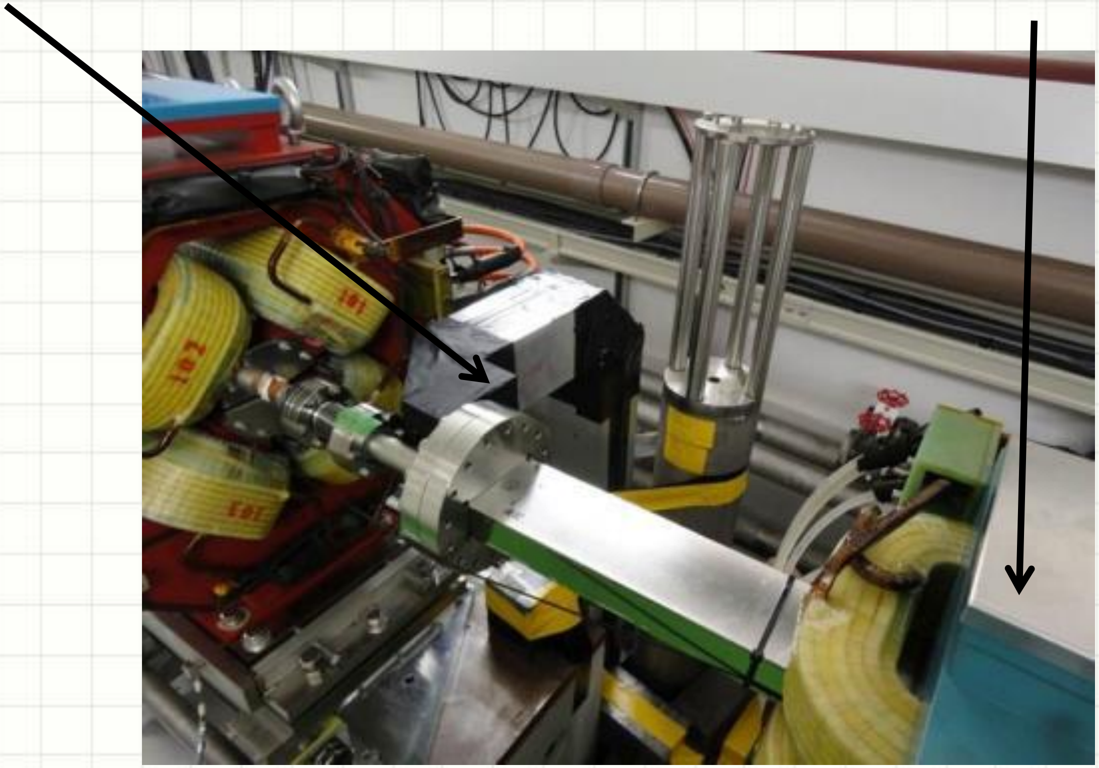
Seed pulse injected into Nd:YAG flashlamp pumped regenerative amplifier – 1.56Hz, 200ps, 10mJ

Image courtesy Dr. L. Nevay, RHUL

Detection

Photons extracted through 1mm Al window
Detector placed next to window

Dipole magnet separates
electrons and photons



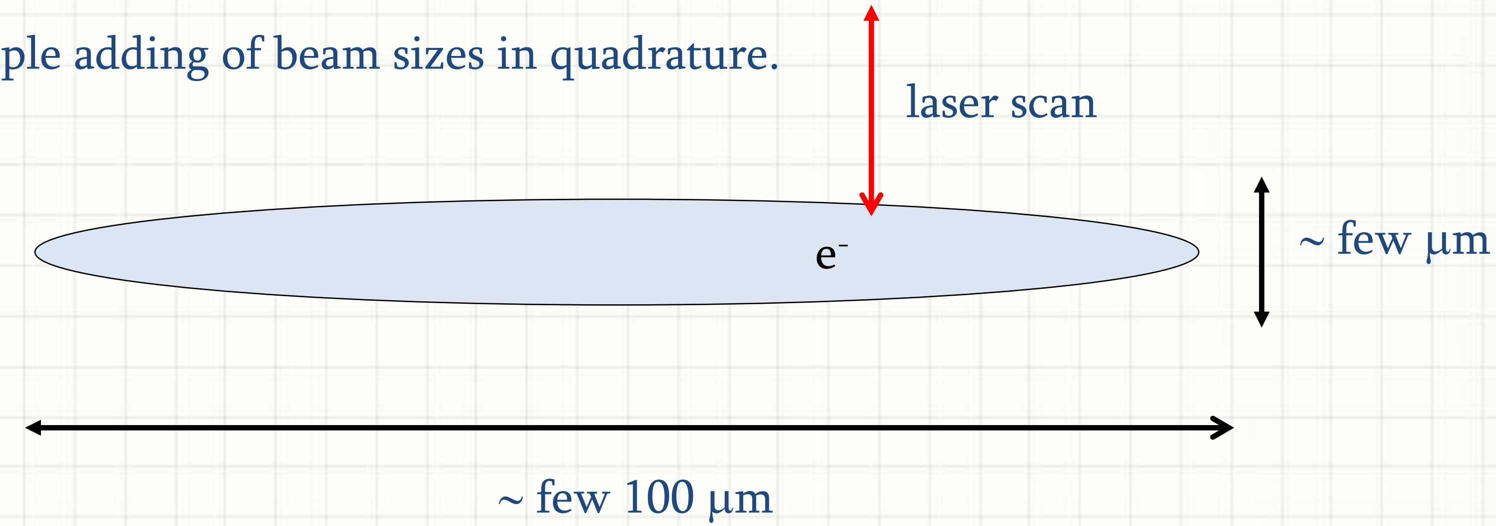
Cherenkov detector – γ converted to e^-/e^+ pairs in lead, generate Cherenkov radiation in aerogel, guided to PMT below beam line.

Photo courtesy Dr. L. Nevay, RHUL

Results and analysis

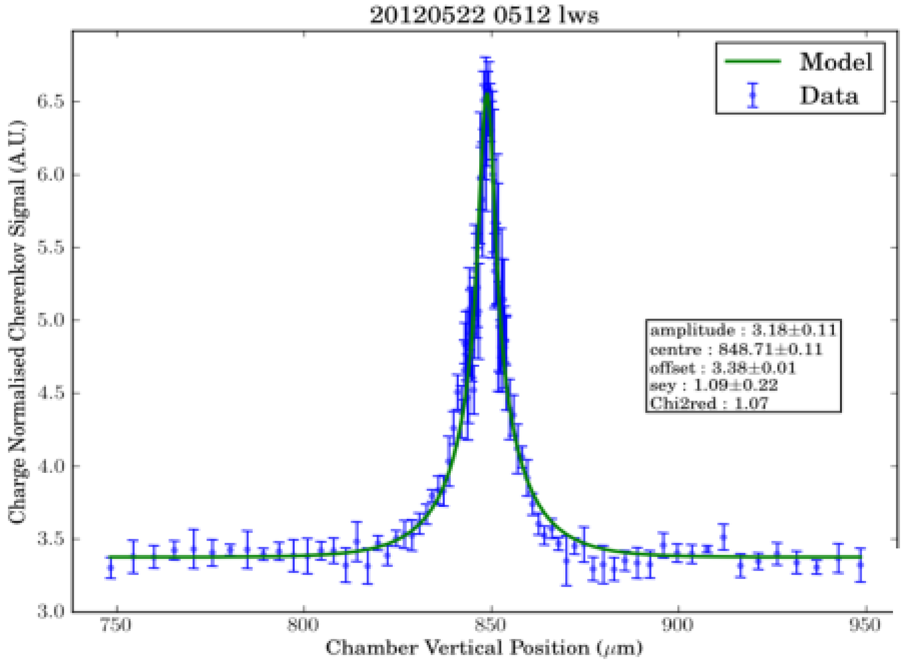
Electron beam aspect ratio very large – cannot assume laser same size across particle beam.

Try to model laser propagation and solve full overlap integral for particle and laser beam
distributions – complex analysis because of electron beam size and laser properties – not
just simple adding of beam sizes in quadrature.



See Nevay et al., PR STAB 17, 072802 (2014)

Preliminary scans and analysis

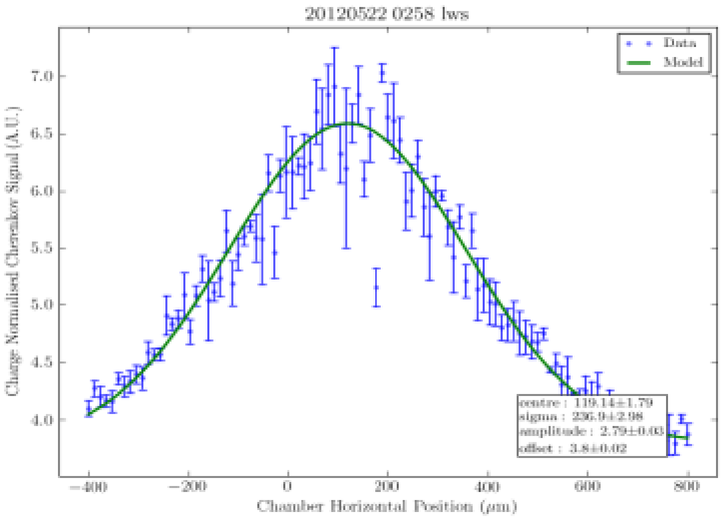


Vertical scan – σ_{ey} = 1.09 ± 0.22 μm

Demonstrated 1μm beam size measurement – scan ~ 2 min.

Data: L. Nevay, A. Aryshev, L. Corner
Analysis: L. Nevay

Horizontal scan –
σ_{ex} = 236.9 ± 2.98μm



Timing and synchronisation in particle accelerators

- Modern large accelerators and free electron laser complexes need timing synchronisation for components such as beam, diagnostics, data acquisition at the fs level or even < fs.

- Fibre based distribution of signals derived from mode-locked pulsed lasers are now in use or planned at several facilities worldwide.

- As well as distributing a signal 'clock' need to be able to measure jitter and correct for it.

- Measurements of jitter between mode locked lasers using optical techniques has shown < 100 fs as jitter measurement.

See for example:

- Peng et. al., Optics Letters 21, 19982 (2013)
- https://desy.cfel.de/ultrafast_optics_and__x_rays_division/research/timing_distribution_and_synchronization/

Lasers driving accelerators – plasma wakefield accelerators

- Conventional accelerators are widely used in science and medicine.
  - Acceleration gradient limited by electrical breakdown to < 100 MV/m.
  - This sets the size (& cost) of the machine.

Diamond, UK

LHC

Plasma accelerators – how they work

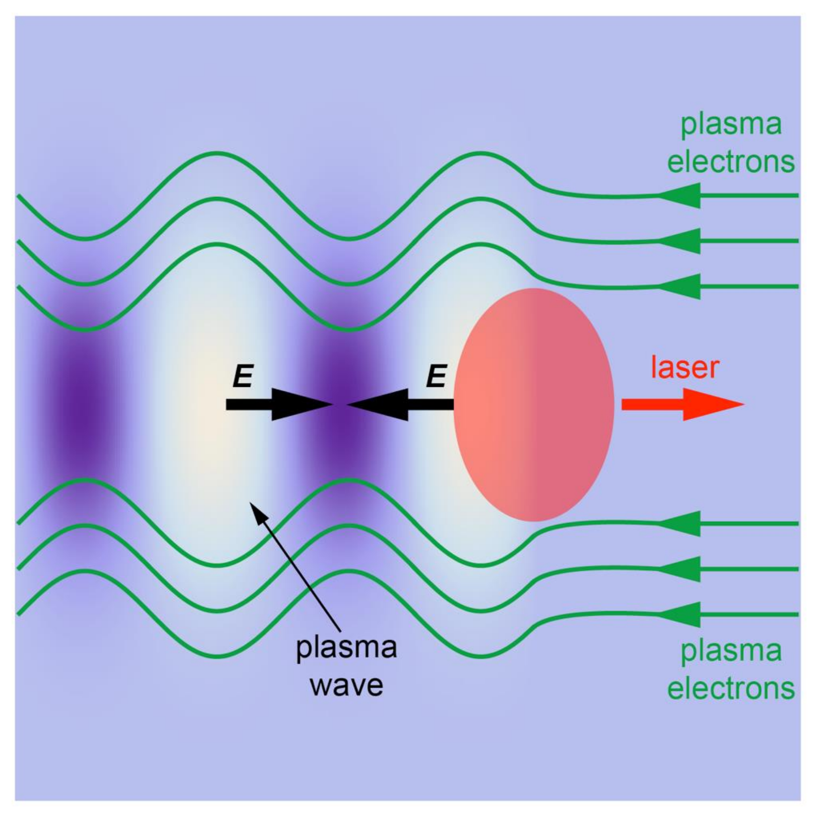


Diagram courtesy Prof. S. Hooker, Oxford

- Ponderomotive force of an intense laser pulse expels electrons from the region of the pulse to form a trailing plasma wakefield.
- The wakefield moves at speed of laser pulse (i.e. close to speed of light).
- Electric fields within wakefield can accelerate charged particles.
- Huge accelerating gradients – 1000 x conventional accelerators.
- 4 GeV in 9cm.
- 3.25 GeV in 14mm.
- Massive potential for reducing size and cost of particle accelerators.

See for example:

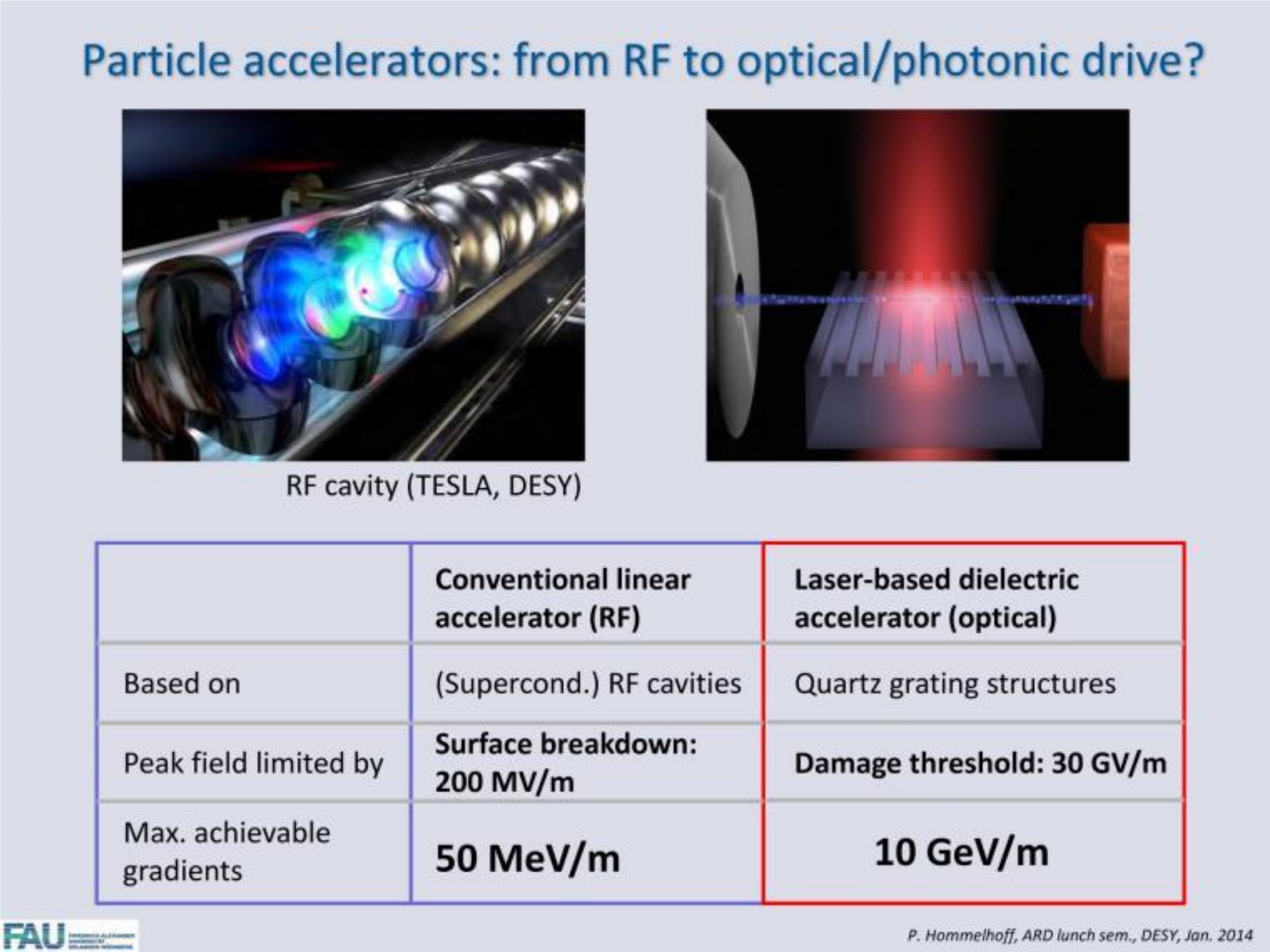
- Esarey et. al., Rev. Mod. Phys 81 1229 (2009)
- Kim et. al., Phys. Rev. Letts. 111 165002 (2013)

Laser plasma accelerators - What's the catch?

- Sounds great – why aren't all accelerators plasma based?
- Mainly driver problems – lasers required are 100s TW or PW, inefficient so heat up, only fire once an hour/every 20 mins.
- Even fastest PW laser in the world only fires at 1Hz – too slow for real applications.
- Also length of accelerator – only over ~ 10cm so far, need to show that many stages can be put together to get to really high energy.
- Quality of electron bunches not as good as conventional accelerators yet.
- These are all active areas of research.
- Not forgetting laser driven proton and ion acceleration, and positron acceleration.

courtesy Dr. L. Corner, University of Liverpool

Dielectric laser accelerators



Particle accelerators: from RF to optical/photonic drive?

RF cavity (TESLA, DESY)

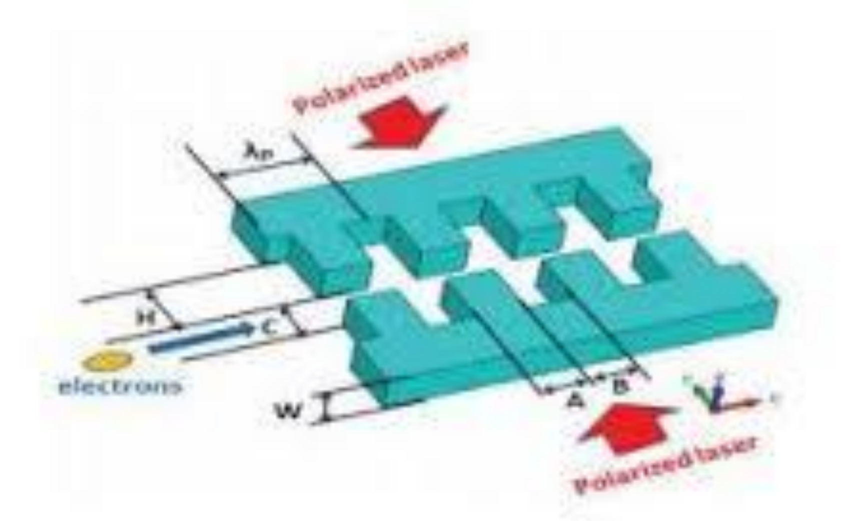
	Conventional linear accelerator (RF)	**Laser-based dielectric accelerator (optical)**
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**50 MeV/m**	**10 GeV/m**

P. Hommelhoff, ARD lunch sem., DESY, Jan. 2014

Slide courtesy Dr. P. Hommelhoff, Friedrich-Alexander-Universitat, Erlangen

Dielectric laser accelerators

- New area of accelerator research.
- Have shown acceleration of relativistic and non-relativistic electrons using laser and dielectric structures.
- Also beam manipulation e.g. deflection for use as beam position monitor.



https://www.liv.ac.uk/quasar/research/novel_accelerators/

See for example:

- Breuer et. al., Phys. Rev. ST Accel. Beams 17 021301 (2014)
- Peralta et. al., Nature 503 91 (2014)

Direct laser acceleration in vacuum

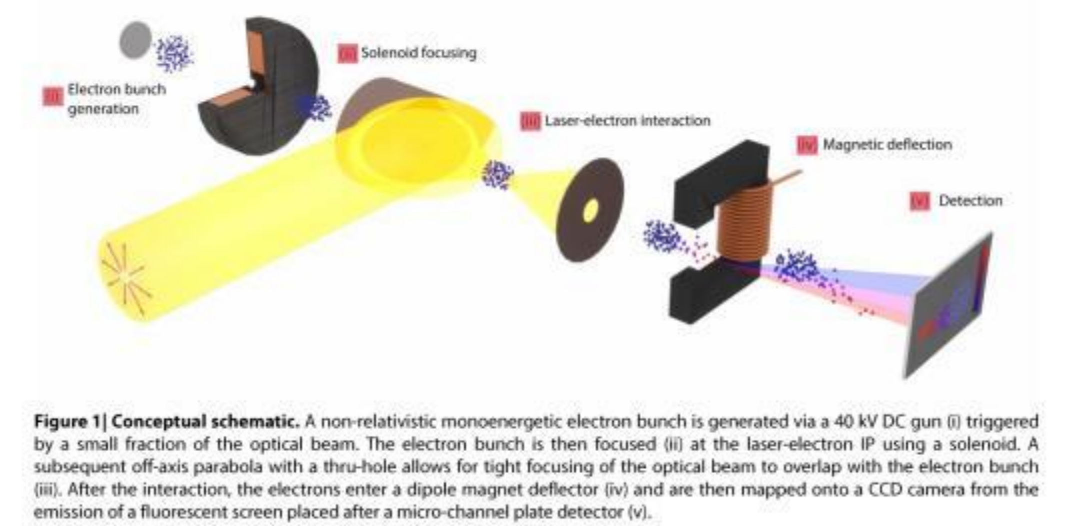
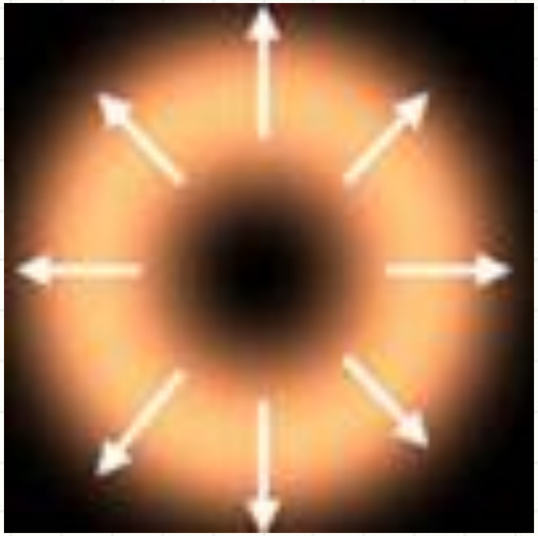


Figure 1| Conceptual schematic. A non-relativistic monoenergetic electron bunch is generated via a 40 kV DC gun (i) triggered by a small fraction of the optical beam. The electron bunch is then focused (ii) at the laser-electron IP using a solenoid. A subsequent off-axis parabola with a thru-hole allows for tight focusing of the optical beam to overlap with the electron bunch (iii). After the interaction, the electrons enter a dipole magnet deflector (iv) and are then mapped onto a CCD camera from the emission of a fluorescent screen placed after a micro-channel plate detector (v).



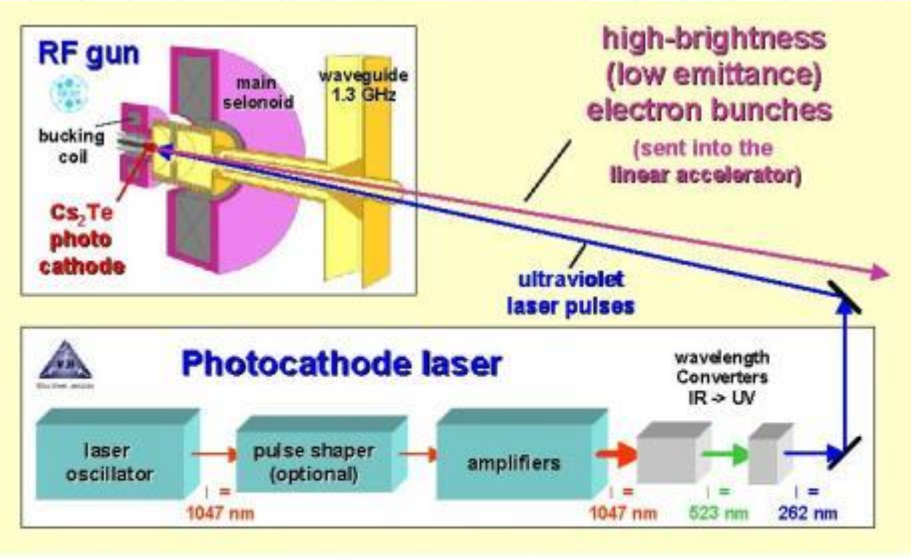
arXiv:1501.05101

- Light has a strong electric field – can we use this to accelerate electrons?
- How to get large on axis component? Focus radially polarised light beam.
- Vacuum acceleration – no medium to breakdown, not unstable.
- Carbajo et. al. Phys Rev. ST Accel. Beams 19, 021303 (2016) shown 3GeV/m – exciting result!

courtesy Dr. L. Corner, University of Liverpool

Lasers as particle sources - Photocathodes

- Can use laser pulses to produce electron bunches from photocathodes.
- Give bunches as short as the laser pulse without additional manipulation.
- Properties of the bunch can be controlled by the laser pulse shape in time and space.
- Laser must be stable and locked to RF for further acceleration.
- Light needed at energies > photocathode workfunction, generally UV.
- Laser needs second or third harmonic frequency conversion due to PC Q.E.
- Large area of laser research – need:
  - High pulse energy
  - Reliable running
  - Excellent pointing stability



See for example:

- Penco et. al., Phys. Rev. Letts. 112 044801 (2014)
- Schreiber et. al., NIM A 445 (2000).

Making a laser

- All laser oscillators (as opposed to amplifiers) have 3 parts:

- Gain medium – gas, solid state, liquid – what provides the lasing transition.

- Pump – source of energy to create population inversion – usually another light source e.g. flashlamp or another laser, can be electrical discharge or current.

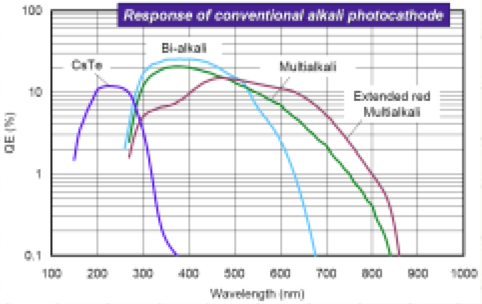
- Cavity – need to recirculate photons to stimulate emission on lasing transition – often mirrors around gain medium, can be medium itself.

- Lasing threshold – when gain (no. photons emitted in round trip) exceeds loss (number lost to absorption, through mirrors etc.).

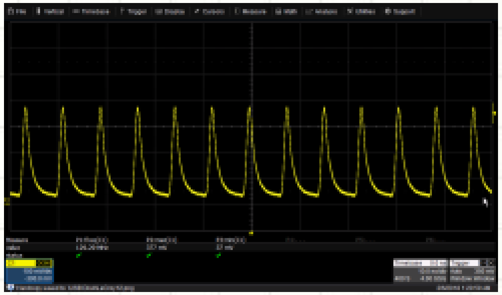
- And that's it!

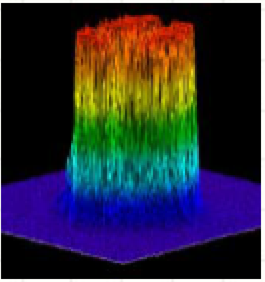
courtesy Dr. L. Corner, University of Liverpool

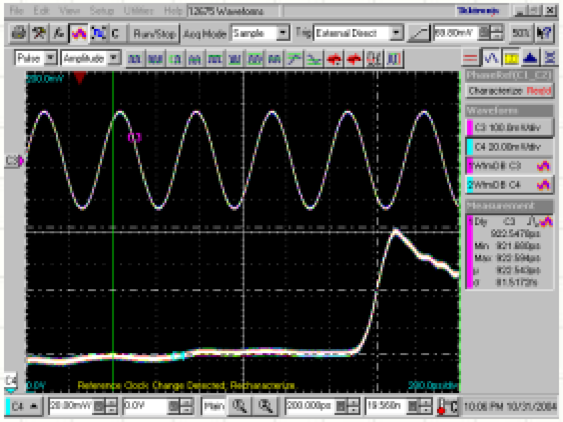
Typical laser pulse parameter requirements for RF gun photocathode



- Pulse energy, **> 10uJ** for Cs2Te
- Pulse duration, **~ 100fs – 10ps**
  - Space-charge limited
- Wavelength, **~ 250nm** for Cs2Te
  - Hence, High Harmonic Generation is needed
  - Conversion efficiency depends on pulse duration and harmonic
- Pulse repetition rate
  - Hz (machine), MHz (multi-bunch), GHz-THz (micro-bunch)
- Timing stability, **< 1ps** (~1 deg. RF phase (2.8GHz))
  - Stabilized and synchronized oscillator
  - Stabilized Laser Transport Line
- Pointing stability, smaller than rms spot size, typ **< 100um**.
  - Stabilized Laser Transport Line
  - Additional spatial filters
- Spatial and temporal pulse shaping
  - Pulse stacking
  - Micro-lens arrays
  - π-shapers



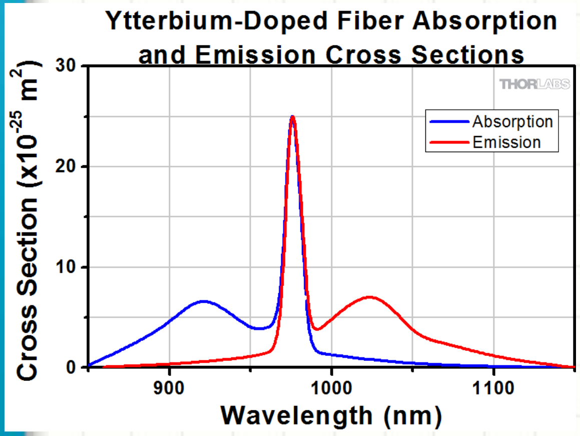




Typical technology (effectively dopants)

Ion	Common host crystals	Important emission wavelengths
neodymium(Nd^{3+})	$Y_3Al_5O_{12}$ (YAG), $YAlO_3$ (YALO), YVO_4 (yttrium vanadate), $YLiF_4$ (YLF), tungstates ($KGd(WO_4)_2$, $KY(WO_4)_2$)	1064, 1047, 1053, 1342, 946 nm
ytterbium(Yb^{3+})	YAG, tungstates (e.g. KGW, KYW, KLuW), YVO_4, borates (BOYS, GdCOB), apatites (SYS), sesquioxides (Y_2O_3, Sc_2O_3)	1030, 1020–1070 nm
erbium (Er^{3+})	YAG, YLF	2.9, 1.6 µm
thulium (Tm^{3+})	YAG	1.9–2.1 µm
holmium (Ho^{3+})	YAG	2.1, 2.94 µm
cerium (Ce^{3+})	YLF, LiCAF, LiLuF, LiSAF, and similar fluorides	0.28–0.33 µm

Ion	Common host crystals	Important emission wavelengths
titanium (Ti^{3+})	sapphire	650–1100 nm
chromium (II) (Cr^{2+})	zinc chalcogenides such as ZnS, ZnSe, and ZnS_xSe_{1-x}	2–3.4 µm
chromium (III) (Cr^{3+})	Al_2O_3 (ruby), $LiSrAlF_6$ (LiSAF), $LiCaAlF_6$ (LiCAF), $LiSrGaF_6$ (LiSGAF)	0.8–0.9 µm
chromium (IV) (Cr^{4+})	YAG, $MgSiO_4$ (forsterite)	1.35–1.65 µm (YAG), 1.1–1.37 µm (forsterite)



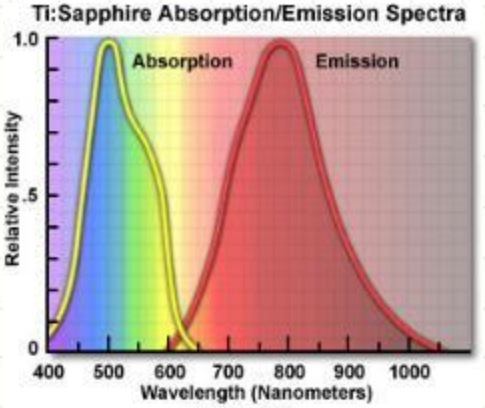
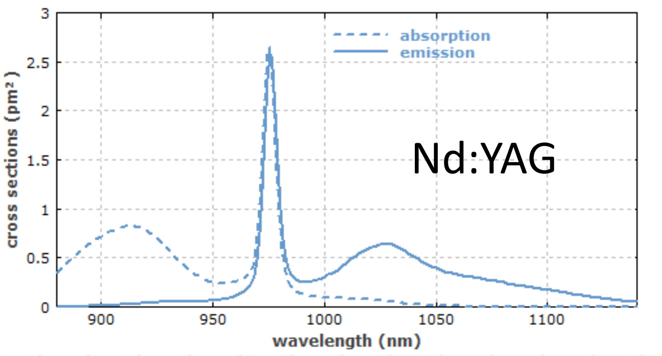
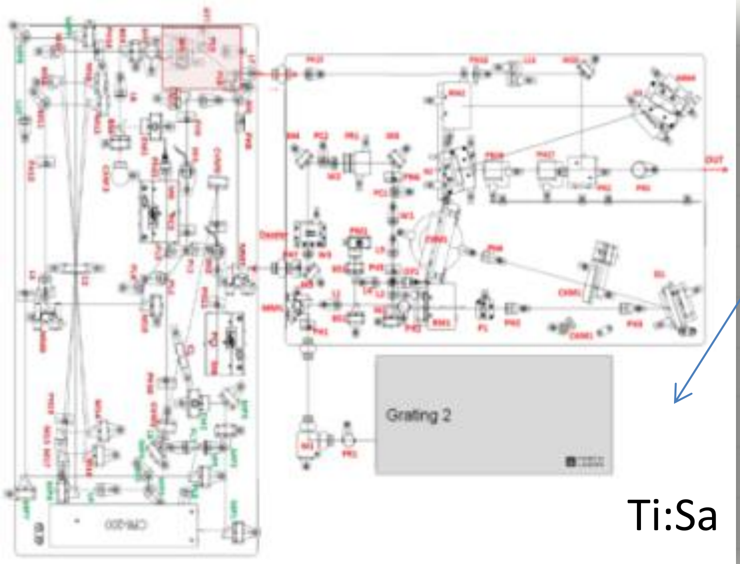


Figure 1



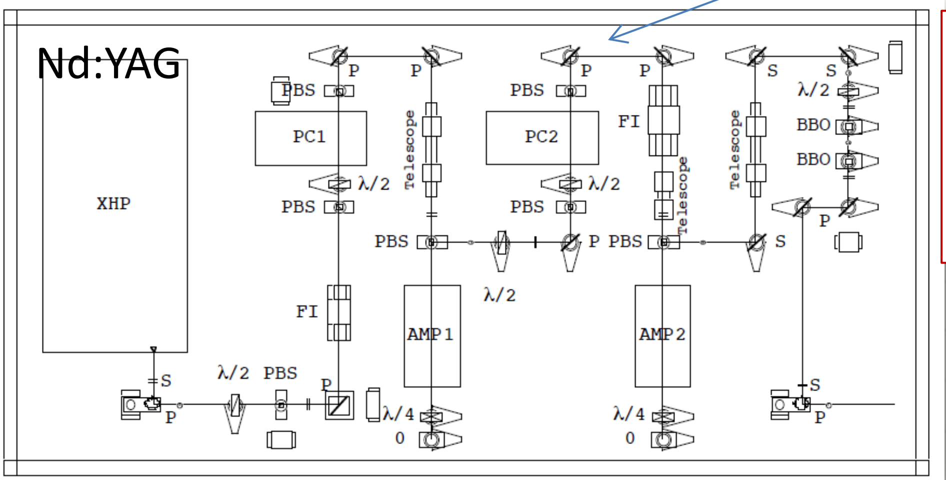
RF Gun laser system technologies

Solid-state-based technology



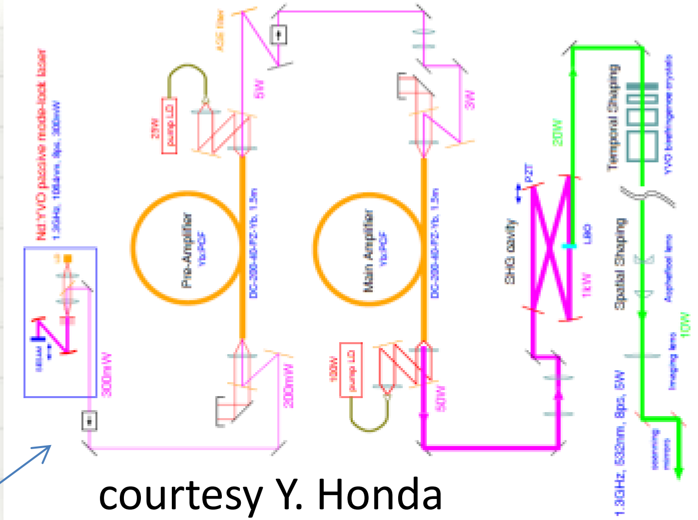
Hz rep.rate
fs pulse
High Energy
Complexity

Hz rep.rate
ps pulse
High Energy
Simplisity



Fiber-based technology

Yb-dopped fiber for example



courtesy Y. Honda

MHz rep.rate
~100 fs pulse
Low Energy
Simplisity

A. Chong, W.H. Renninger, F. W. Wise, Opt. Lett. 33 (2008) 2638:
Numerical simulations of Yb-doped fiber lasers indicate that ~30 fs pulses are possible for a realistic design with off-the-shelf components. Experiments are constrained by the available pump power, but ~75 fs pulses are obtained. (just for oscillator !!!)

Er-doped fiber laser is also promising candidate

What is so Special About ps-fs Lasers?

Short optical pulse.

- Most of energy dissipation and transfer processes occur on the time scale larger than 100 fs.
- Femtosecond laser pulses enable one to generate electron bunches with similar durations (strongly related to generation of THz radiation).
- Specific laser system design approaches.
- Specific gain materials due to optical BW and efficiency with fs pulses.
- Specific pulse diagnostics.

High peak power of the light

- *Peak Power = P. energy / P. duration*
  - 1 mJ pulse with 10 ns duration - **0.1 MW.**
  - 1 mJ pulse with 100 fs duration - **10 GW.**
- Non-linear response of the optical components(e.g., multi-photon absorption, optical harmonics generation, materials ablation, etc.)

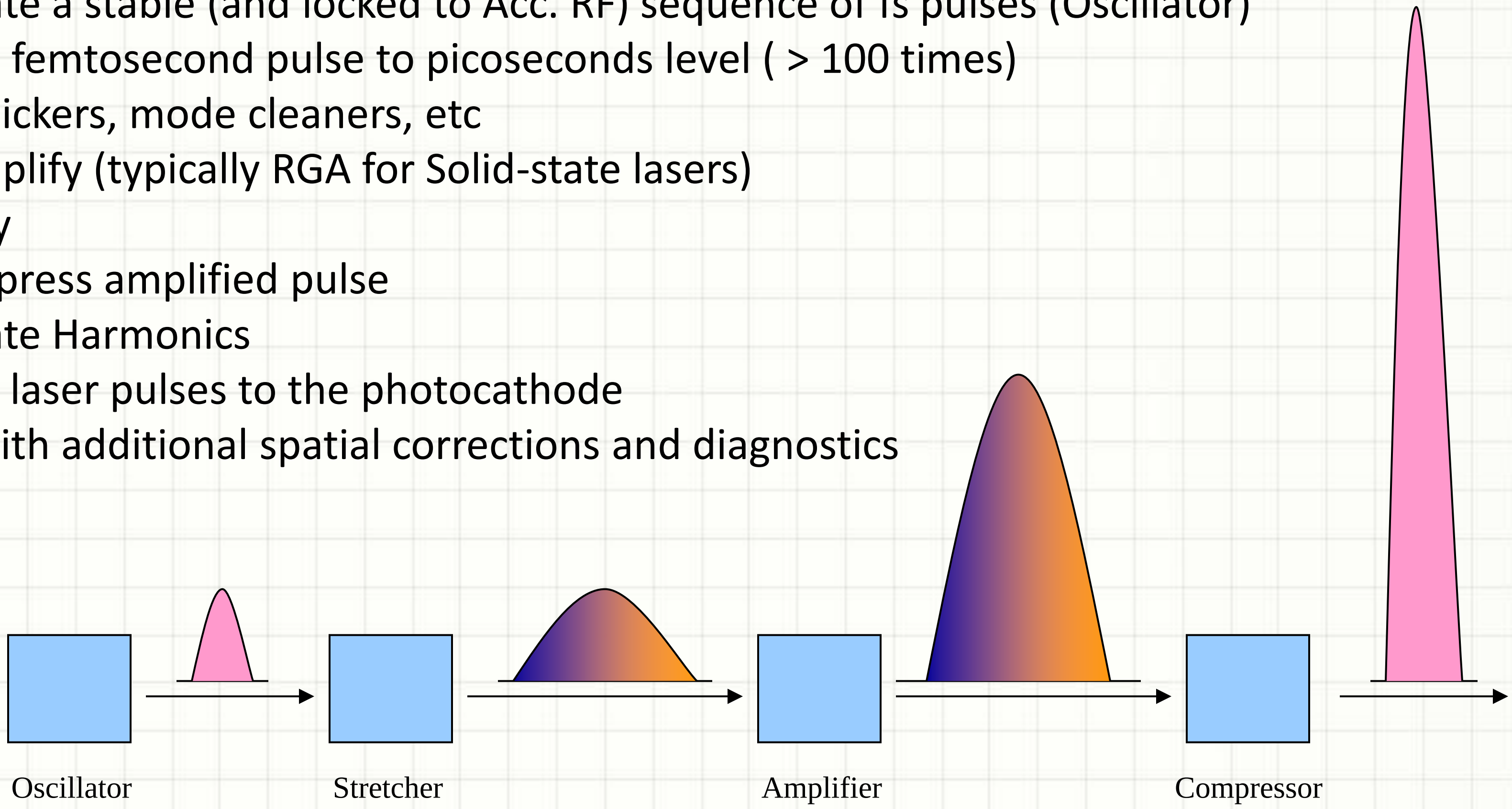
Large bandwidth

- Broadband optical components (mirrors, etc)
- Achromatic lens, waveplates, etc.
- Higher demands for laser safety.

W. Kaiser, ed., “*Ultrashort Laser Pulses: Generation and Applications”,* Springer-Verlag, Berlin, **1993**

Chirped pulse amplification concept

- Generate a stable (and locked to Acc. RF) sequence of fs pulses (Oscillator)
- Stretch femtosecond pulse to picoseconds level (> 100 times)
- Pulse pickers, mode cleaners, etc
- Pre-amplify (typically RGA for Solid-state lasers)
- Amplify
- Recompress amplified pulse
- Generate Harmonics
- Deliver laser pulses to the photocathode
  - With additional spatial corrections and diagnostics

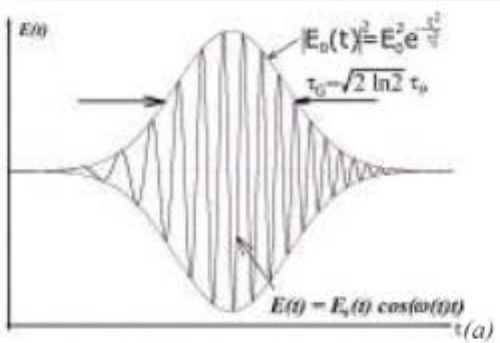


Same approach works for fiber lasers with the only difference in available components.

Time-Frequency Relationship

- A pulse can be defined as a transient in a constant background. The shape of this pulse is the shape of this transient. Intuitively, the pulse shape can be represented by a Gaussian function. It is known that the Fourier transform of a Gaussian function is also a Gaussian function. The general time and frequency Fourier transforms of a pulse can be written as:

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E(\omega)e^{-i\omega t}d\omega \qquad E(\omega) = \int_{-\infty}^{+\infty} E(t)e^{i\omega t}dt$$

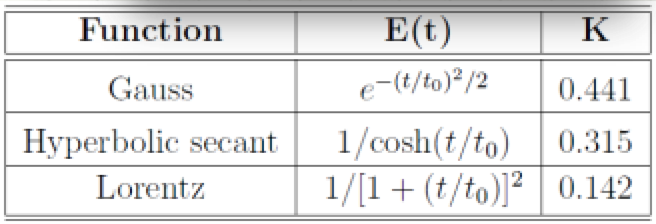


- The relationship between the duration and spectral bandwidth of the laser pulse can be written as:

$$\Delta\nu\Delta t \geqslant \mathrm{K}$$

- where $\Delta\nu$ is the frequency bandwidth measured at full-width at half-maximum (FWHM) with $\omega = 2\pi\nu$ and Δt is the FWHM in time of the pulse and K is a number which depends only on the pulse shape.

Consider it as a homework ->



Function	E(t)	K
Gauss	$e^{-(t/t_0)^2/2}$	0.441
Hyperbolic secant	$1/\cosh(t/t_0)$	0.315
Lorentz	$1/[1+(t/t_0)]^2$	0.142

- Thus in order to generate a laser pulse within femtosecond time domain one needs to use a broad spectral bandwidth. If the above equality is reached, one speaks about a **Fourier-transform-limited** pulse or simply a **transform-limited pulse**. One can also calculate the minimum time duration Δt of a pulse giving a spectrum with $\Delta\lambda$ (nm) at FWHM, central wavelength λ_0 (nm) and the speed of light (m/s) c as:

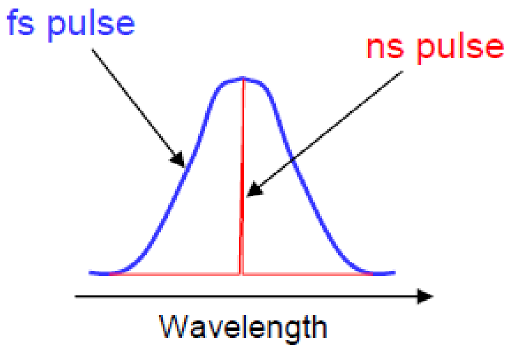
$$\Delta t \geqslant \mathrm{K}\frac{\lambda_0^2}{\Delta\lambda \cdot c}$$

Time-Frequency Relationship

Femtosecond laser pulses are usually ***Fourier transform-limited pulses***

$\Delta\omega \cdot \Delta t \approx 2\pi \rightarrow \Delta\omega \approx 2\pi/\Delta t \rightarrow$ Large spectral bandwidth for short pulses

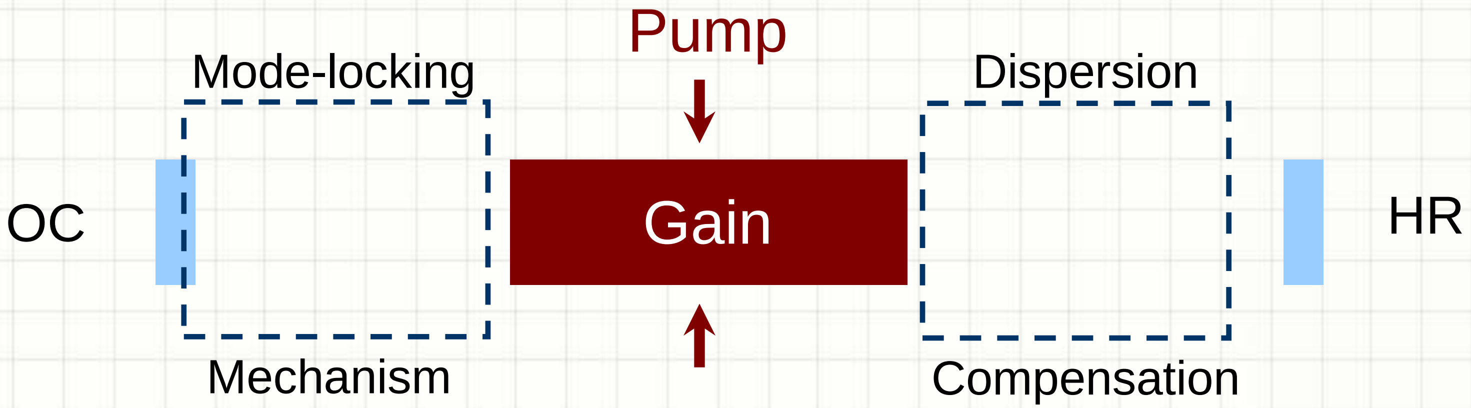
$\Delta\lambda \approx \lambda^2/(c\Delta t)$ $\Delta\lambda \approx$ 21 nm for 100 fs pulses with $\lambda_0 = 800$ nm



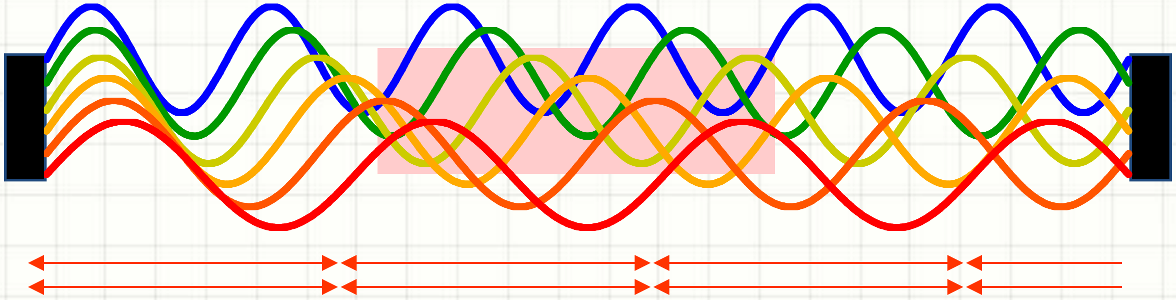
Large bandwidth limits the choice of the laser active medium (broad-band materials only, e.g., Ti:Sapphire, laser dyes) and laser cavity design (no bandwidth limiting elements, such as narrowband mirrors)

Basic principles of ultrafast lasers

Components of ultrafast laser system



Cavity modes



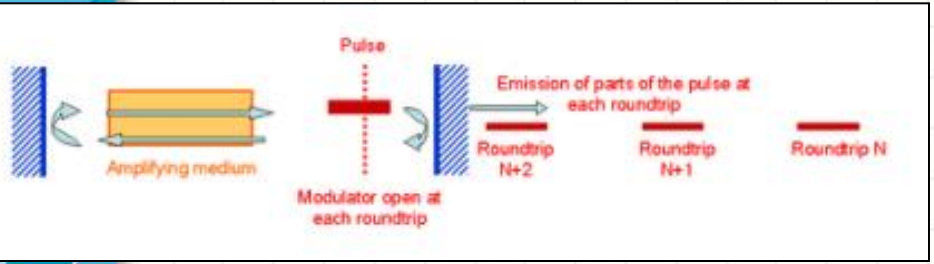
$\lambda_n = 2\,L/n$

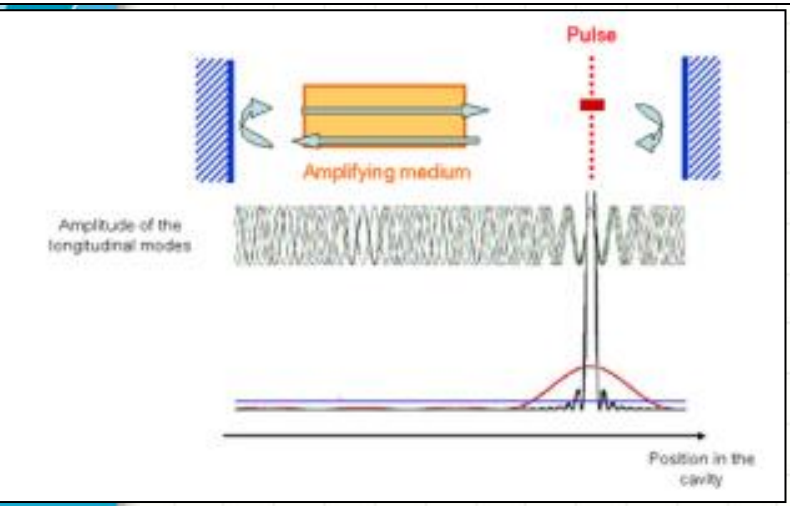
n – positive integer

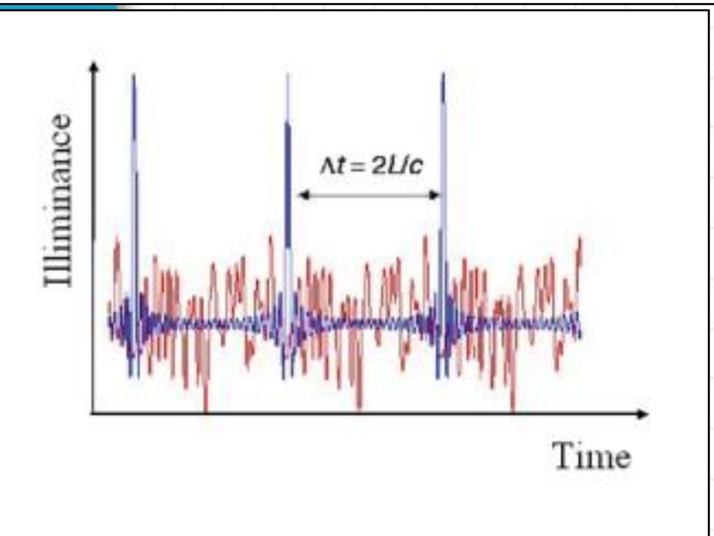
$\Delta f = c/2\,L$

frequency separation between adjacent modes

Mode-locking





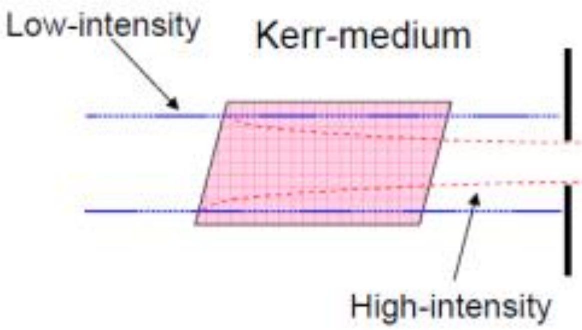


- Ignition
  - Dispersive pulse compression – external starting mechanism.
  - Instantaneous increase in net gain (Kerr lens) upon application of perturbation (mirror wobbling, truly self-starting).
- Passive mode-locking
  - Semiconductor Saturable Absorber Mirrors (SESAM), ps pulses
  - Kerr lens
  - Nonlinear polarization rotation(NLPR)
  - Q-switched Mode Locking, effectively instability.
- Active mode-locking
  - Periodic modulation of the resonator losses or of the round-trip phase change, achieved e.g. with an acousto-optic or electro-optic modulator, a Mach–Zehnder integrated-optic modulator, or a semiconductor electro-absorption modulator.

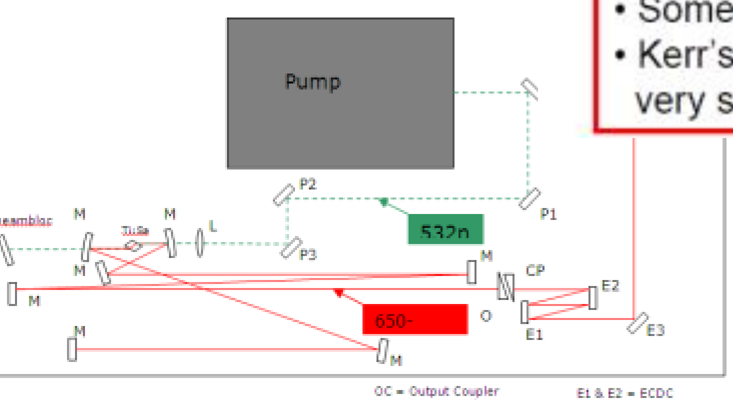
Ti:Sa Oscillator

Kerr-lens mode-locking

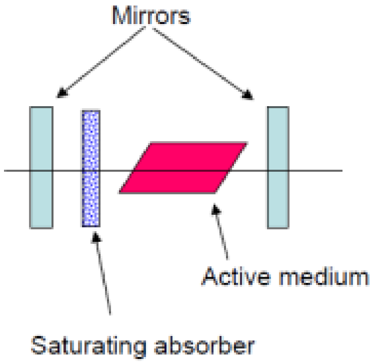
- Kerr's effect – inetnsity-dependent index of refraction: $n = n_0 + n_2 I$
- The e/m field inside the laser cavity has Gaussian distribution of intensity which creates similar distribution of the refractive index.
- High-intensity beam is self-focused by the photoinduced lens.

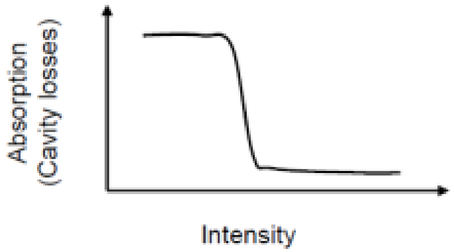


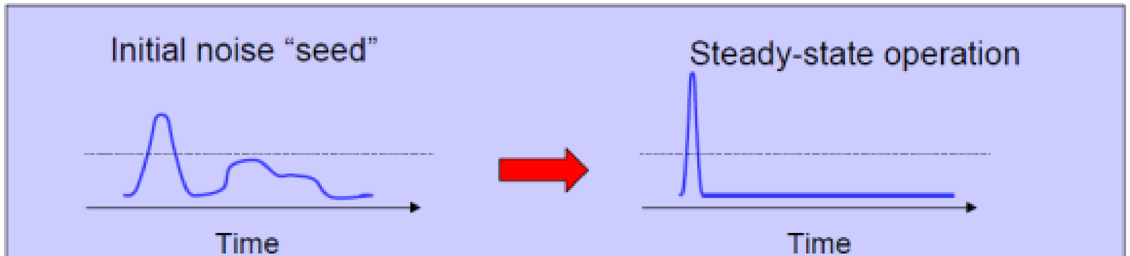
- High-intensity modes have smaller cross-section and are less lossy. Thus, Kerr-lens is similar to saturating absorber!
- Some lasing materials (e.g. Ti:Sapphire) can act as Kerr-media
- Kerr's effect is much faster than saturating absorber allowing one generate very short pulses (~5 fs).



Saturating absorber technique

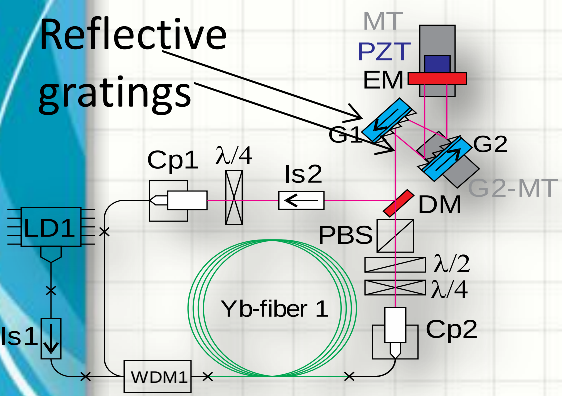






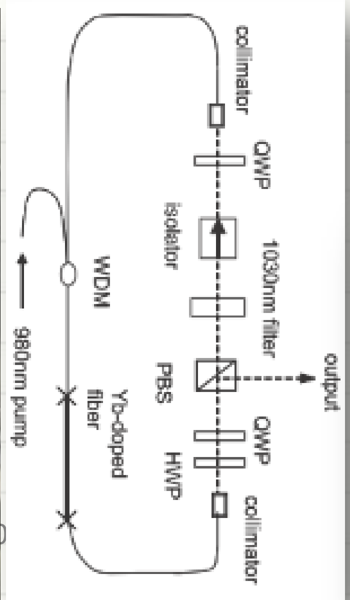
Fiber Oscillator

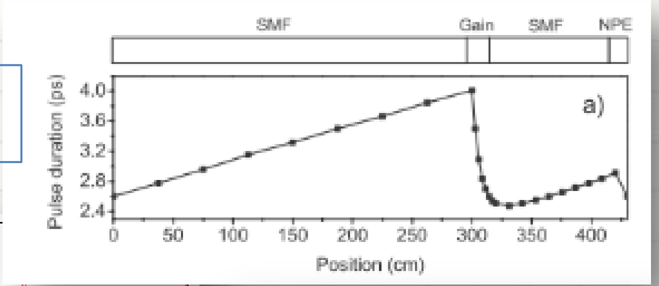
Andy Chong, “All-normal-dispersion femtosecond Fiber laser”, Vol. 14, No. 21 / OPTICS EXPRESS 10095, 2006

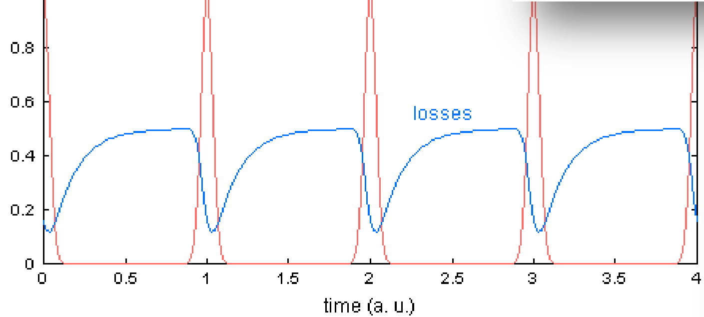


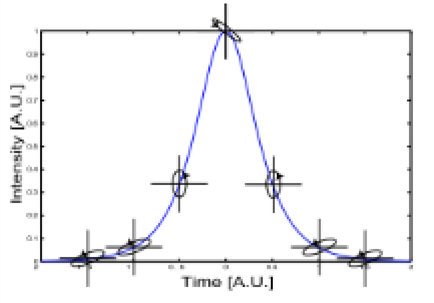
- Nonlinear polarization rotation(NLPR) :
  - A power-dependent polarization change is converted into a power-dependent transmission through a polarizer. NLPR converts the differential phase shift to amplitude modulation.
    - stable soliton
    - stretched-pulse
    - self-similar
    - all-normal-dispersion pulse
- Solitons are caused by a cancellation of nonlinearity and dispersion.
- For stable soliton fiber lasers the energy of a single pulse is limited by the nonlinear phase shift induced by the high peak power. The pulse will break into multiple pulses when the energy rises to 0.1 nJ.
- Analog to dispersion-managed soliton, an alteration of positive and negative dispersion part inside a laser cavity.
- Produce highly desirable Gaussian pulse shapes and broad pulse spectra.

SMF: Single-mode fiber
NPE: Nonlinear polarization evolution





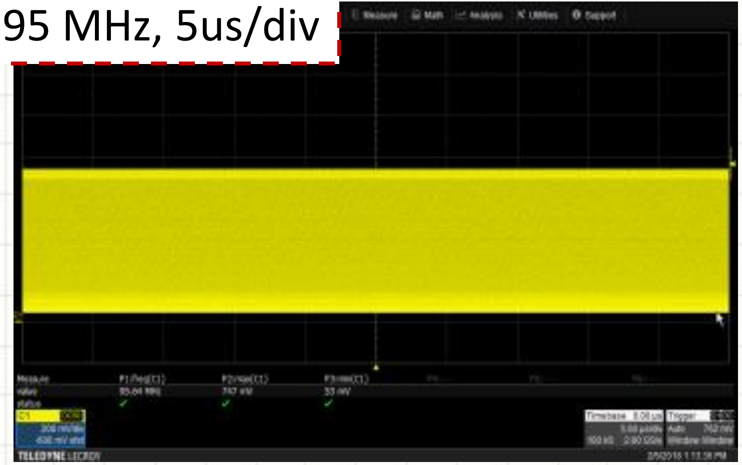




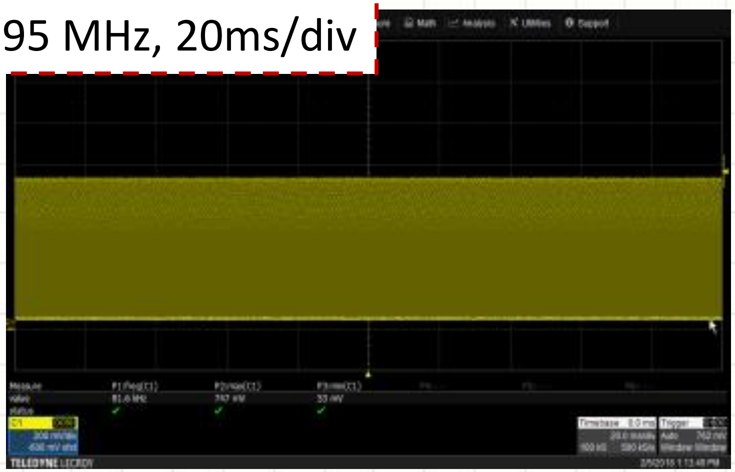
Stability

95 MHz, 20ns/div

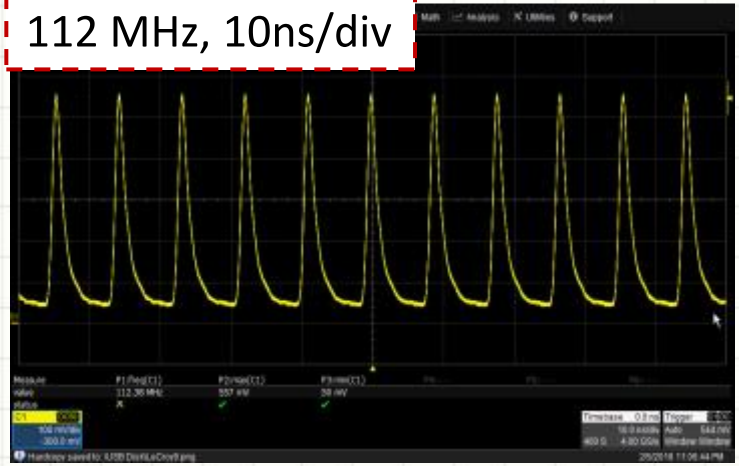
95 MHz, 5us/div



95 MHz, 20ms/div



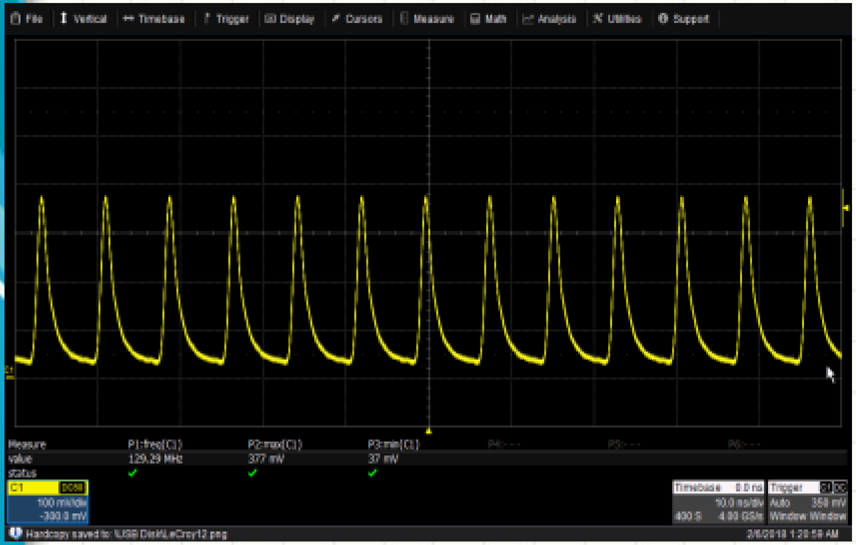
112 MHz, 10ns/div



Rep.rate and BW

Output power was 110mW, rms stability 0.25%

129 MHz, 10ns/div



Measure	P1:freq(C1)	P2:max(C1)	P3:min(C1)
value	129.29 MHz	377 mV	37 mV
status	✓	✓	✓

C1 100 mV/div -300.0 mV

Timebase 0.0 ns 10.0 ns/div 400 S 4.00 GS/s

Trigger Auto 358 mV

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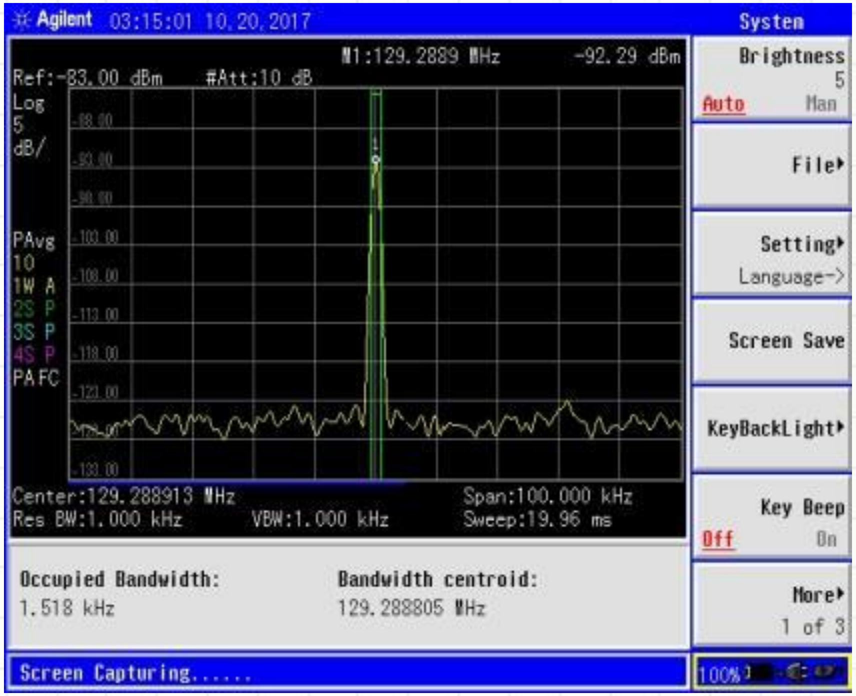


M1:129.2889 MHz -92.29 dBm

Ref:-83.00 dBm #Att:10 dB

Log 5 dB/

PAvg 10

Center:129.288913 MHz

Res BW:1.000 kHz VBW:1.000 kHz

Span:100.000 kHz

Sweep:19.96 ms

Occupied Bandwidth: 1.518 kHz

Bandwidth centroid: 129.288805 MHz

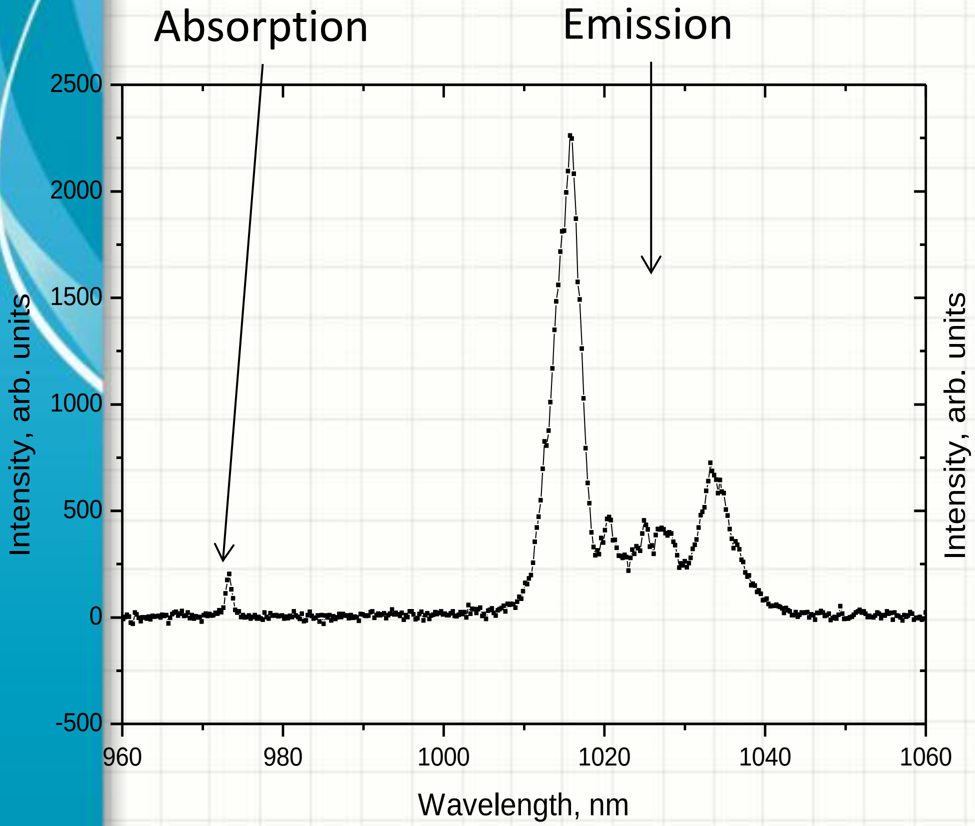
Screen Capturing......

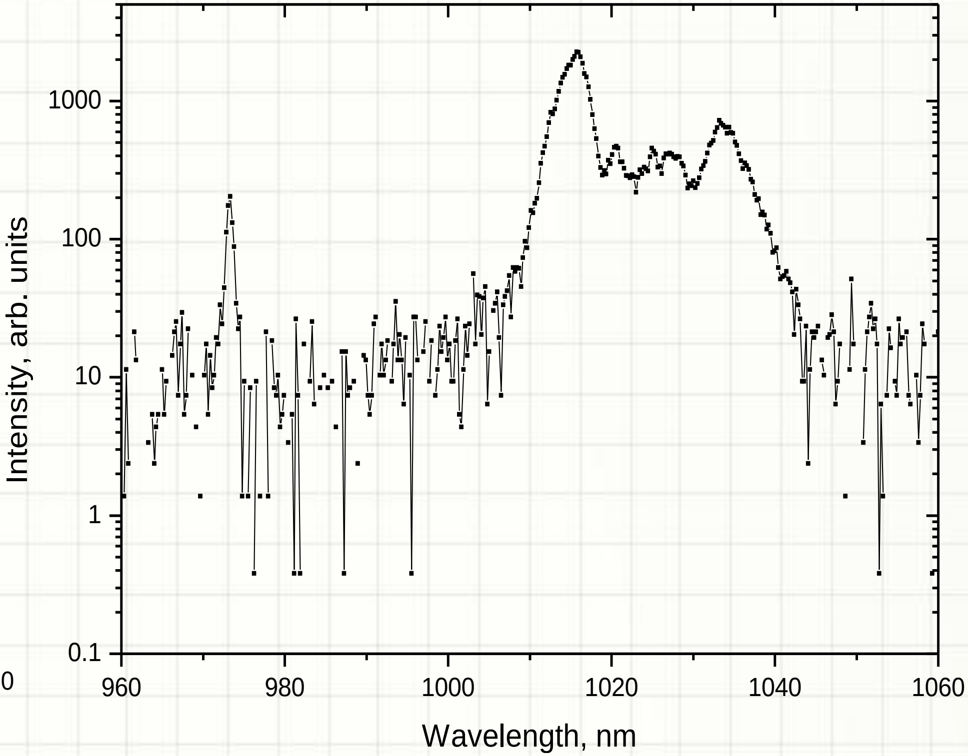
Contrast: 37mV/377mV = 0.098

Spectral width

FWHM optical BW > 25nm

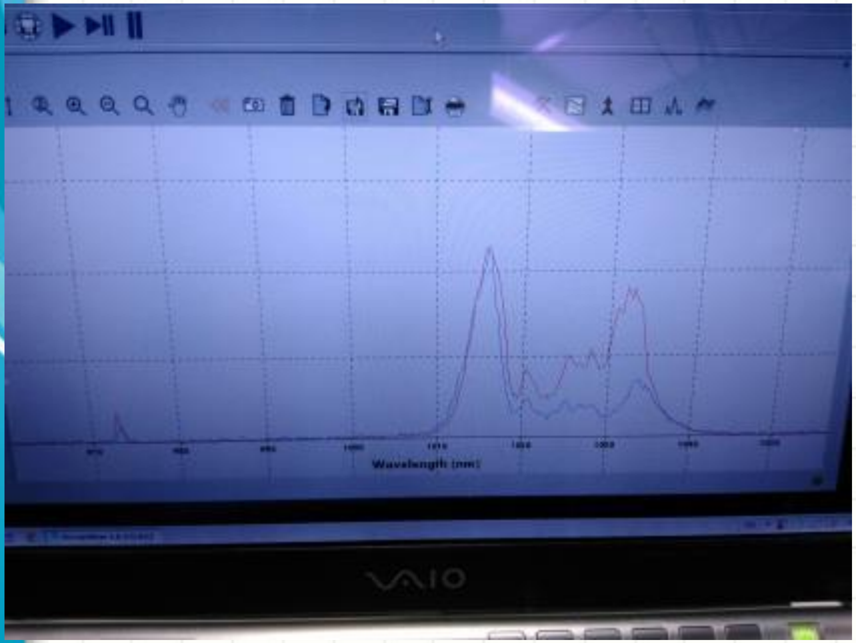
Further tuning should be applied to flatten peaks of emitted spectrum

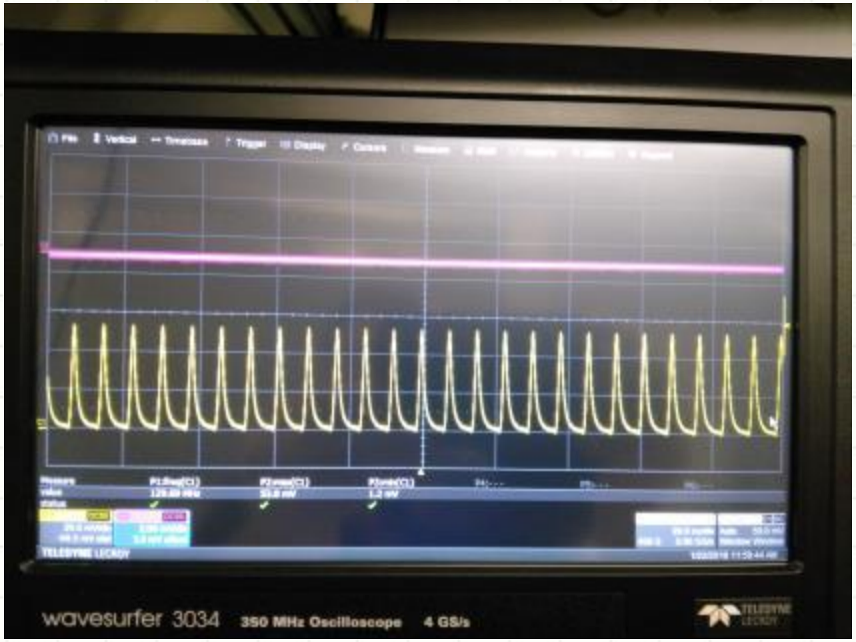




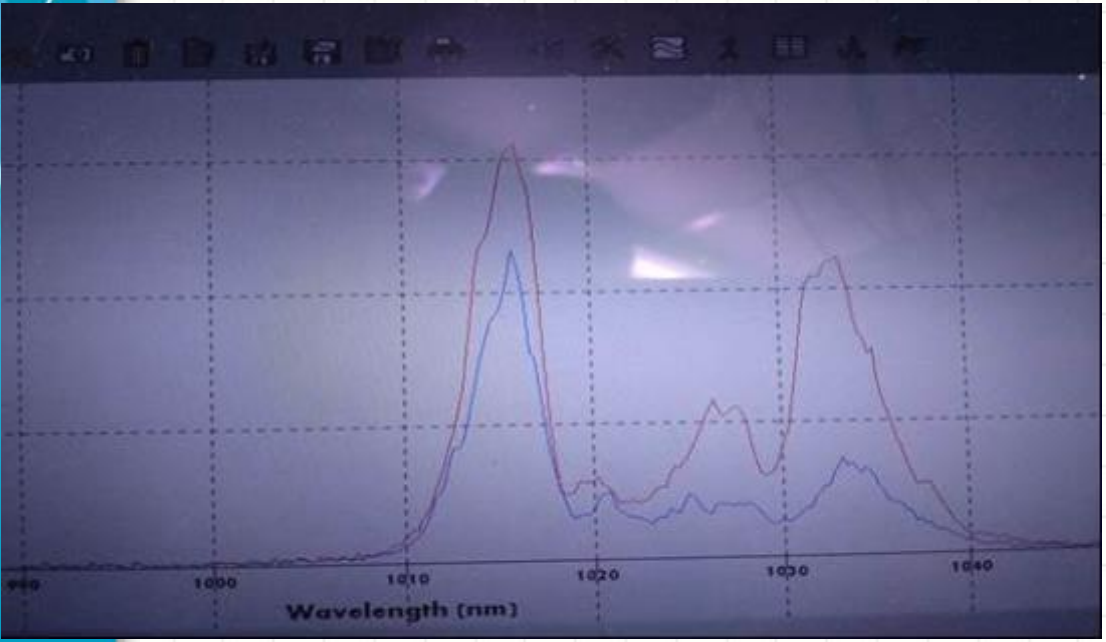
Oscillator performance with small dielectric end-mirror

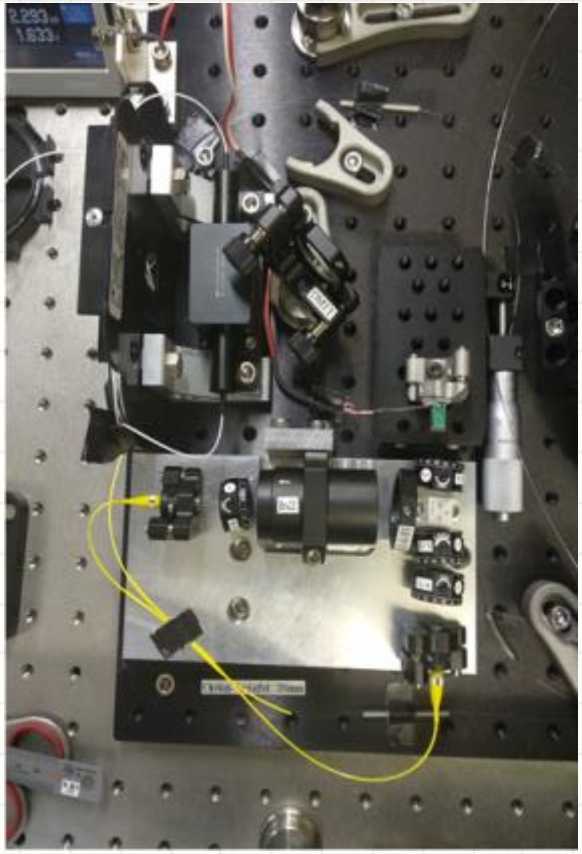
~ 135mW, 0.2% rms stability





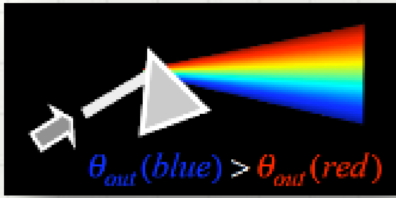
Oscillator performance with small dielectric end-mirror





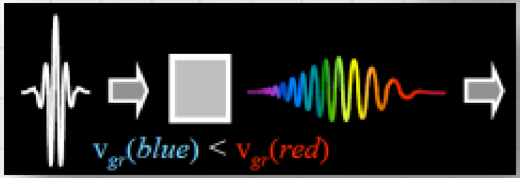
Dispersion and Group velocity

- Dispersion in Optics: The dependence of the refractive index on wavelength has two effects on a pulse, one in space and the other in time.
- "Chirp" $d^2n/d\lambda^2$ and "Angular dispersion" $dn/d\lambda$
- Both of these effects play major roles in ultrafast optics.
- Dispersion disperses a pulse in space (angle):



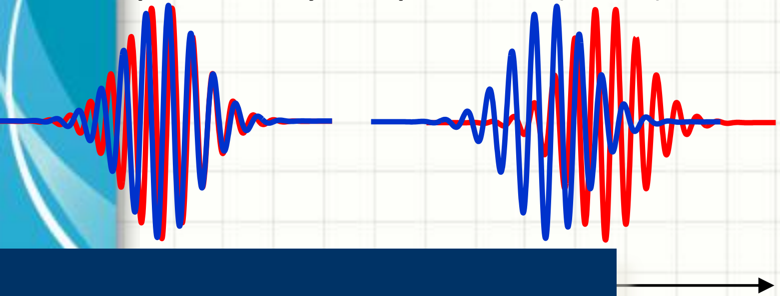
$\theta_{out}(blue) > \theta_{out}(red)$

- Dispersion also disperses a pulse in time:



$v_{gr}(blue) < v_{gr}(red)$

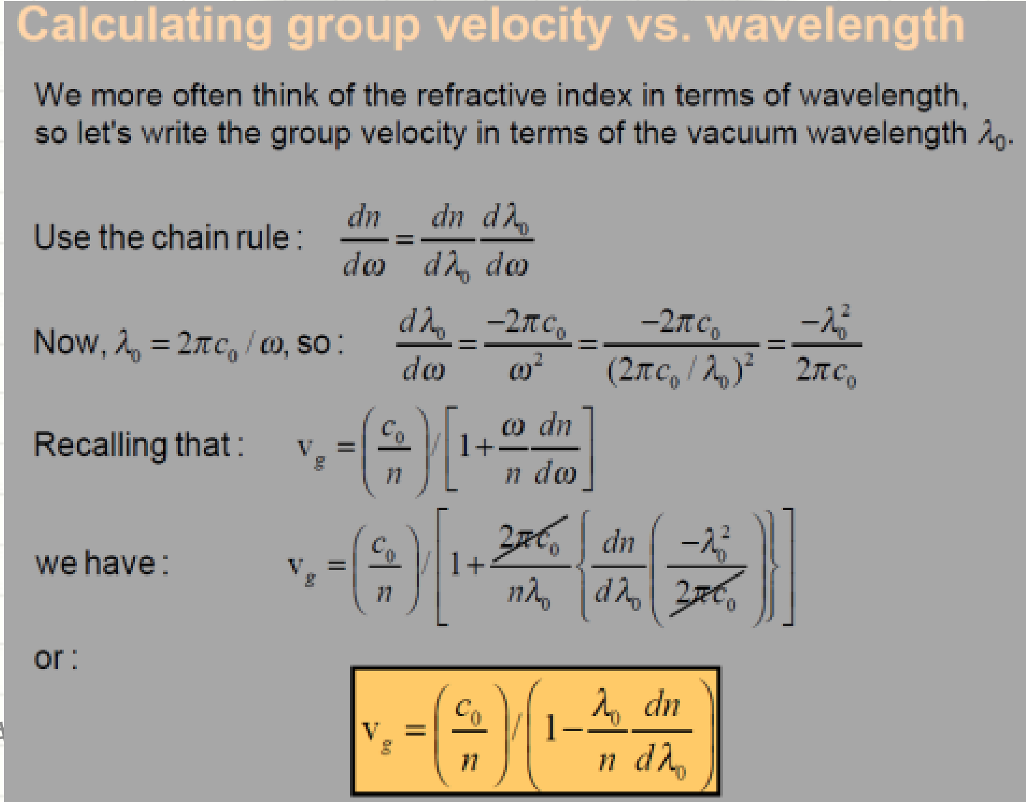
Group Velocity Dispersion (GVD)



$v_g < v_{phase}$

- $v = c / n$ – speed of light in a medium
- n –depends on wavelength, $dn/d\lambda < 0$ – normal dispersion

- Because of GVD, red components (longer wavelengths) of the pulse propagate faster than blue components (shorter wavelengths) leading to pulse stretching (aka "chirp").
- GVD can be compensated by material with abnormal dispersion.



Calculating group velocity vs. wavelength

We more often think of the refractive index in terms of wavelength, so let's write the group velocity in terms of the vacuum wavelength λ_0.

Use the chain rule : $\frac{dn}{d\omega} = \frac{dn}{d\lambda_0}\frac{d\lambda_0}{d\omega}$

Now, $\lambda_0 = 2\pi c_0 / \omega$, so : $\frac{d\lambda_0}{d\omega} = \frac{-2\pi c_0}{\omega^2} = \frac{-2\pi c_0}{(2\pi c_0 / \lambda_0)^2} = \frac{-\lambda_0^2}{2\pi c_0}$

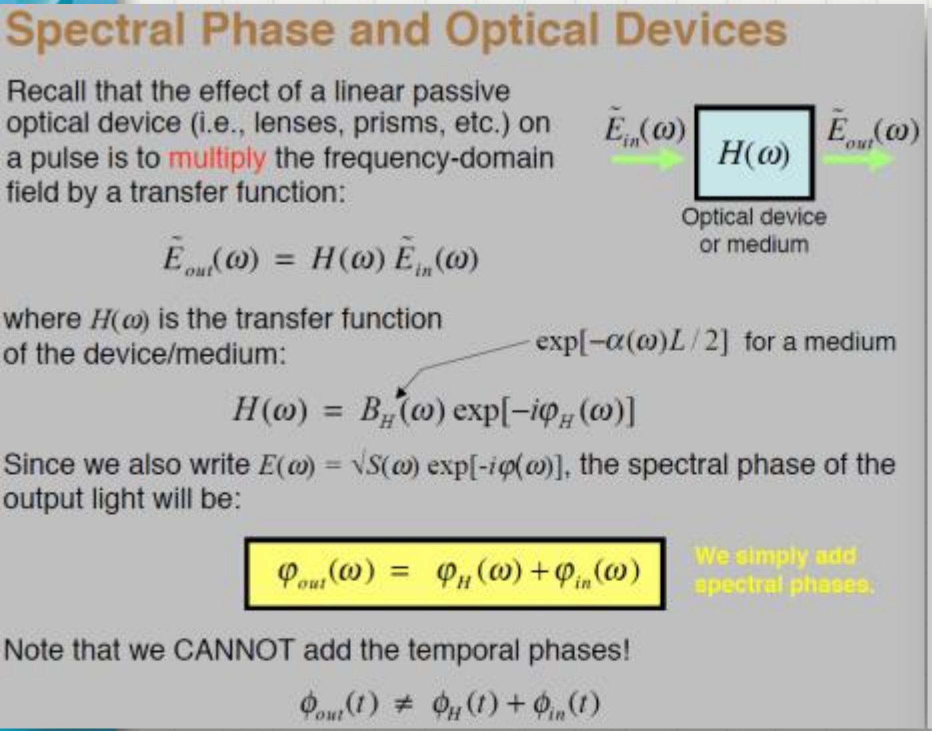
Recalling that : $v_g = \left(\frac{c_0}{n}\right) \Big/ \left[1 + \frac{\omega}{n}\frac{dn}{d\omega}\right]$

we have : $v_g = \left(\frac{c_0}{n}\right) \Big/ \left[1 + \frac{\cancel{2\pi c_0}}{n\lambda_0}\left\{\frac{dn}{d\lambda_0}\left(\frac{-\lambda_0^2}{\cancel{2\pi c_0}}\right)\right\}\right]$

or :

$$\boxed{v_g = \left(\frac{c_0}{n}\right) \Big/ \left(1 - \frac{\lambda_0}{n}\frac{dn}{d\lambda_0}\right)}$$

Group-Velocity Dispersion



Spectral Phase and Optical Devices

Recall that the effect of a linear passive optical device (i.e., lenses, prisms, etc.) on a pulse is to multiply the frequency-domain field by a transfer function:

$\tilde{E}_{in}(\omega)$ → $H(\omega)$ → $\tilde{E}_{out}(\omega)$

Optical device or medium

$$\tilde{E}_{out}(\omega) = H(\omega)\,\tilde{E}_{in}(\omega)$$

where $H(\omega)$ is the transfer function of the device/medium:

$\exp[-\alpha(\omega)L/2]$ for a medium

$$H(\omega) = B_H(\omega)\exp[-i\varphi_H(\omega)]$$

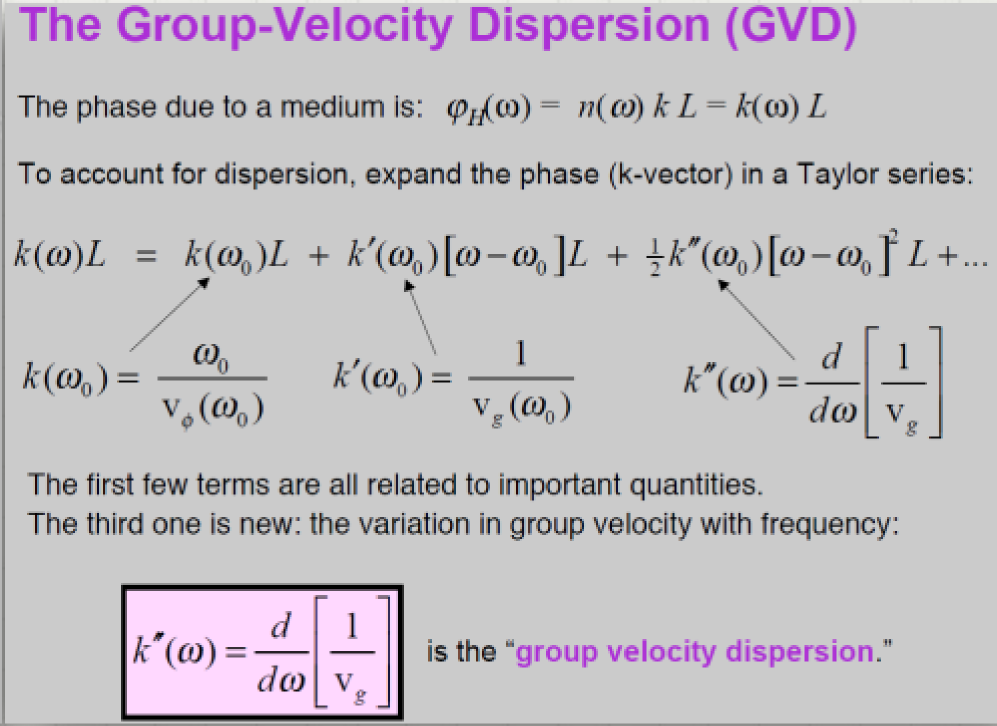
Since we also write $E(\omega) = \sqrt{S(\omega)}\exp[-i\varphi(\omega)]$, the spectral phase of the output light will be:

$$\boxed{\varphi_{out}(\omega) = \varphi_H(\omega)+\varphi_{in}(\omega)}$$

We simply add spectral phases.

Note that we CANNOT add the temporal phases!

$$\phi_{out}(t) \neq \phi_H(t)+\phi_{in}(t)$$



The Group-Velocity Dispersion (GVD)

The phase due to a medium is: $\varphi_H(\omega) = n(\omega)\,k\,L = k(\omega)\,L$

To account for dispersion, expand the phase (k-vector) in a Taylor series:

$$k(\omega)L = k(\omega_0)L + k'(\omega_0)[\omega-\omega_0]L + \tfrac{1}{2}k''(\omega_0)[\omega-\omega_0]^2 L + \ldots$$

$$k(\omega_0) = \frac{\omega_0}{v_\phi(\omega_0)} \qquad k'(\omega_0) = \frac{1}{v_g(\omega_0)} \qquad k''(\omega) = \frac{d}{d\omega}\left[\frac{1}{v_g}\right]$$

The first few terms are all related to important quantities.
The third one is new: the variation in group velocity with frequency:

$$\boxed{k''(\omega) = \frac{d}{d\omega}\left[\frac{1}{v_g}\right]}$$

is the "group velocity dispersion."

The effect of group velocity dispersion

- GVD means that the group velocity will be different for different wavelengths in the pulse.
- Because ultrashort pulses have such large bandwidths, GVD is a bigger issue than for cw light.

GVD yields group delay dispersion (GDD).

We can define delays in terms of the velocities and the medium length L.

The phase delay:

$$k(\omega_0) = \frac{\omega_0}{v_\phi(\omega_0)} \qquad \text{so:} \qquad t_\phi = \frac{L}{v_\phi(\omega_0)} = \frac{k(\omega_0)L}{\omega_0}$$

The group delay:

$$k'(\omega_0) = \frac{1}{v_g(\omega_0)} \qquad \text{so:} \qquad t_g(\omega_0) = \frac{L}{v_g(\omega_0)} = k'(\omega_0)L$$

The group delay dispersion (GDD):

$$k''(\omega) = \frac{d}{d\omega}\left[\frac{1}{v_g}\right] \qquad \text{so:} \qquad \boxed{GDD = \frac{d}{d\omega}\left[\frac{1}{v_g}\right]L = \overset{GDD = GVD\ L}{k''(\omega)L}}$$

Units: fs² or fs/Hz

Propagation of the pulse manipulates it.

Dispersive pulse broadening is unavoidable.

If φ_2 is the pulse 2nd-order spectral phase on entering a medium, and $k''L$ is the 2nd-order spectral phase of the medium, then the resulting pulse 2nd-order phase will be the sum: $\varphi_2 + k''L$.

A linearly chirped input pulse has 2nd-order phase: $\varphi_{2,in} = \dfrac{\beta/2}{\alpha^2+\beta^2}$

(This result pulls out the ½ in the Taylor Series.)

Emerging from a medium, its 2nd-order phase will be:

$$\varphi_{2,out} = \frac{\beta/2}{\alpha^2+\beta^2} + GDD = \frac{\beta/2}{\alpha^2+\beta^2} + \frac{\lambda_0^3}{2\pi c_0^2}\frac{d^2 n}{d\lambda_0^2}L \longleftarrow$$

This result, with the spectrum, can be inverse Fourier-transformed to yield the pulse.

A positively chirped pulse will broaden further;
a negatively chirped pulse will shorten.
Too bad material GDD is always positive in the visible and near-IR…

Manipulating the phase of light

Recall that we expand the spectral phase of the pulse in a Taylor Series:

$$\varphi(\omega) = \varphi_0 + \varphi_1\,[\omega-\omega_0] + \varphi_2\,[\omega-\omega_0]^2/2! + \ldots$$

and we do the same for the spectral phase of the optical medium, H:

$$\varphi_H(\omega) = \underset{\text{phase}}{\varphi_{H0}} + \underset{\text{group delay}}{\varphi_{H1}}\,[\omega-\omega_0] + \underset{\text{group delay dispersion (GDD)}}{\varphi_{H2}}\,[\omega-\omega_0]^2/2! + \ldots$$

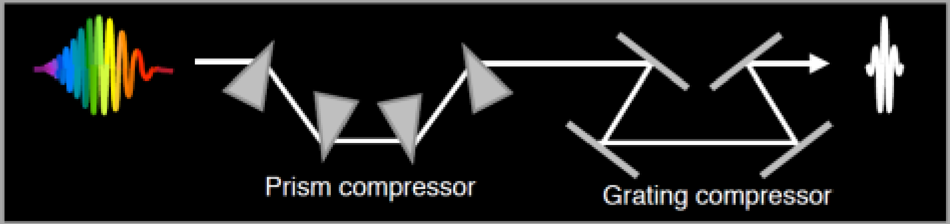
So, to manipulate light, we must add or subtract spectral-phase terms.

For example, to eliminate the linear chirp (second-order spectral phase), we must design an optical device whose second-order spectral phase cancels that of the pulse:

$$\varphi_2 + \varphi_{H2} = 0 \qquad \text{i.e.,} \qquad \left.\frac{d^2\varphi}{d\omega^2}\right|_{\omega_0} + \left.\frac{d^2\varphi_H}{d\omega^2}\right|_{\omega_0} = 0$$

Compensating 2nd and 3rd-order spectral phase

Use both a prism and a grating compressor. Since they have 3rd-order terms with opposite signs, they can be used to achieve almost arbitrary amounts of both second- and third-order phase.



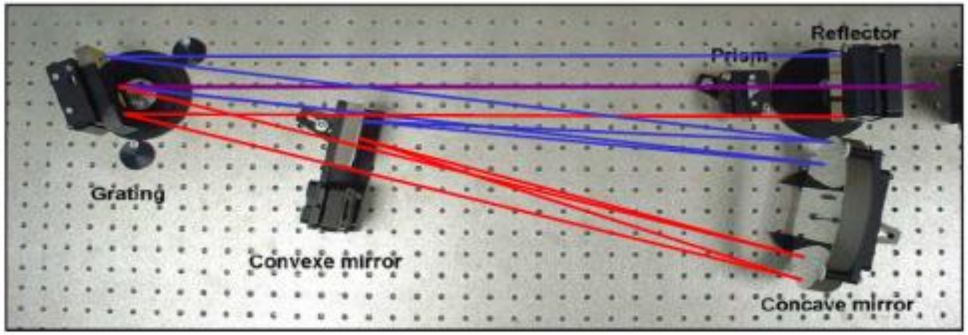
Given the 2nd- and 3rd-order phases of the input pulse, φ_{input2} and φ_{input3}, solve simultaneous equations:

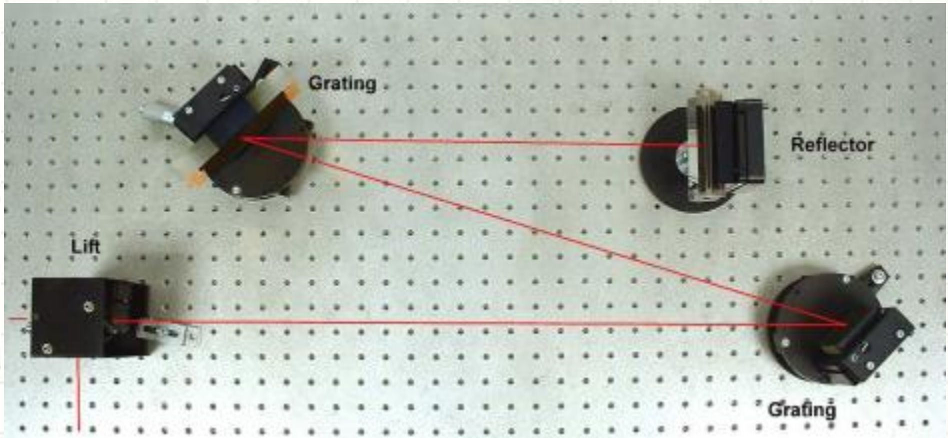
$$\varphi_{input2} + \varphi_{prism2} + \varphi_{grating2} = 0$$
$$\varphi_{input3} + \varphi_{prism3} + \varphi_{grating3} = 0$$

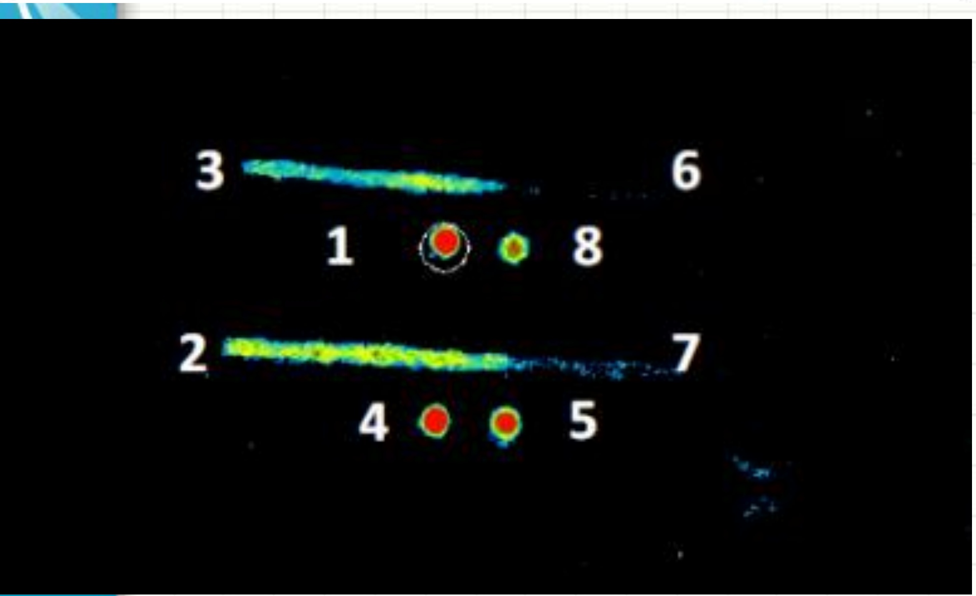
This design was used by Fork and Shank at Bell Labs in the mid 1980's to achieve a 6-fs pulse, a record that stood for over a decade.

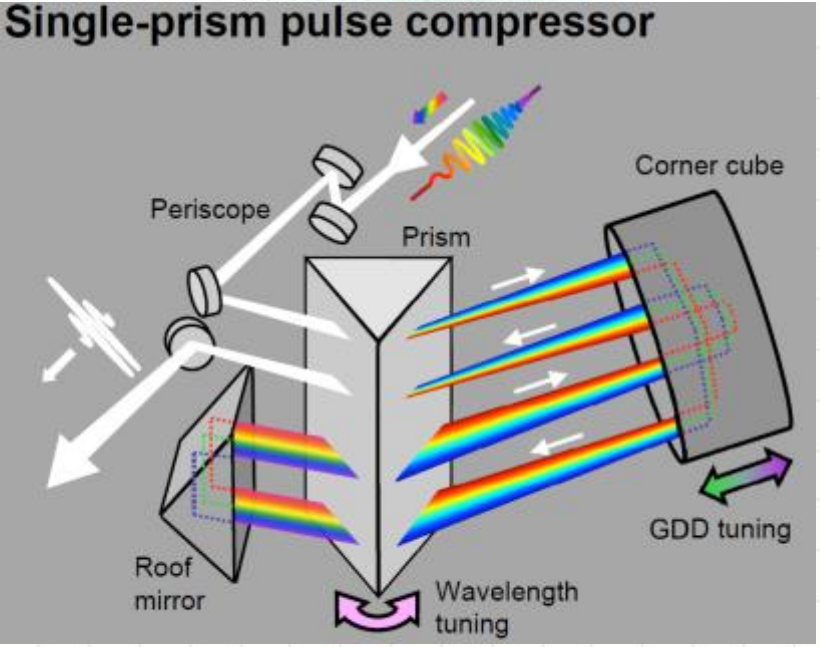
Stretcher and Compressor

“Aberration-free stretcher design for ultra-short pulse amplification” G. Cheriaux, F. Salin and al. OPTICS LETTERS March 15 1996

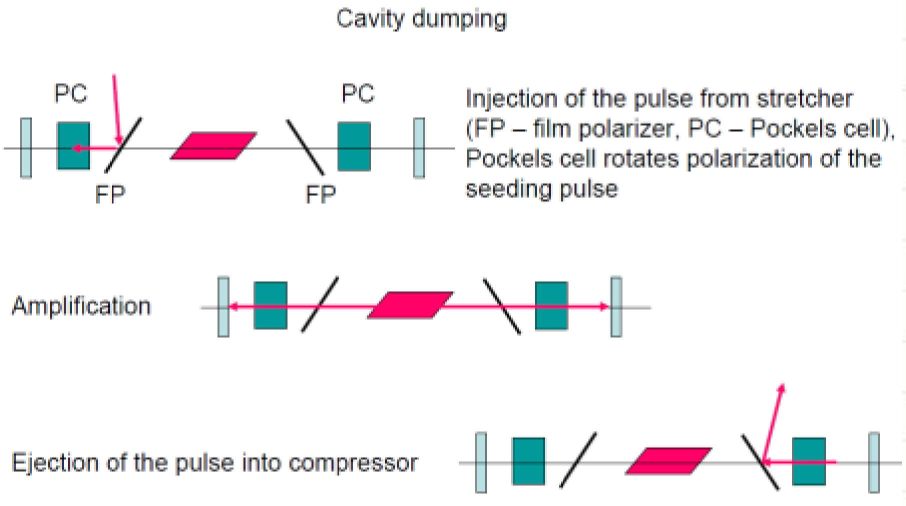








Pre-amplifier. RGA

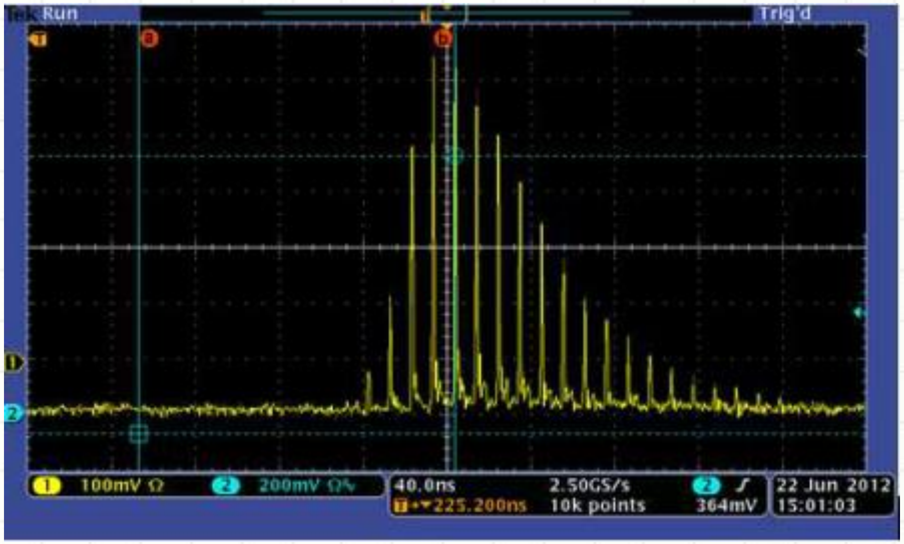


Cavity dumping

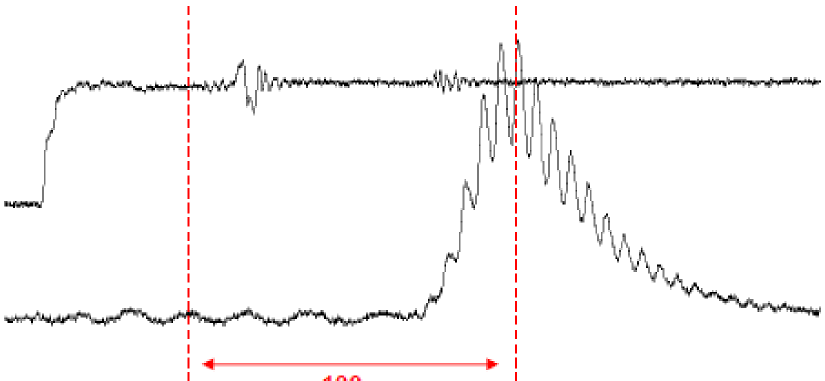
Injection of the pulse from stretcher (FP – film polarizer, PC – Pockels cell), Pockels cell rotates polarization of the seeding pulse

Amplification

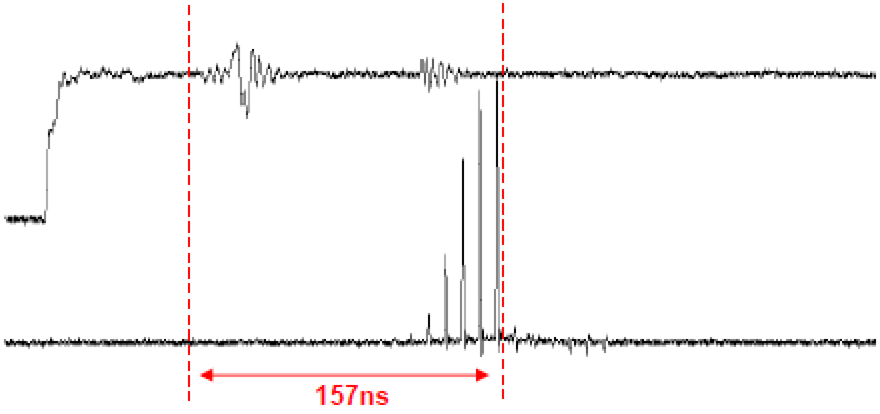
Ejection of the pulse into compressor



*Build-up time is measured prior to the seeding Pockels cell activation

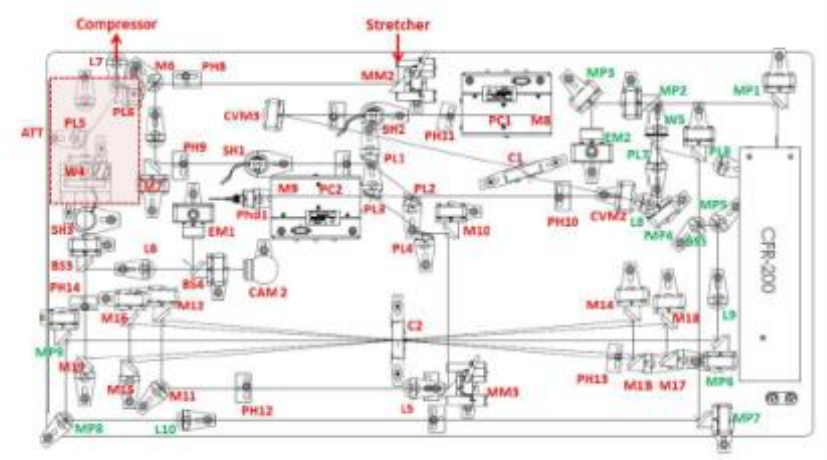


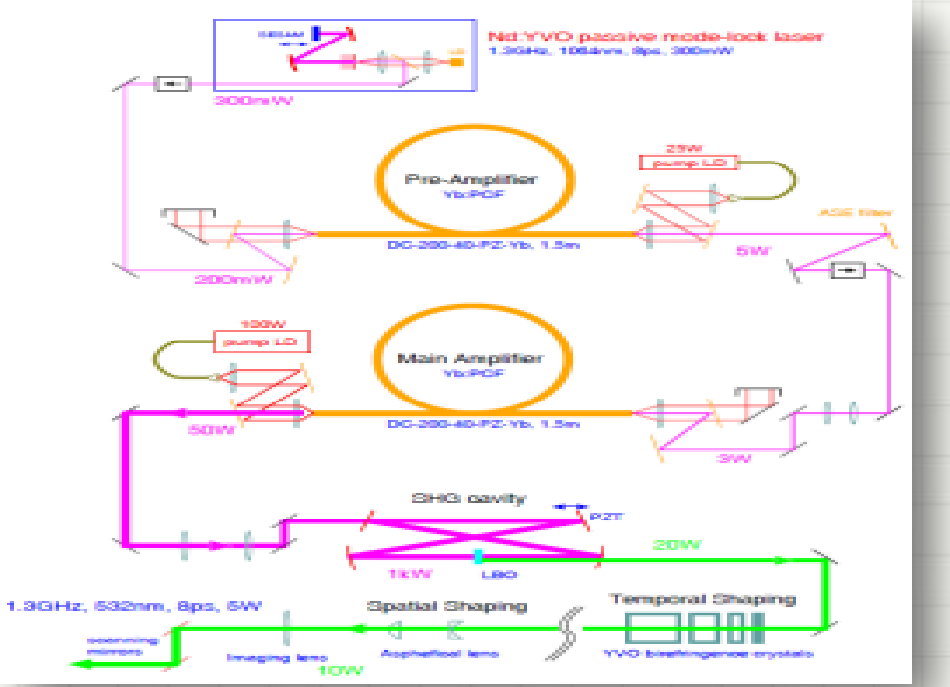
Free running time build-up time

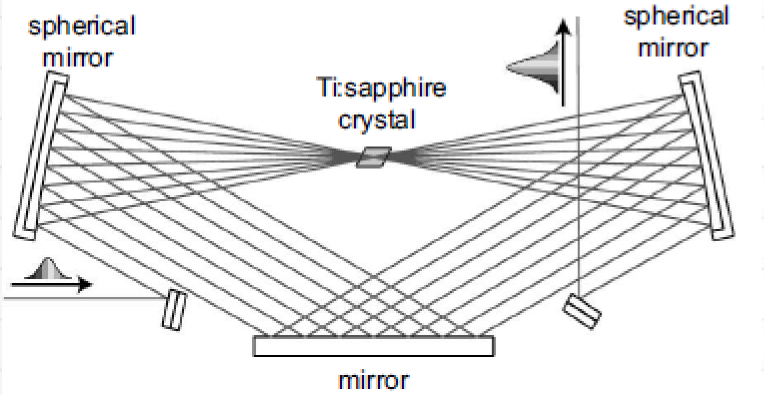


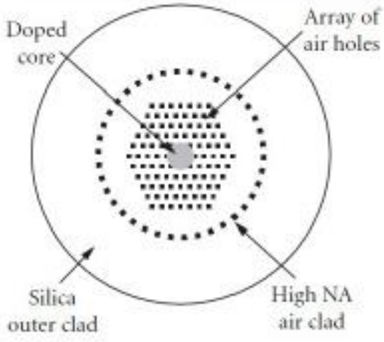
Seeded build-up time and extracted

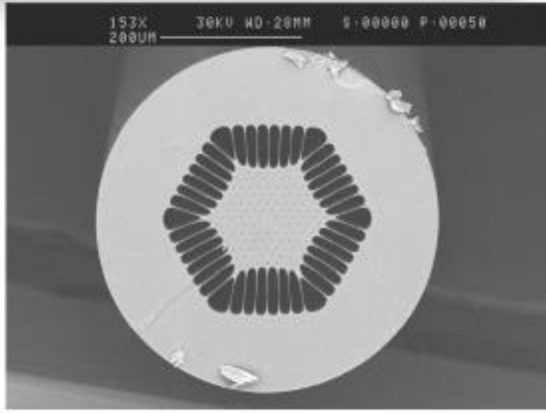
Amplifier


Compressor
Stretcher
L7
M6
PH8
MM2
MP3
MP2
MP1
ATT
PL5
PL6
CVM3
SH2
PH11
PC1
M8
W5
EM2
PH9
SH1
PL1
C1
PL7
PL8
W4
M9
PC2
PL3
PL2
Phd1
EM1
M10
PH10
CVM2
L8
MP4
MP5
BS5
SH3
L6
PL4
CFR-200
BS3
BS4
CAM 2
PH14
M16
M13
M14
M18
L9
C2
MP9
M19
M15
M11
PH12
L5
MM3
PH13
M15
M17
MP6
MP8
L10
MP7

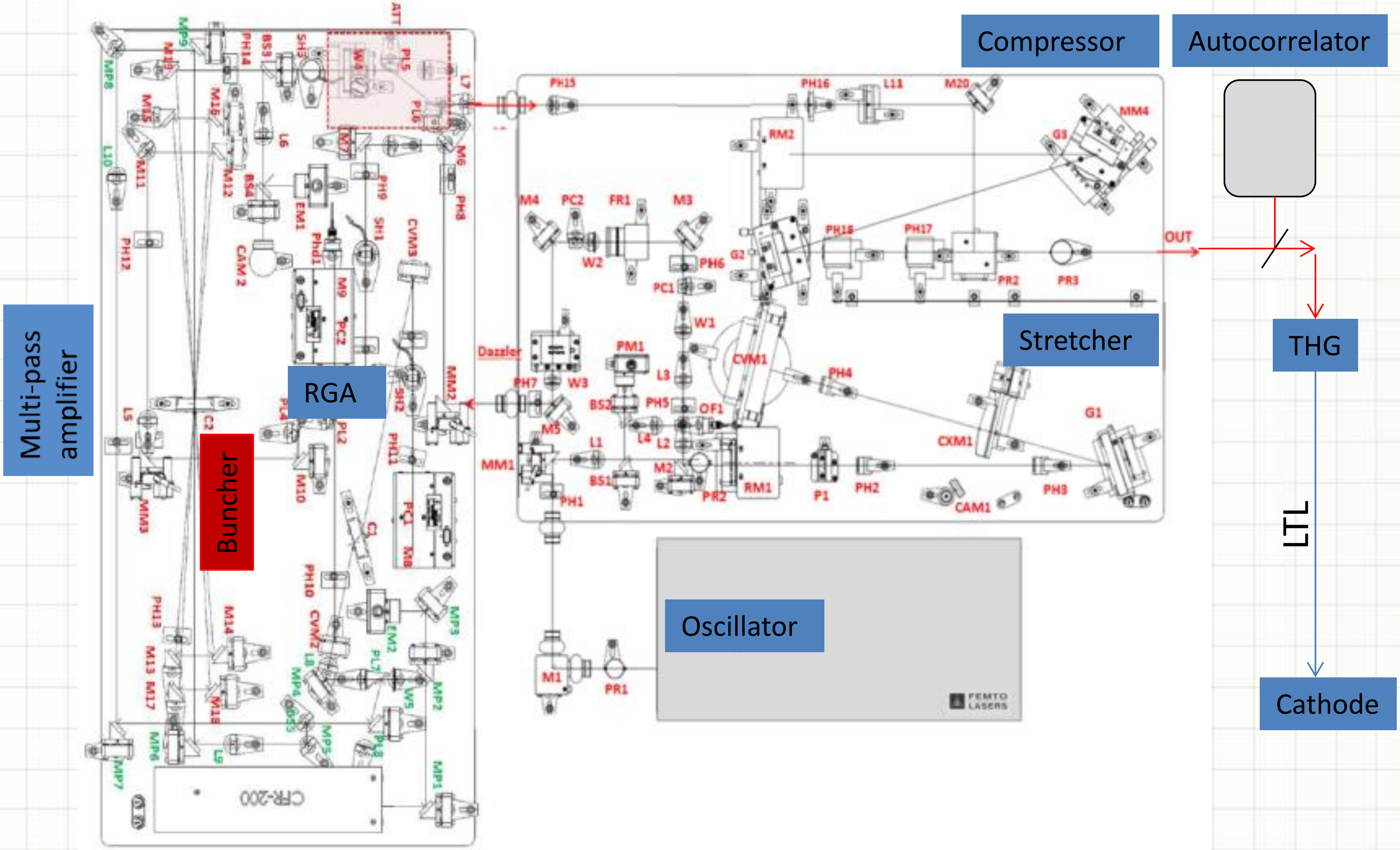

Nd:YVO passive mode-lock laser
1.3GHz, 1064nm, 8ps, 300mW
SESAM
300mW
Pre-Amplifier
Yb:PCF
25W
pump LD
ASE filter
DC-200-40-PZ-Yb, 1.5m
5W
200mW
100W
pump LD
Main Amplifier
Yb:PCF
DC-200-40-PZ-Yb, 1.5m
50W
3W
SHG cavity
PZT
20W
1kW
LBO
1.3GHz, 532nm, 8ps, 5W
Spatial Shaping
Temporal Shaping
scanning mirrors
Imaging lens
Aspherical lens
YVO birefringence crystals
10W


spherical mirror
spherical mirror
Ti:sapphire crystal
mirror

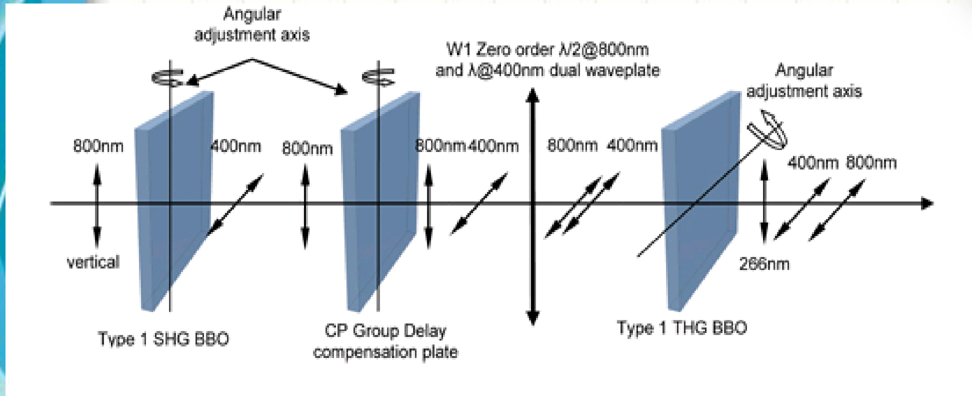

Doped core
Array of air holes
Silica outer clad
High NA air clad


153X
200UM
30KV WD:20MM
S:00000 P:00050

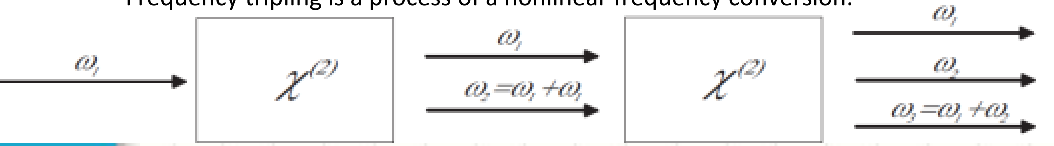
Ti:Sa Laser system: general layout



Harmonics

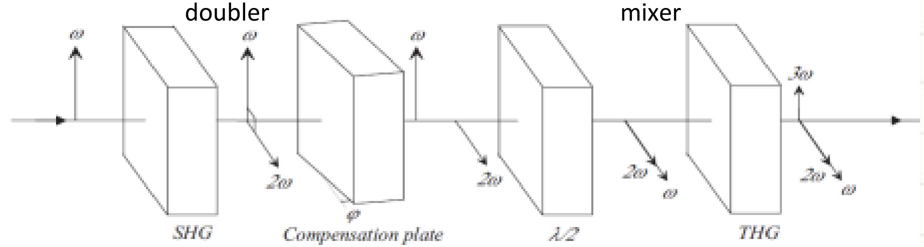


Frequency tripling is a process of a nonlinear frequency conversion.

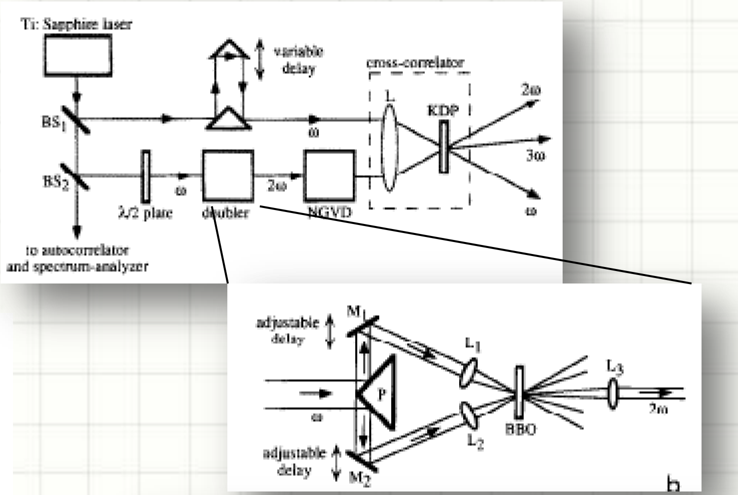


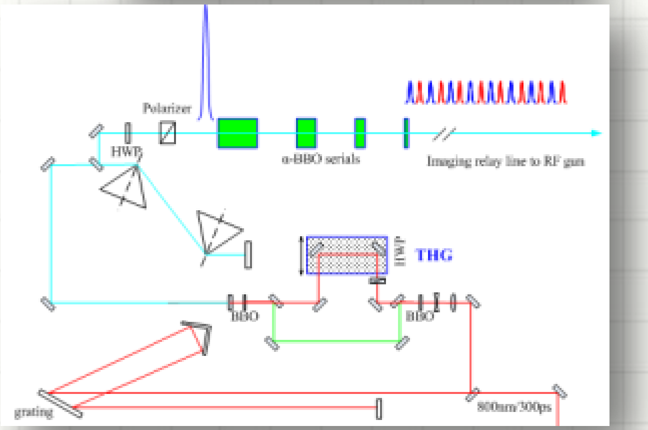
frequency doubler

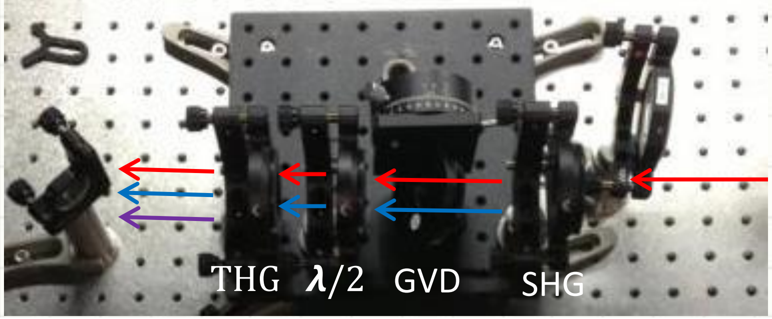
sum frequency mixer



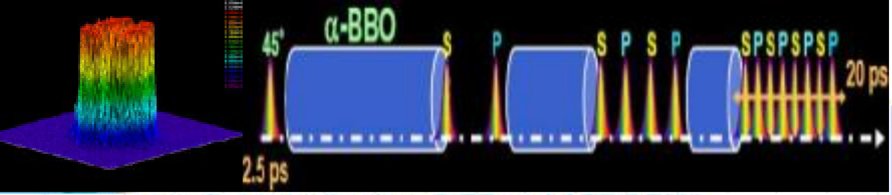
BBO, Type1	Calcite	Achromatic Half-wave plate	BBO, Type1
θ = 29.2deg	ψ= 45deg		θ = 44.3deg
ψ~ 90deg		ψ~ 90deg	ψ~ 90deg
L= 0.2mm	L= 1.7mm	L= 2mm	L= 0.05mm



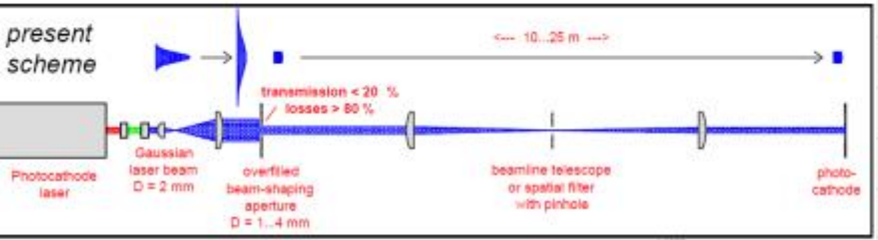




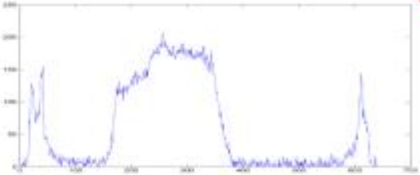
- C. Radzewicz, Optics communications 117 (1995) 295-302.
- Lixin YAN, Preliminary Experiments on Ultrashort Bunch Train Production by UV Pulse Stacking, Tsinghua University

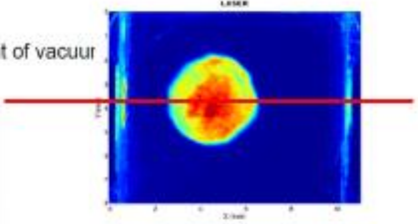


Gaussian to flat top clipping: PITZ and ATF/DESY



- Imaging the overfilled iris on laser table
- Problem: larger pointing jitter than iris in front of vacuur
- Jitter about 0.5 of diameter min/max



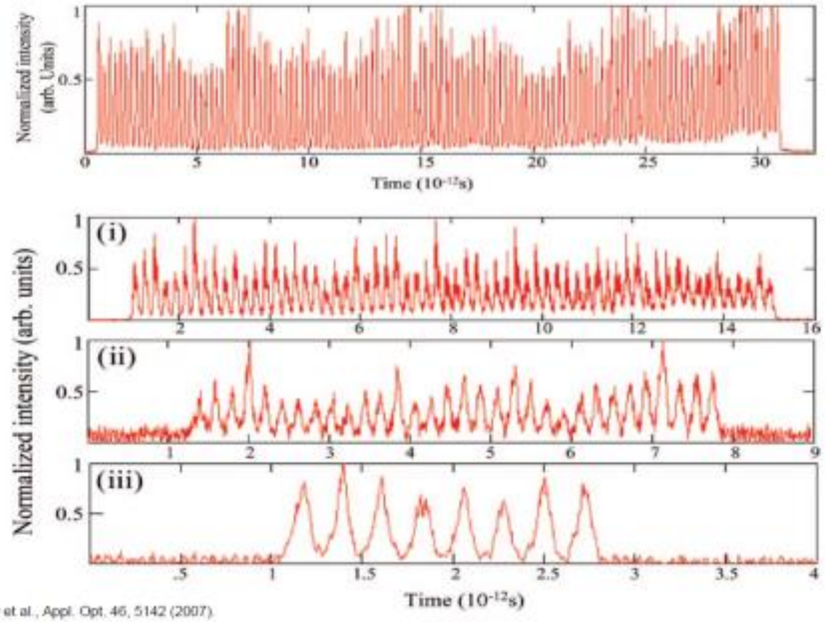


Ingo Will, Max-Born Institute

S. Schreiber, DEZY

PITZ mini pulse shaping workshop, 2007

Results, for pulse trains at 800 nm

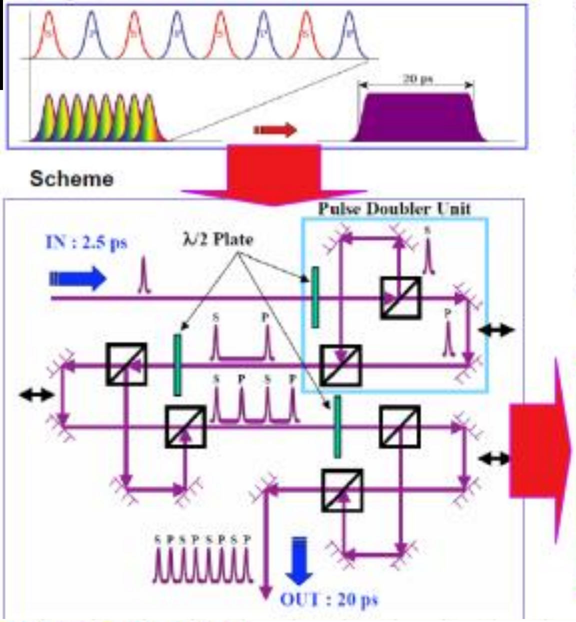


Dromey et al., Appl. Opt. 46, 5142 (2007)

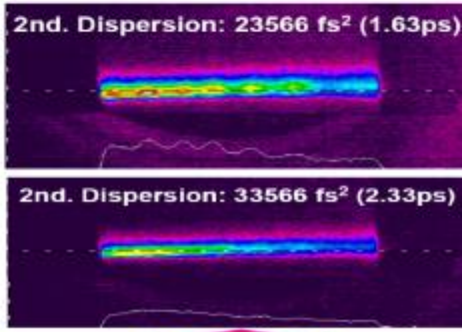
Implementation at Spring8

Target

Scheme



Results

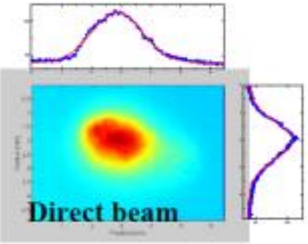


Setup

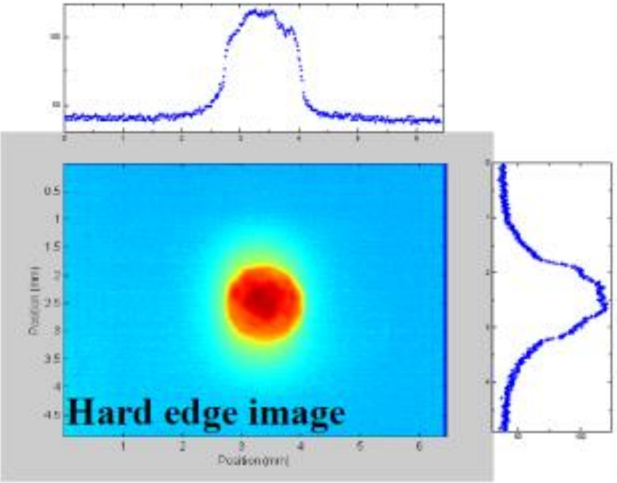
Tomizawa, Quantum Electronics 37, 697 (2007)

Beam clipping

- Slef-explaining but obvious far from perfect and low efficiency

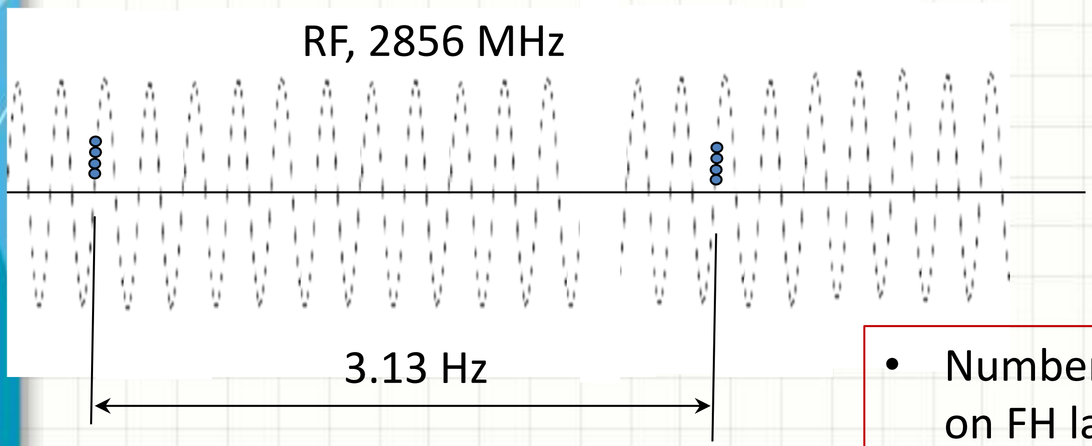


- BNL TTF
- APS PC gun
- LCLS



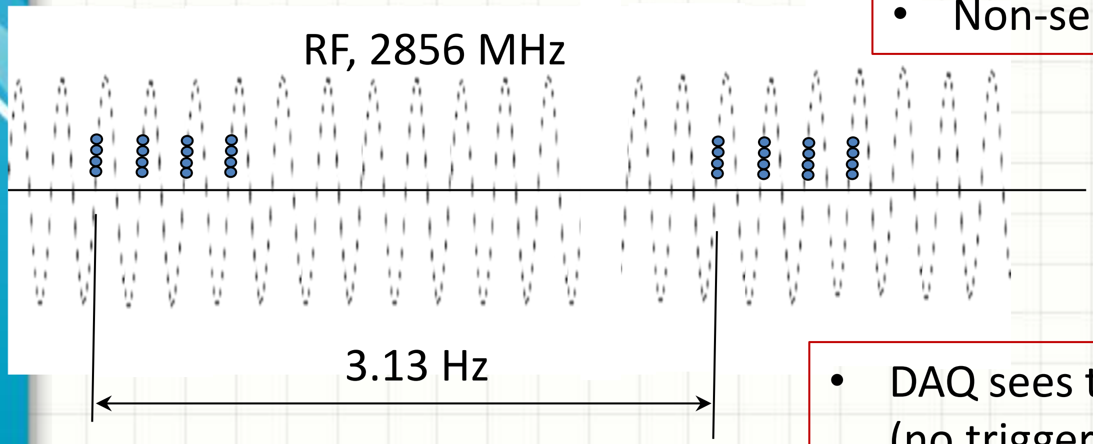
Y. Li, APS

Multi-micro-bunch, concept



4 micro-bunches
1 multi-bunch (1 RF bucket)

- Number of filled RF buckets depends only on FH laser energy budget
- Non-sequential RF bucket filling is possible



4 micro-bunches
4 multi-bunch (4 RF buckets)

- DAQ sees this micro-train as a single event (no trigger modification is required)
- Micro-bunch spacing changing simultaneously in all buckets

RF bucket period ~350ps

“Buncher”, second (current) prototype

General sheme of 16-buncher

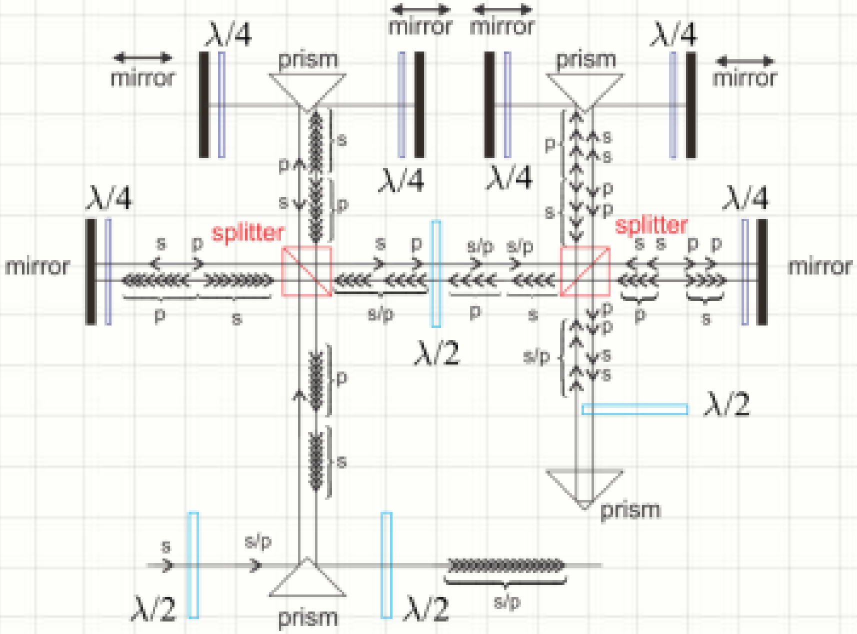
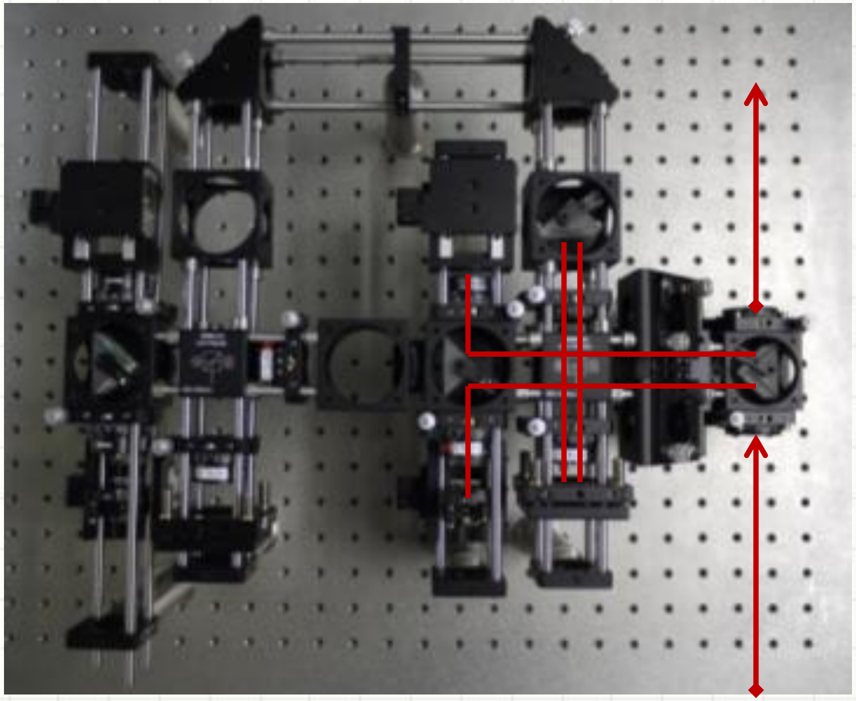
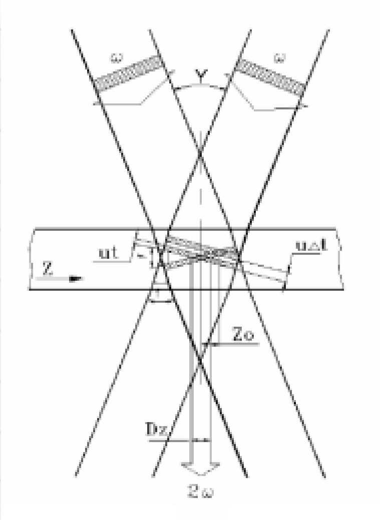


Photo of pre-assembled buncher

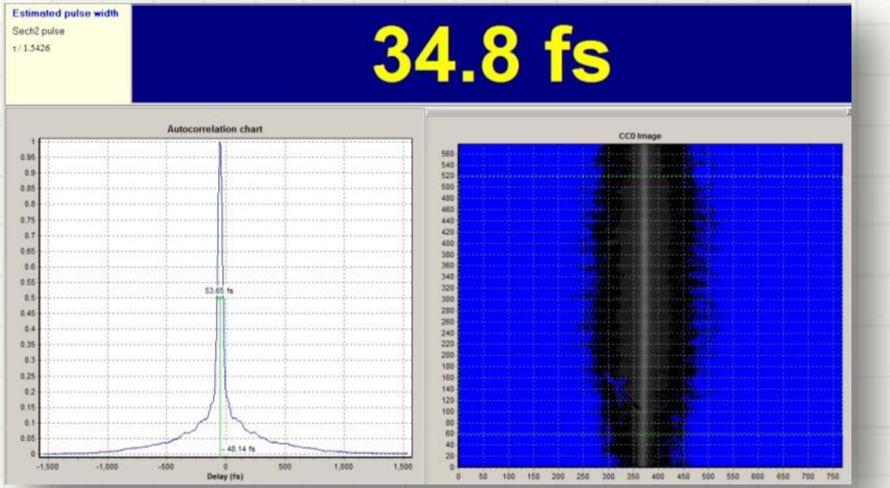


- All bits were delivered in September 2014.
- Assembled and tested (laser side only) in Nov.-Dec. 2014
- Tested (e-beam generation) in Jan. – Feb. 2015

FSTB: fs Single Shot cross-correlator

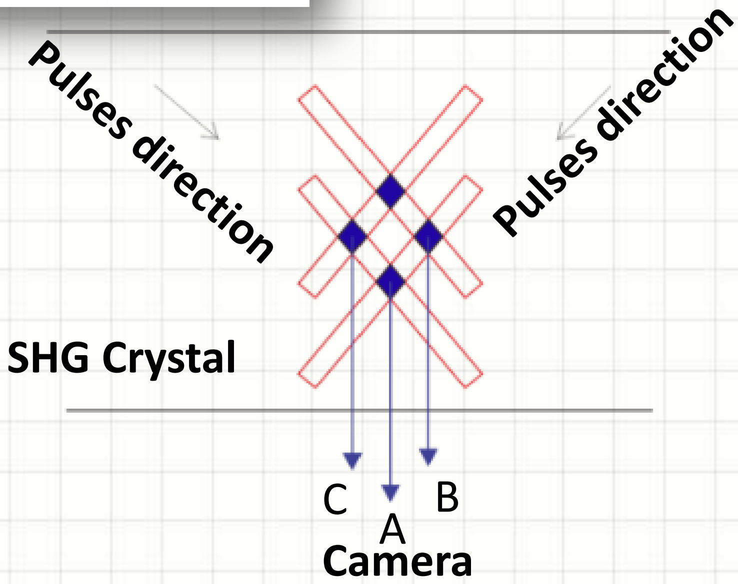


The method based on the registration of cross distribution of Second Harmonic (SH) energy produced in nonlinear crystal under non-collinear interaction of two beams with determined aperture.



Estimated pulse width
Sech2 pulse
τ / 1.5426

34.8 fs



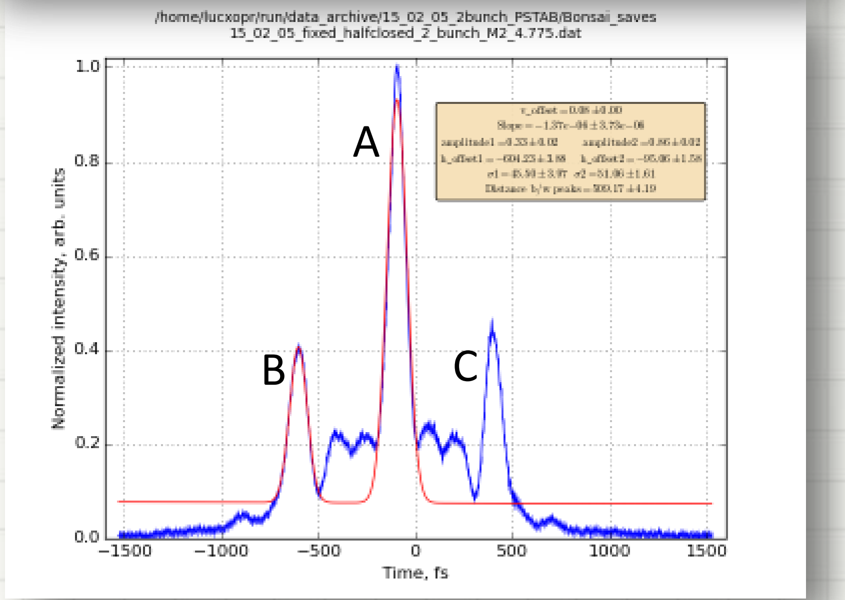
Pulses direction

Pulses direction

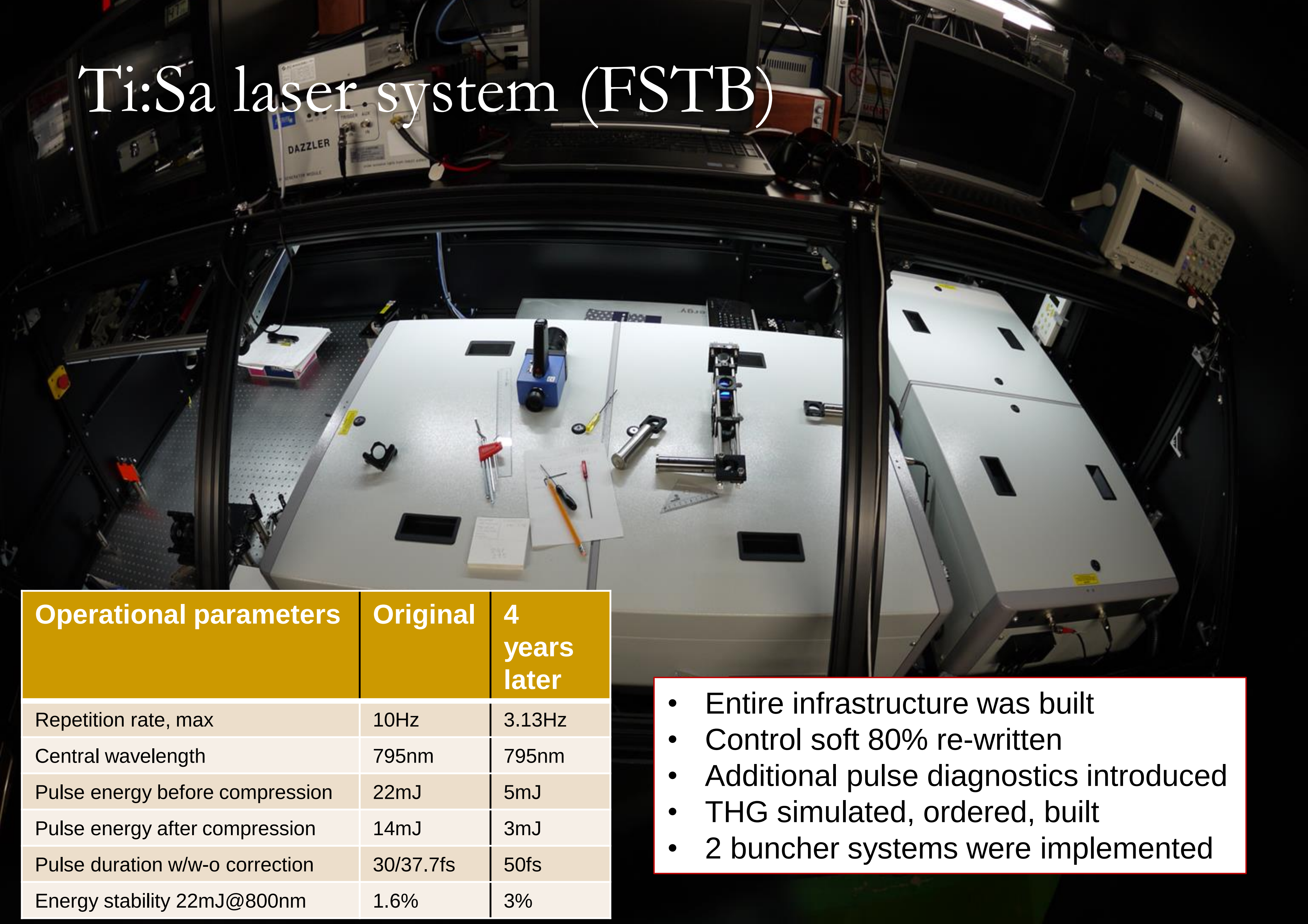
SHG Crystal

C A B

Camera



Ti:Sa laser system (FSTB)

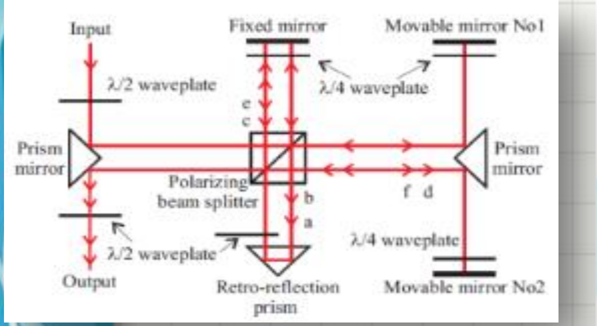


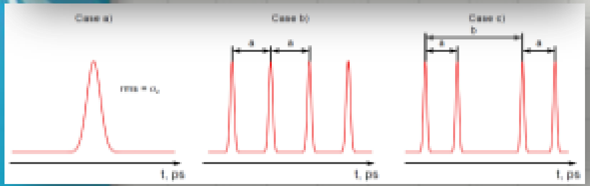
Operational parameters	Original	4 years later
Repetition rate, max	10Hz	3.13Hz
Central wavelength	795nm	795nm
Pulse energy before compression	22mJ	5mJ
Pulse energy after compression	14mJ	3mJ
Pulse duration w/w-o correction	30/37.7fs	50fs
Energy stability 22mJ@800nm	1.6%	3%

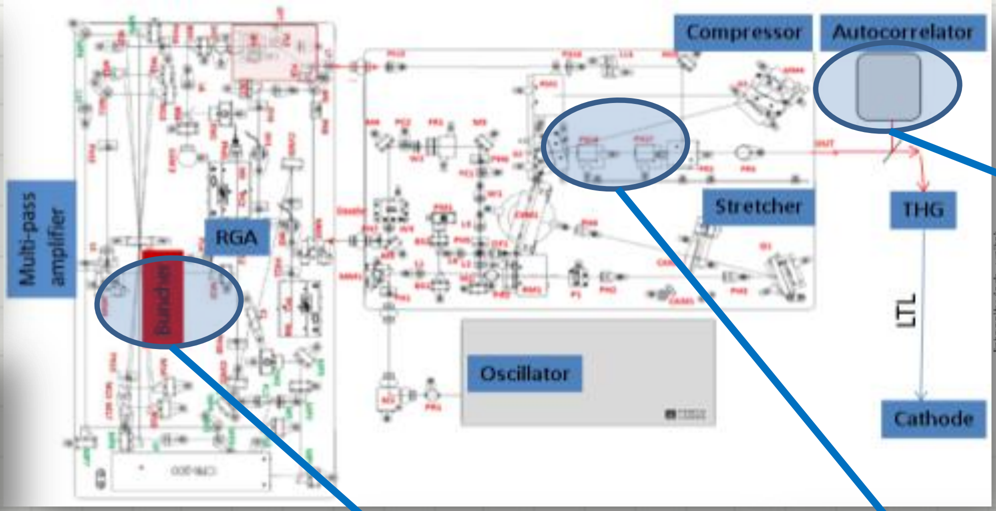
- Entire infrastructure was built
- Control soft 80% re-written
- Additional pulse diagnostics introduced
- THG simulated, ordered, built
- 2 buncher systems were implemented

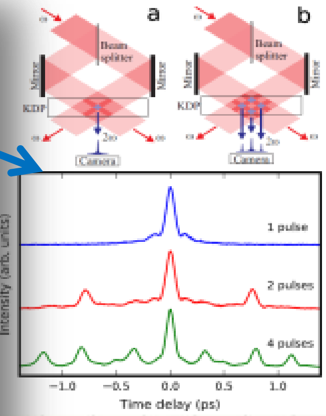
Multi-micro-bunch, implementation

Present condition: 4x4 pulses, ~50 fs each, converted to 266nm, 10uJ

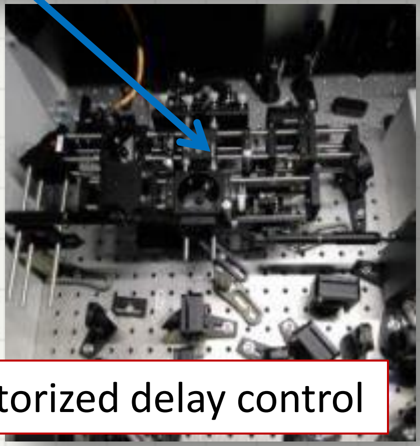








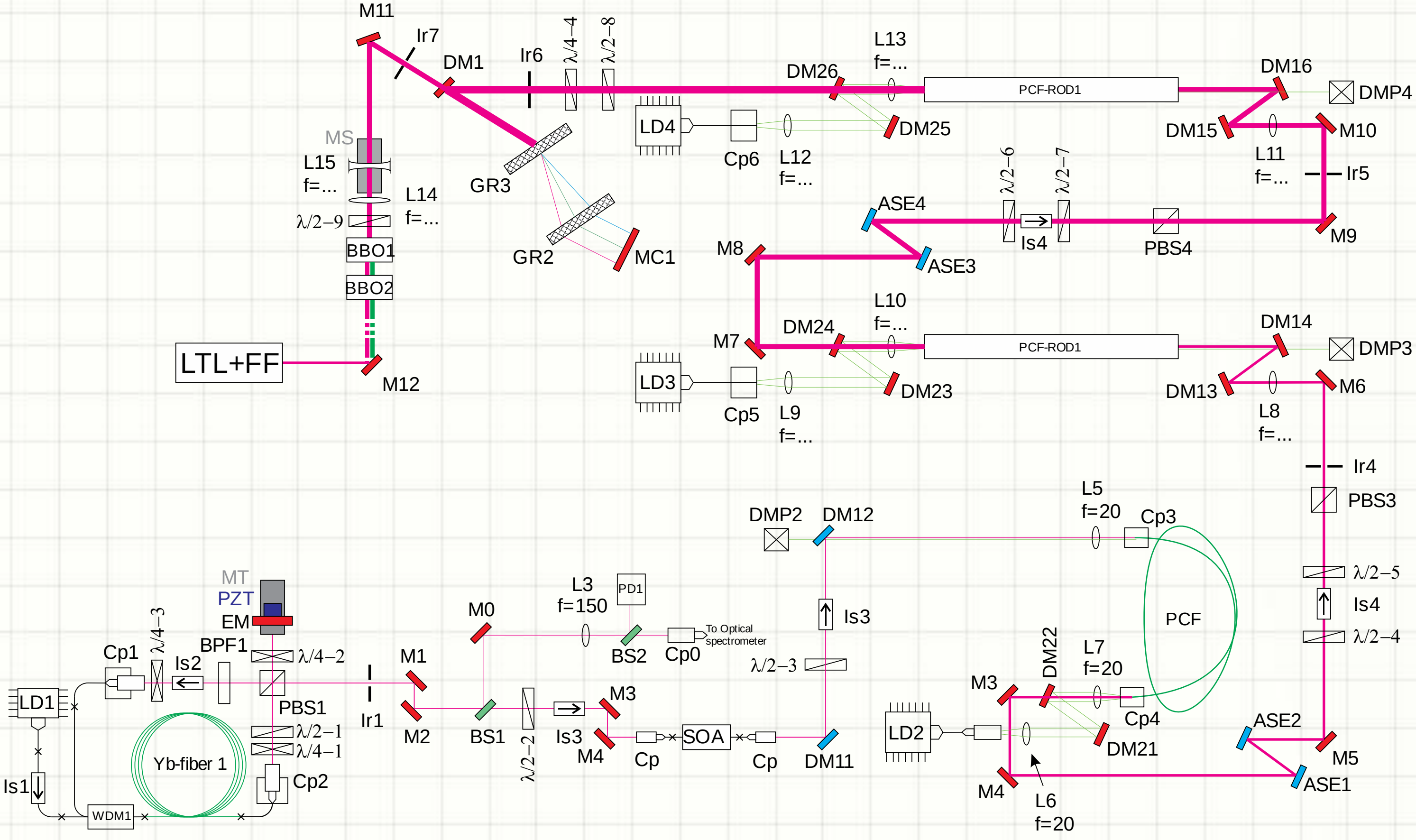
- **Total splitting efficiency ~20%**
- New design with total 10-20% loses is possible.
- Beam expander was removed.
- Multi-pass Amp, Compressor, THG, LTL re-tuned.
- Micro-bunch
  - Separation: +/- 5 ps
  - Stability: < 20 fs (lower than meas. resolution)
- Multi-bunch
  - Separation: 350ps +/- 30 ps



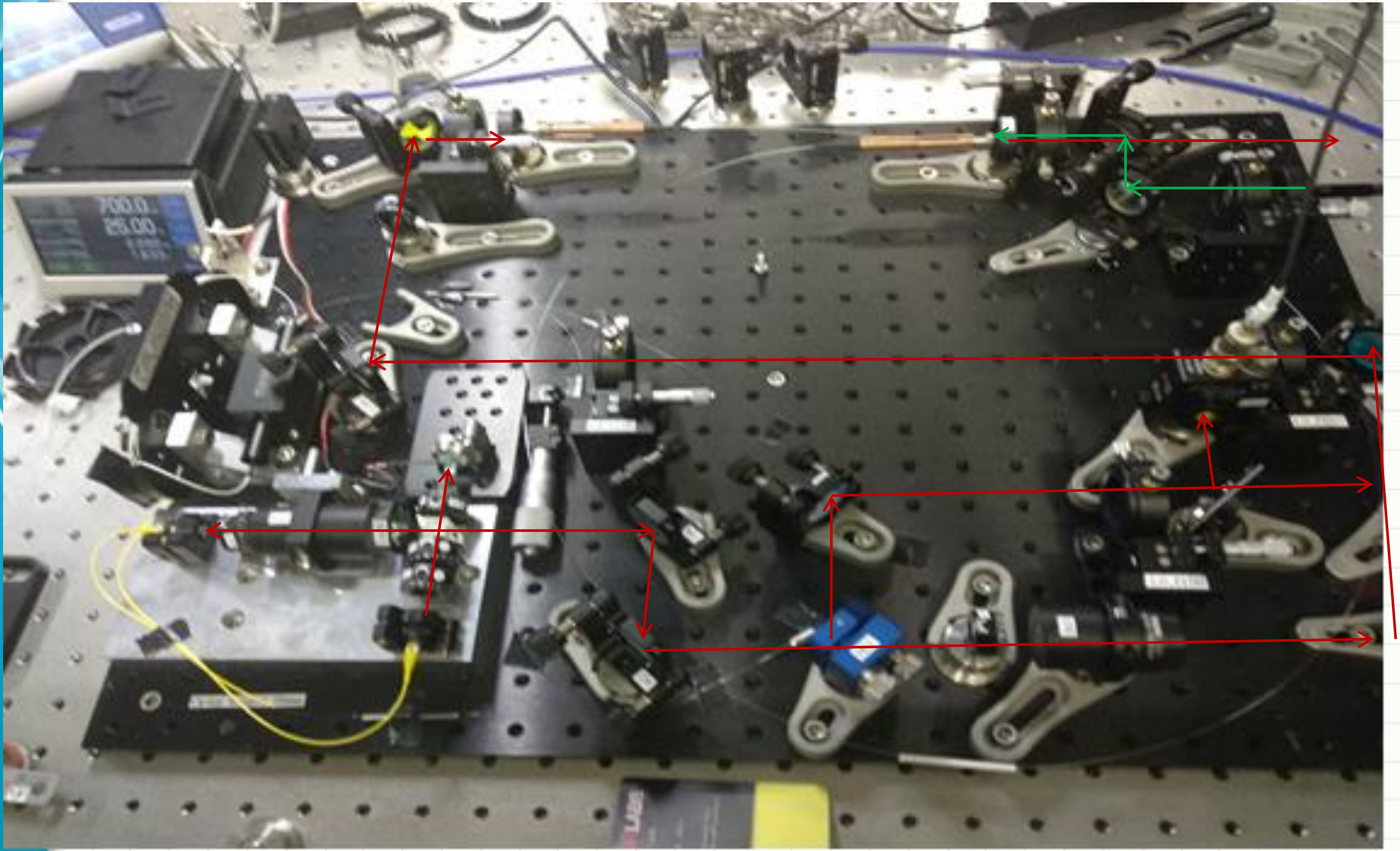
Motorized delay control

Manual delay control

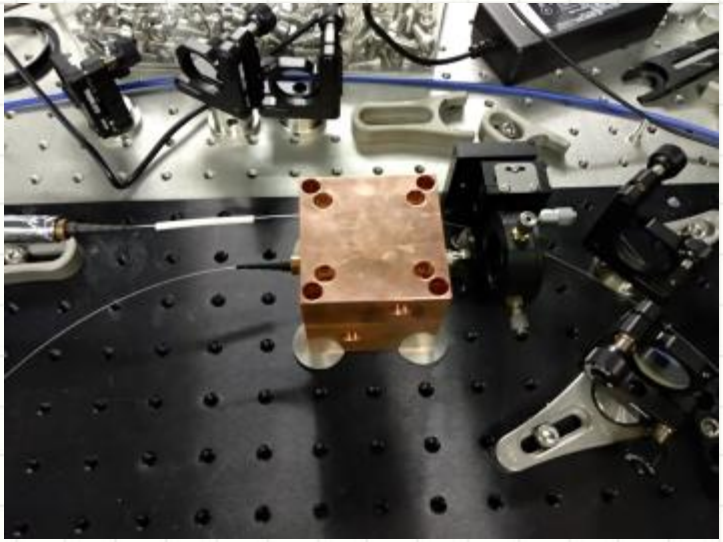
Pre-amplifier, PCF and modified laser system diagram



Whole system (Osc. + Pre.amp)



Pre. Amp tests



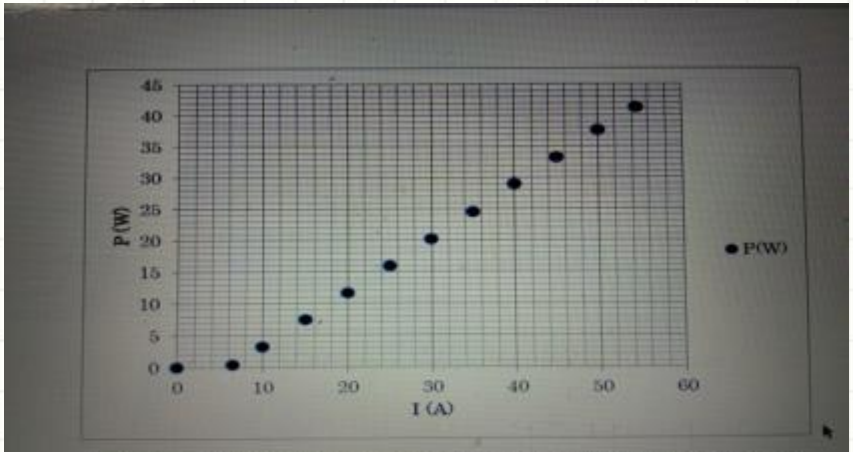


Figure 4.5 Output power variation of laser diode with change in LD current

power, when seed laser is turned off.

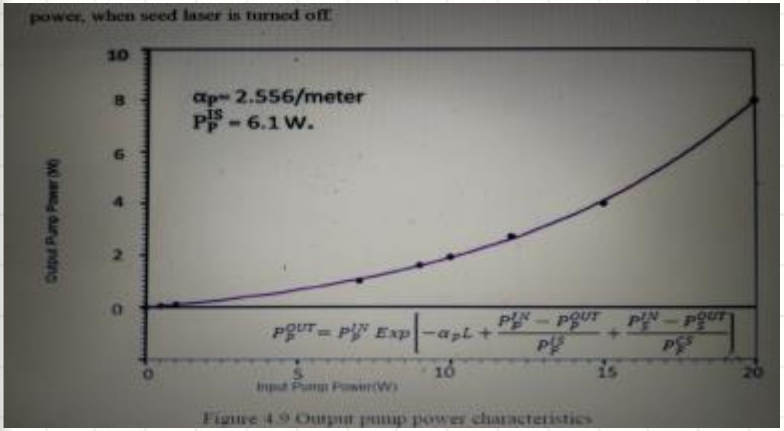
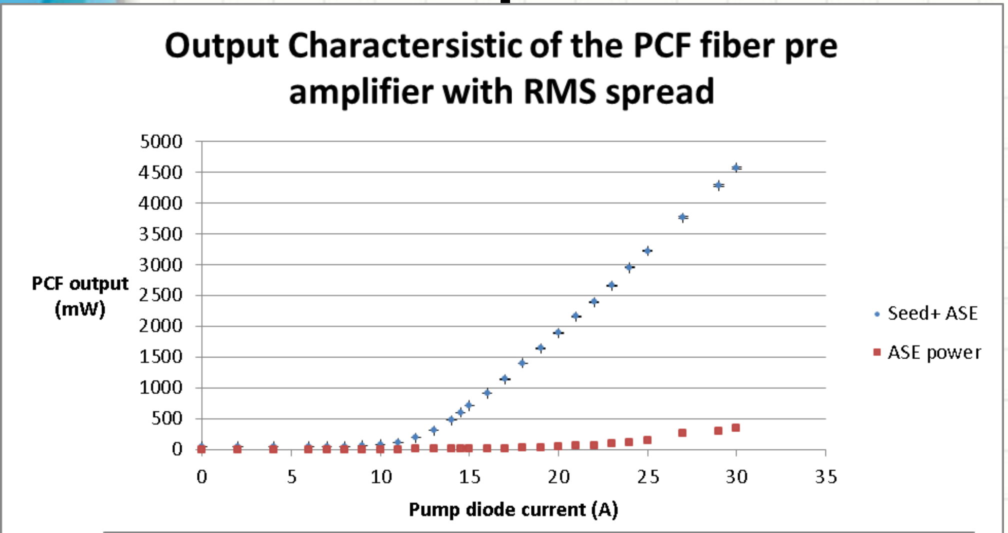


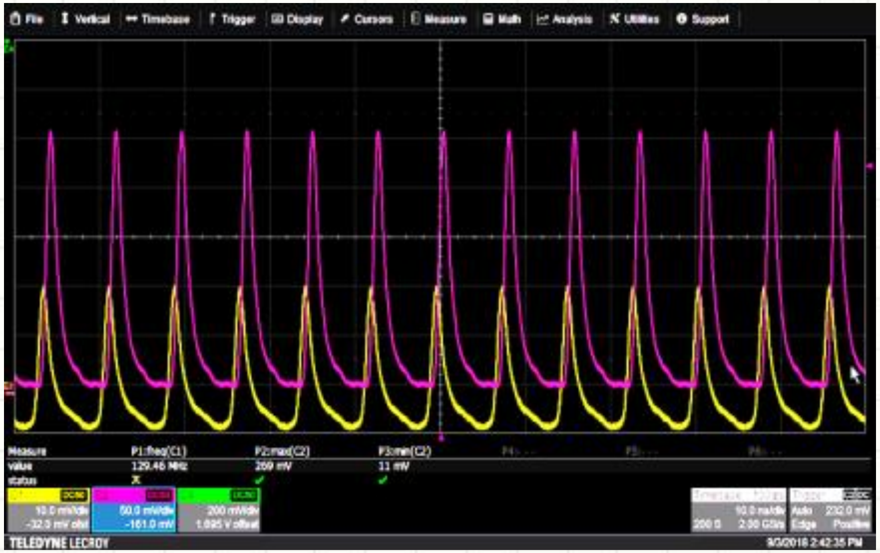
Figure 4.9 Output pump power characteristics

Current(A)	Out Put pump power (mW)
6.3	24
9	135
12.2	300
15	521
17	752
19.1	1050
20.2	1230

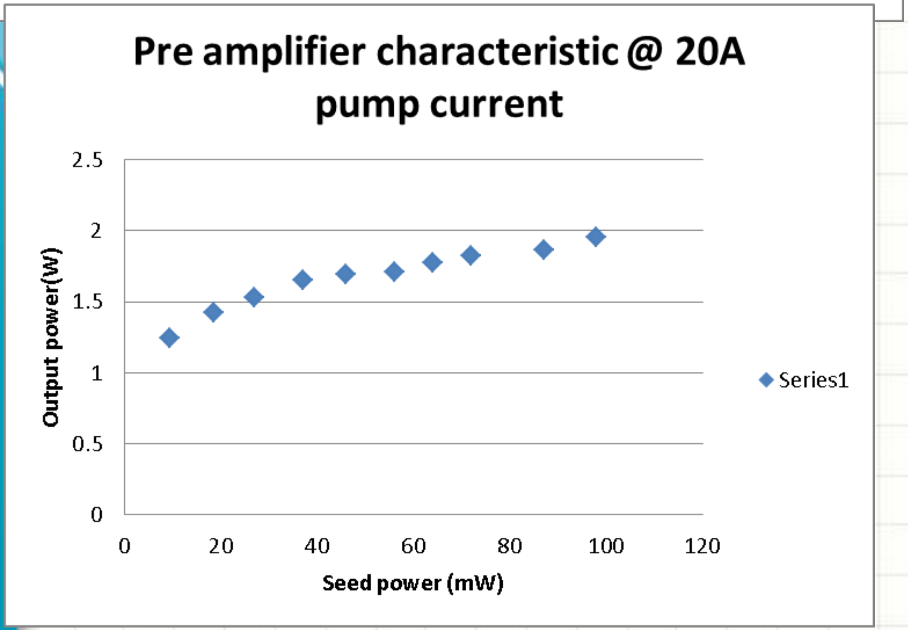
Pre. Amp. tests



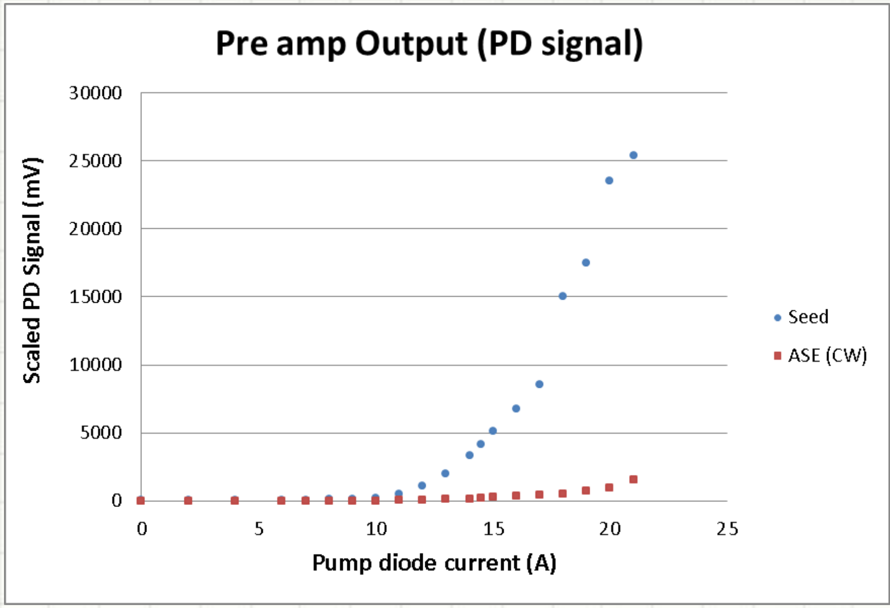
Output Charactersistic of the PCF fiber pre amplifier with RMS spread



Measure	P1:freq(C1)	P2:max(C2)	P3:min(C2)
value	129.46 MHz	269 mV	11 mV
status	✗	✓	✓

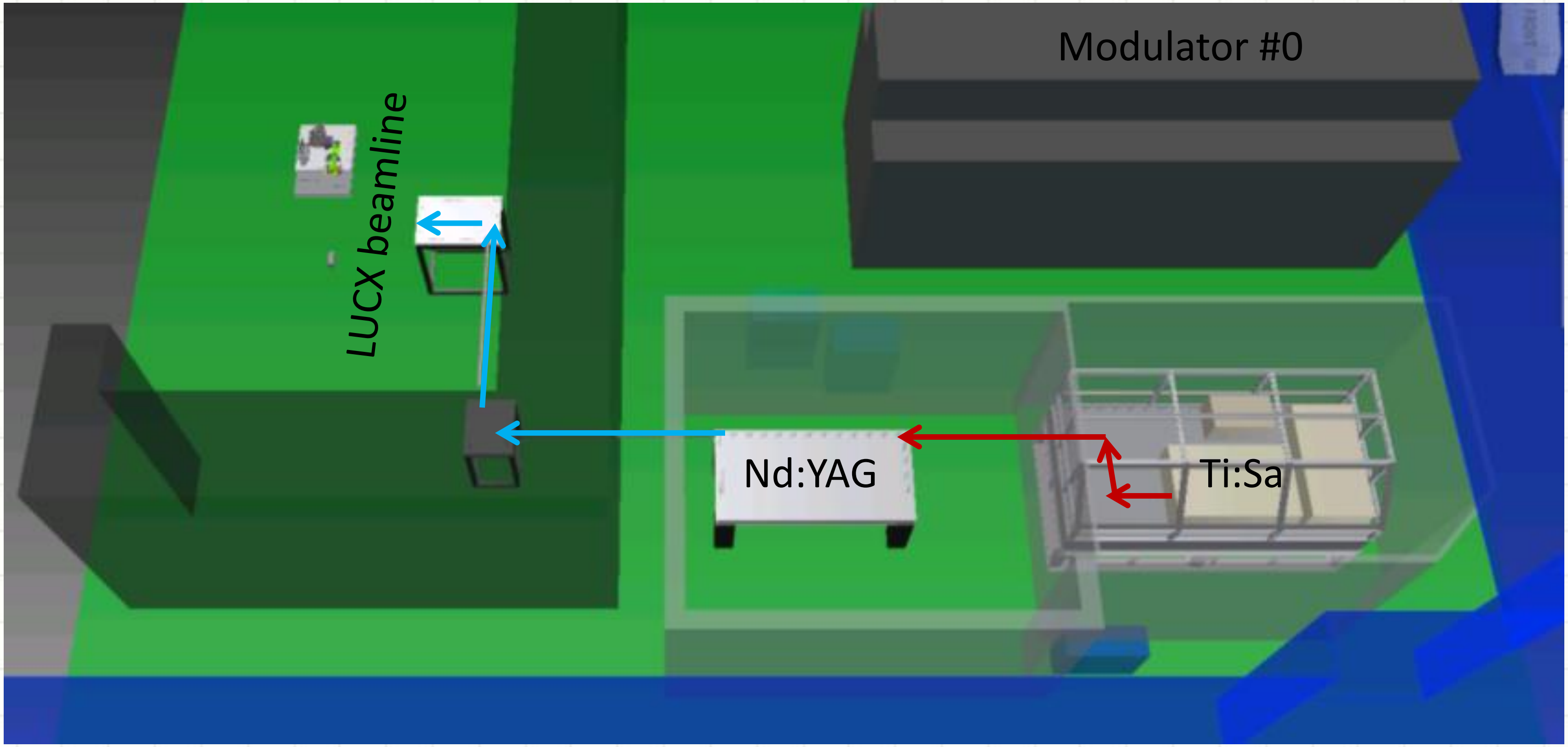


Pre amplifier characteristic @ 20A pump current

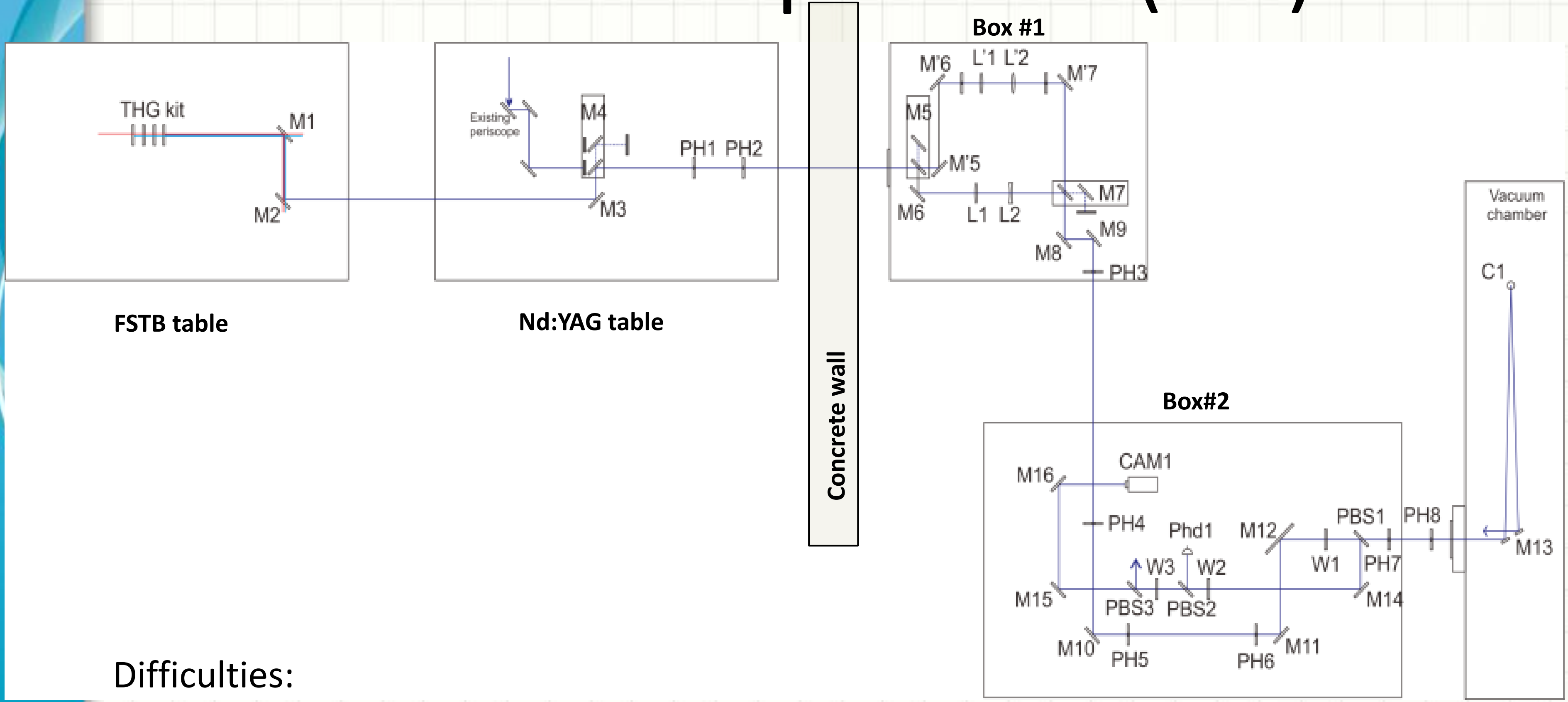


Pre amp Output (PD signal)

LUCX-FSTB-THz, 3D model

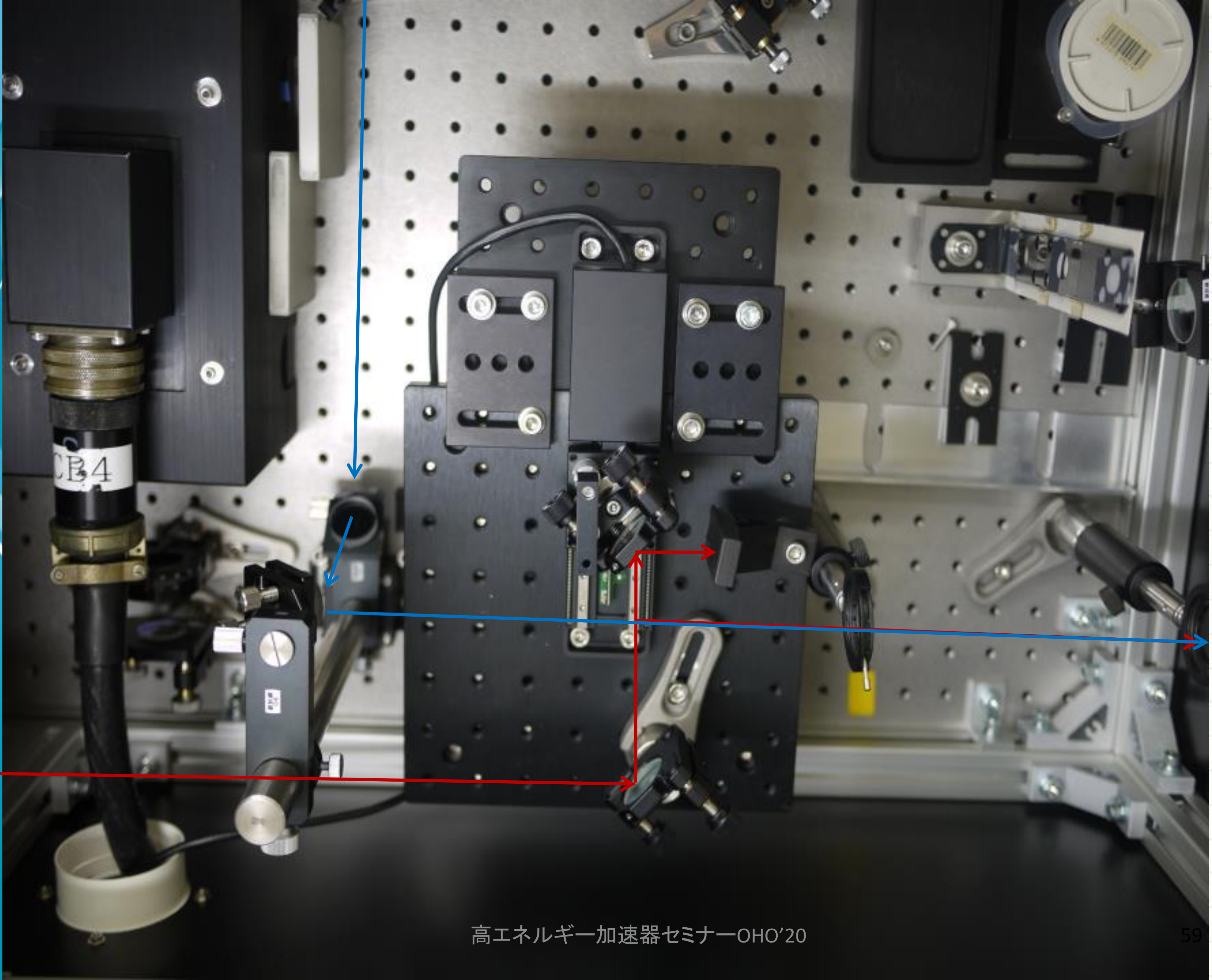


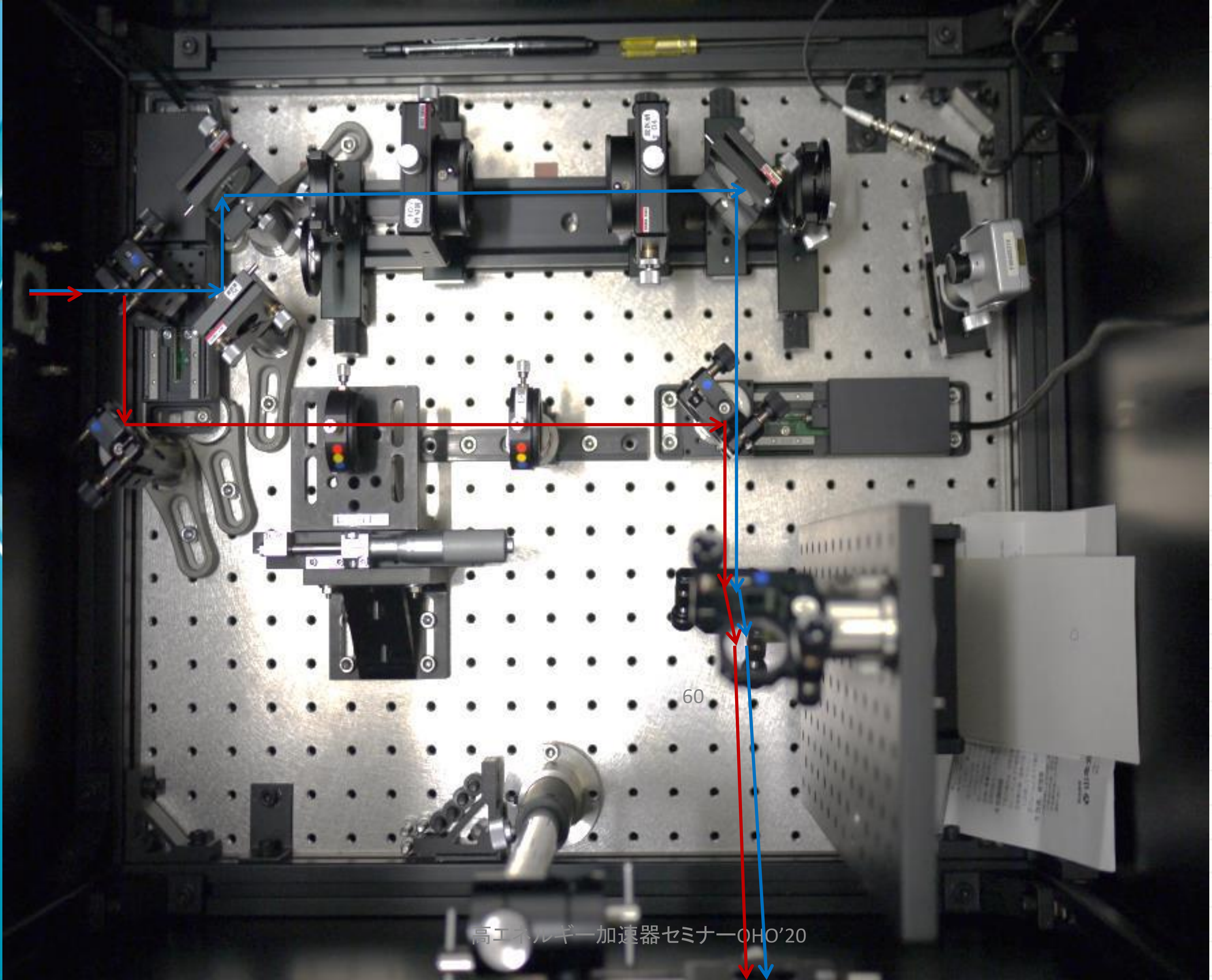
LUCX laser transport line (LTL)



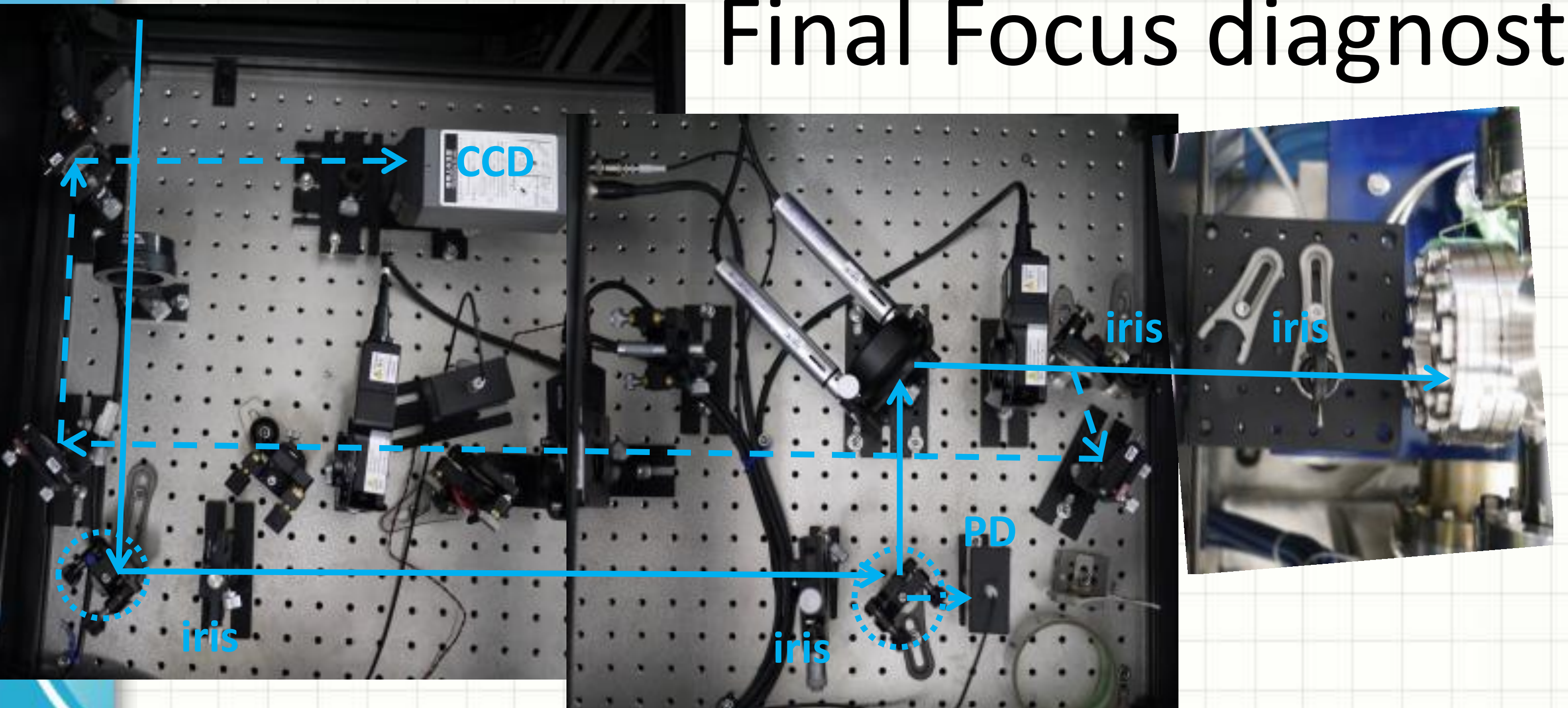
Difficulties:

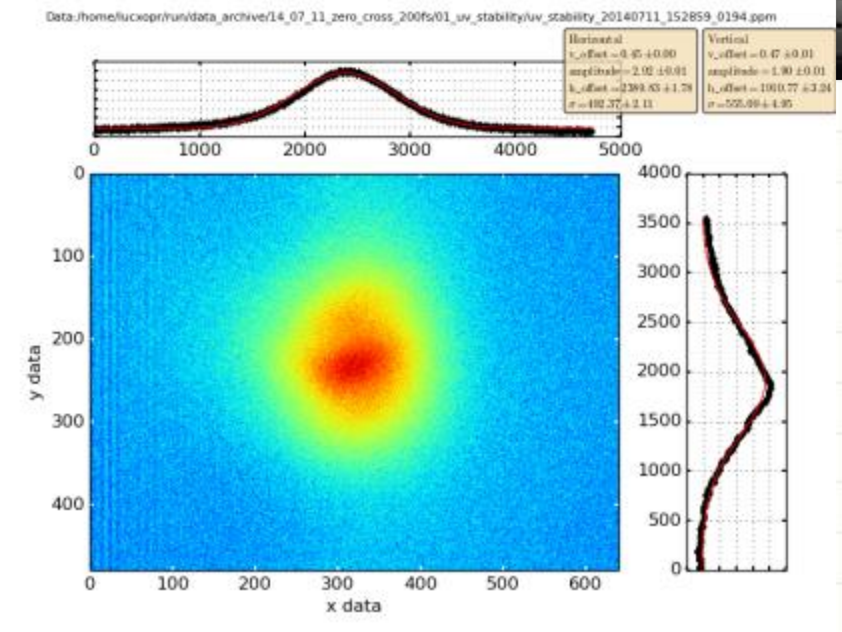
1. Selecting either of two laser beams: Nd:YAG of Ti:Sa
2. Separate focusing systems.
3. Same FF and “virtual cathode”
4. Relatively long optical path


CB4



Final Focus diagnostics

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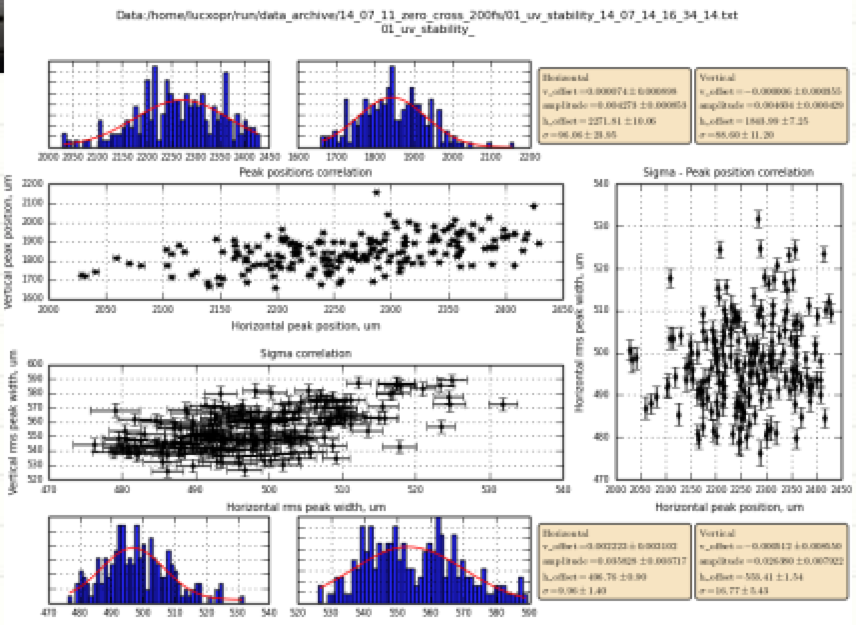
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01_uv_stability_

Conclusion

- Lasers are a vital part of modern particle accelerators.
- It is used as diagnostics, timing systems, sources of particles, drivers of new accelerators.
- Research and development of new laser sources will drive improvements in:
  - Particle accelerators – smaller, cheaper, more efficient.
  - Particle temporal distribution (important for light sources – THz FELs, Compton, etc)
  - Particle beam diagnostics

Materials

- **Jean-Claude Diels, Wolfgang Rudolph**: “Ultrashort laser pulse phenomena”, Second edition, 2006
- **Tone Rotar**, “Ultrashort laser pulses”, Ms Thesis.
- **Carlo Antoncini**, “Ultrashort Laser Pulses”, Lecture notes.
- **Yuelin Li**, ANL, 2008 USPAS, summer session lecture notes.
- **Valerii Ter-Mikirtychev**, “Fundamentals of Fiber Lasers and Fiber Amplifiers”, Springer, 2014
- **Yan YOU**, “Yb-doped Mode-locked fiber laser based on NLPR”, 2012
- **Alexander Mikhailovsky**, “Basics of femtosecond laser spectroscopy”
- **Jeremy R. Gulley**, “Simulation of Ultrashort Laser Pulse Propagation and Plasma Generation in Nonlinear Media”.
- **S. LI** et al. PHYS. REV. ACCEL. BEAMS 20, 080704 (2017)
- **H. Tomizawa**, “Adaptiveaptive3D-Laser pulse shaping System to Minimize Emittance for Photocathode RF gun”, WEBAU01, FEL 2007
- **L. Corner**, Lasers in Particle Accelerators, CERN Accelerator Course, Budapest 11th Oct 2016

Thank you very much!