Laser system for Compton polarimeter and ODR beam size measurement

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Outline

- Motivation
- Laser requirements
- Laser system
  - Gain-switched seed
  - Amplifier
  - Frequency doubler
  - Laser beam shaper
- ODR e^- beam size measurement
- Summary & future plan

Polarimeters at CEBAF

Why we need polarimeters?

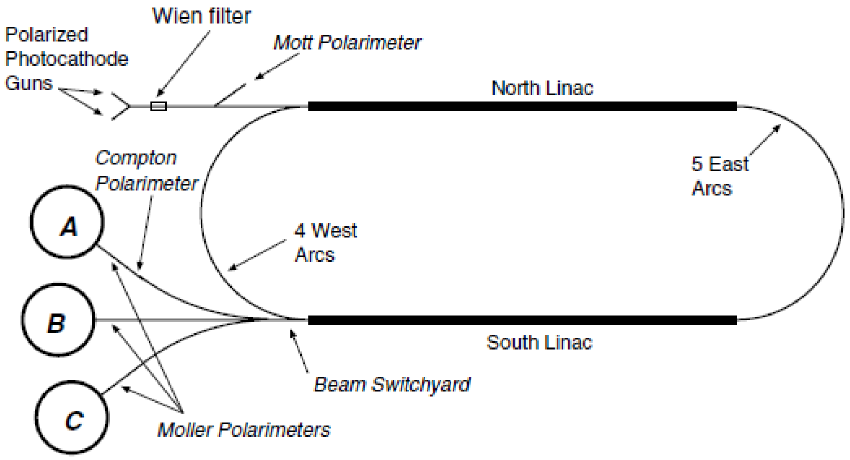
The Continuous Electron Beam Accelerator Facility (CEBAF) produces highly polarized e beam for nuclear physics studies, e^- polarization is needed with high precision (1%)

What's available?

Mott polarimeter /injector	solid target	for low energy beam
Møller polarimeter / Hall A, B, C	solid target	for low intensity beam

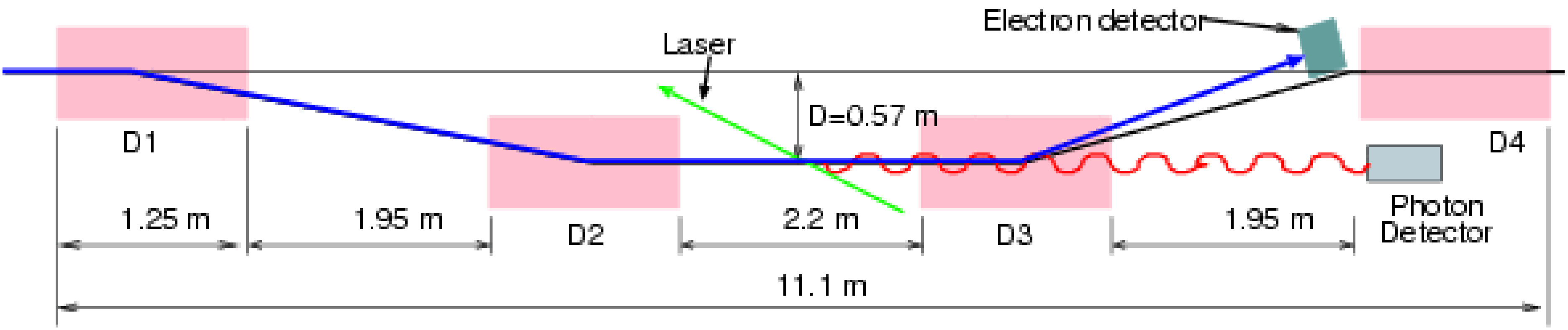
Why need Compton polarimeter?

Compton polarimeter/ Hall A
Based on laser electron beam interaction, accurately measuring and monitoring of the beam polarization while running experiment



Polarimeters at CEBAF

Compton polarimeter overview



Schematics of Compton polarimeter

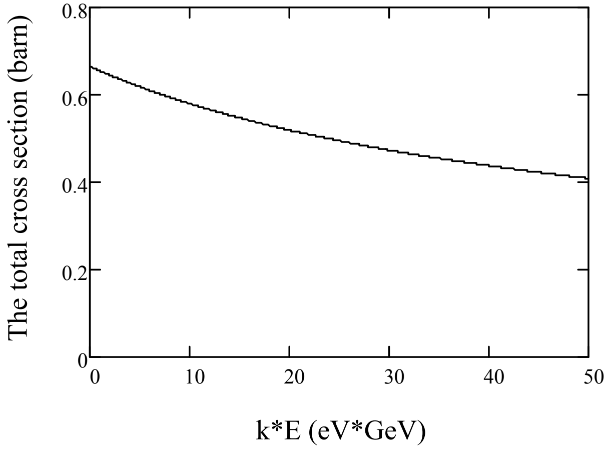
Basic parameters of e^- beam

Parameters of e beam for Qweak	Values
Rep. rate	499 MHz
Energy	1.16 GeV
Bunch length	<200 fs
Current	~80 μ A

Laser requirements for Compton

The time needed to conduct polarization measurement depends on three things:

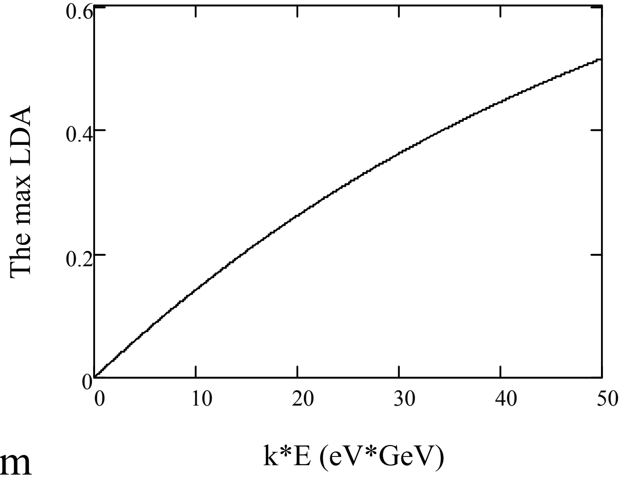
1. The unpolarized Compton cross section (laser energy)
2. The mean longitudinal asymmetry (laser energy)
3. The luminosity (laser beam size, electron beam size and crossing angle)



Basic laser requirements

Parameters	Values
Rep. Rate	499 MHz
Pulse width	10 ps to 30 ps (rms)
Beam quality	M^2~1 (~Gaussian beam)*
Wavelength	532 nm
Power	>10 W Average

*Ratio of beam parameter product of a beam to that of Gaussian beam



Laser system design considerations

Configuration: oscillator vs. MOPA

Oscillator:

- Difficult to control
- Zero power for any element failure

MOPA:

- Easier to tune laser parameters
- Easier to modulate
- Potential for power scaling

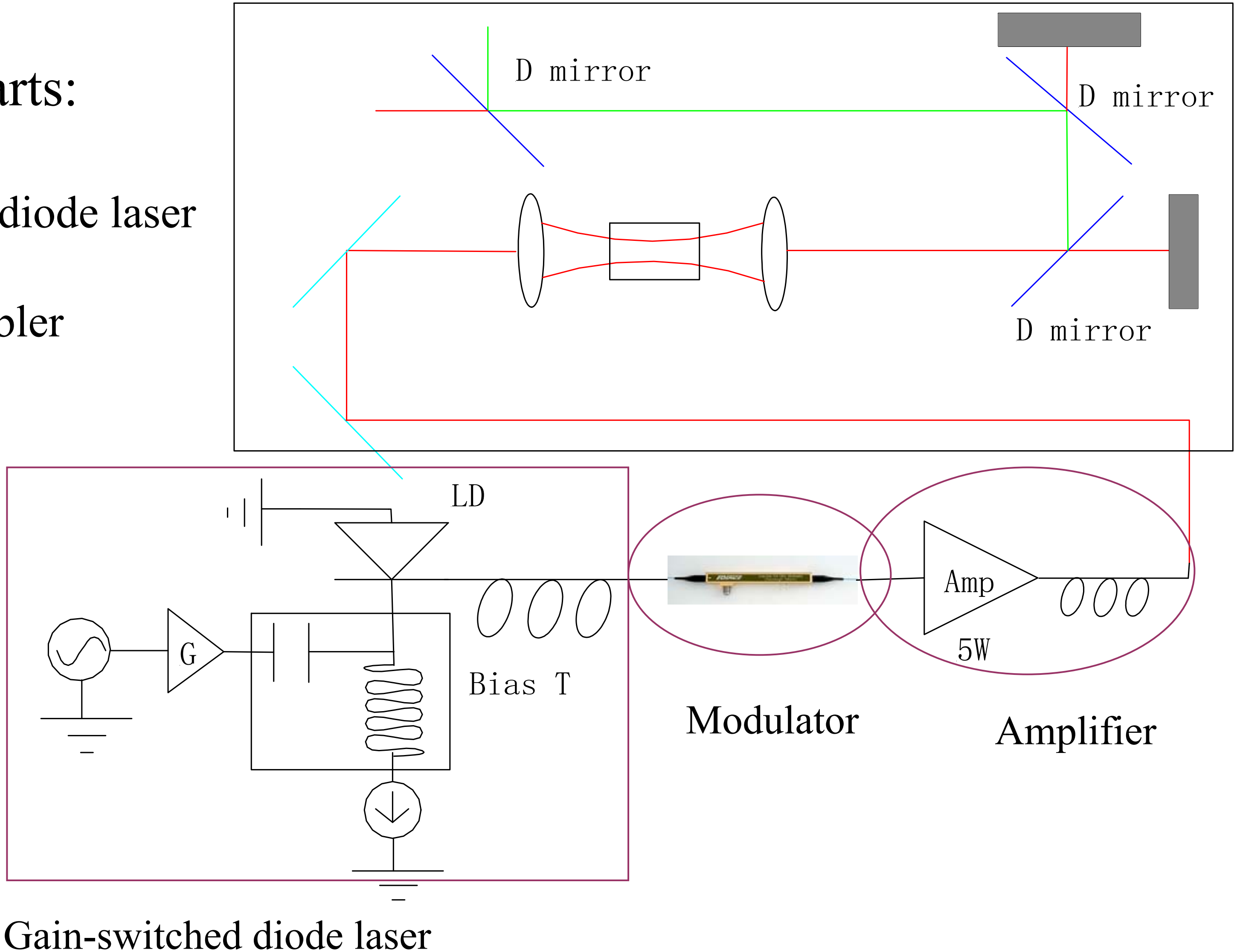
Laser seed: Q-switching, mode-locking, gain-switching

- Q-switching: too slow, long pulse
- Mode-locking: most common technique, need RF loop to synchronize, inflexible rep. rate

Laser system overview

Three major parts:

1. Gain-switched diode laser
2. Fiber amplifier
3. Frequency doubler



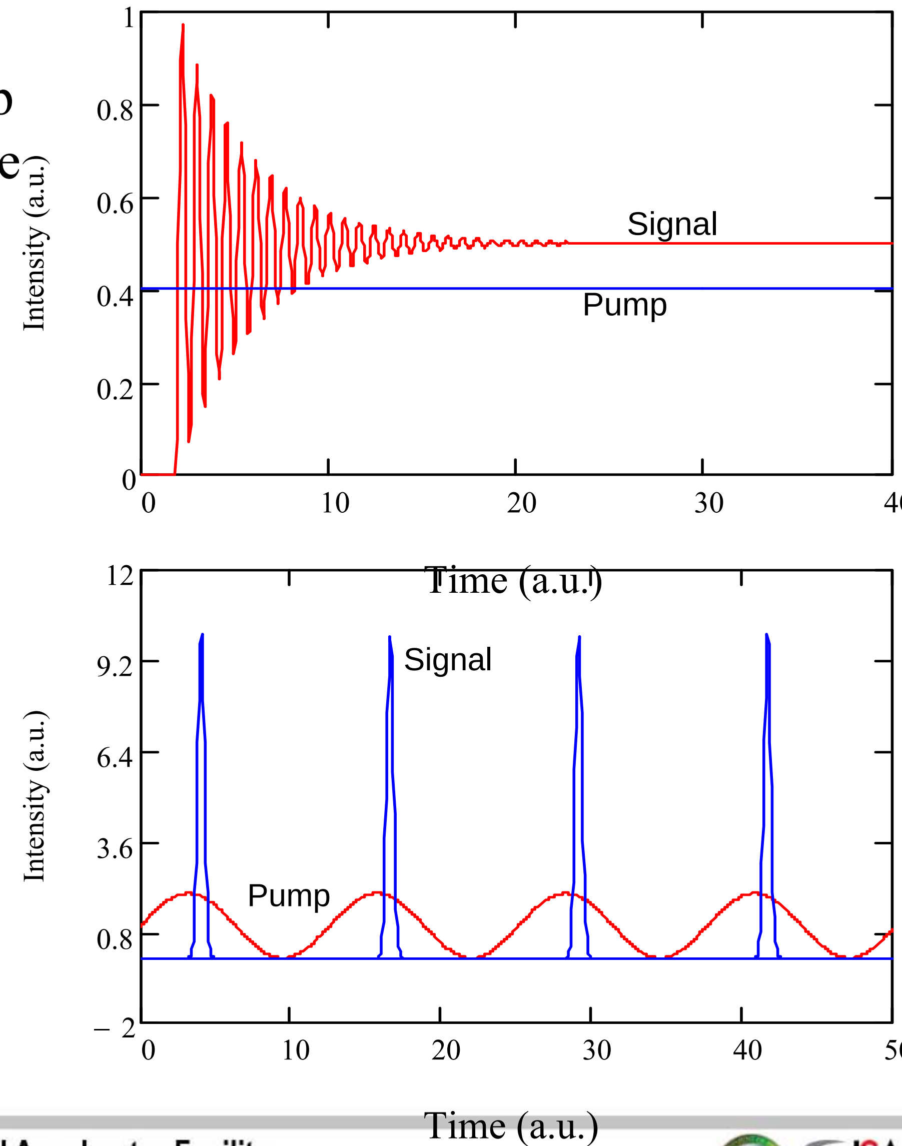
Laser seed: gain-switching (GS)

Principles:

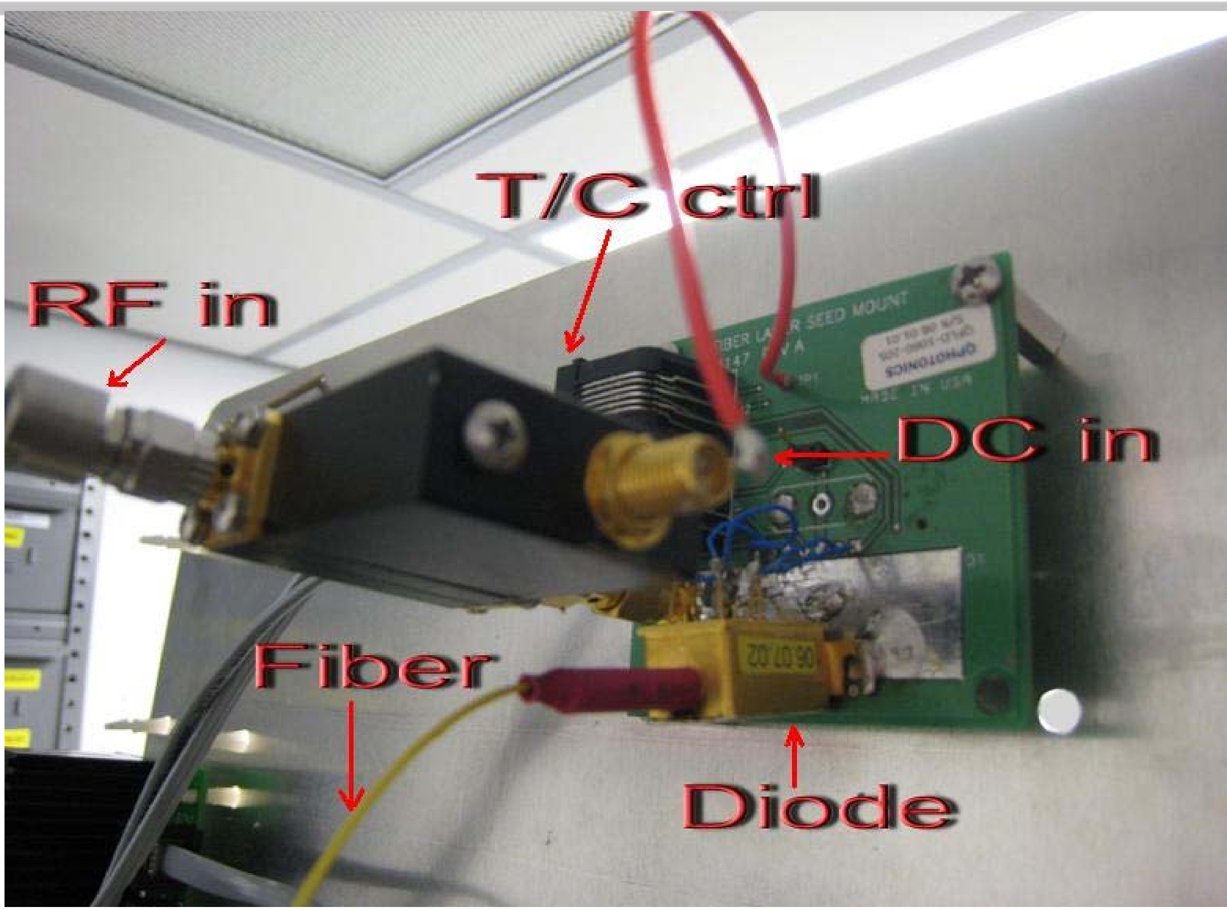
Instead of constant pump, a sinusoidal pump is applied to the laser medium, the amplitude and frequency of the pump are adjusted so that only the first spike of relaxation oscillation occurs within one pump cycle.

Advantages:

1. Frequency adjustable from ~100 MHz to tens of GHz
2. Easy to synchronize with RF
3. Tens of ps short laser pulses



Laser seed: assembly of GS diode seed



<u>Supporting device:</u>

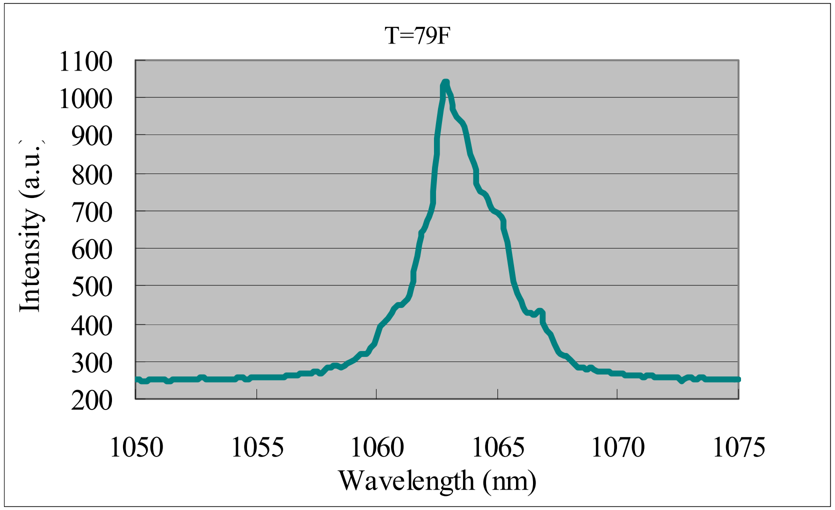
RF source + RF amplifier

Temp controller
(LFI3751, 0.003 ºC)

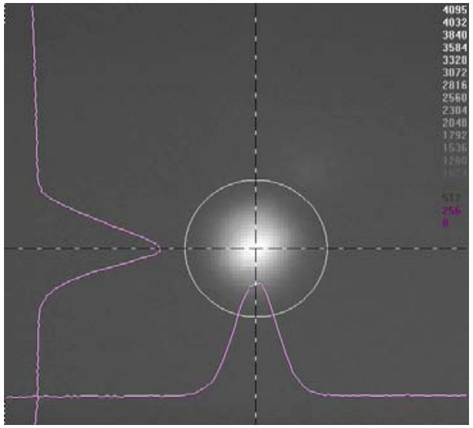
Current driver
(MPL500)

Pros:
Compact & economical
Thermoelectric cooler, no water cooling
No alignment required
Single mode fiber output (polarization maintaining /PM fiber available)

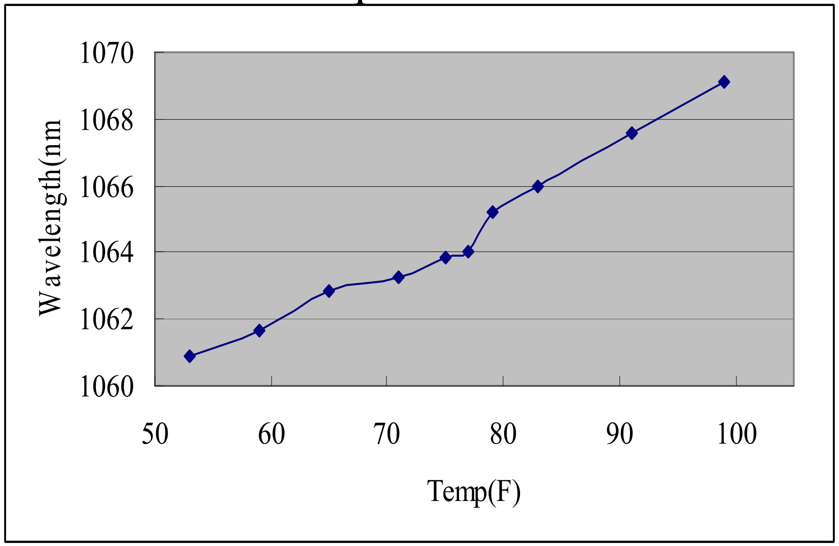
Laser seed: basic parameters



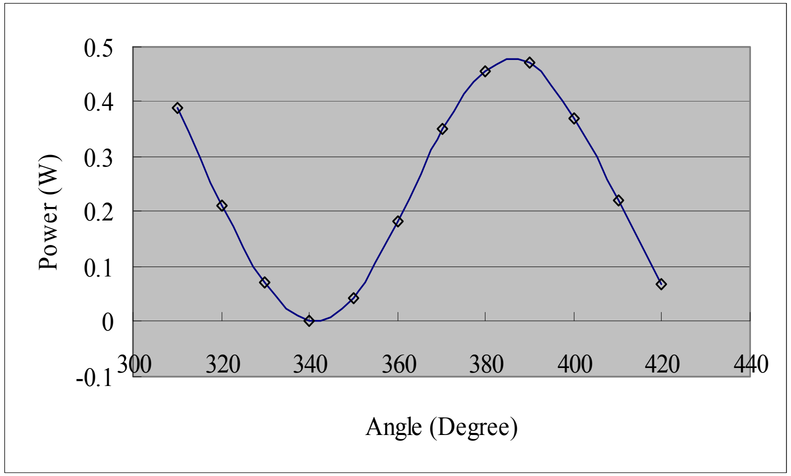
spectrum



0.8 mm FWHM beam size



Dependency of wavelength on temperature



P=(Pmax-Pmin)/(Pmax+Pmin)=99.2%

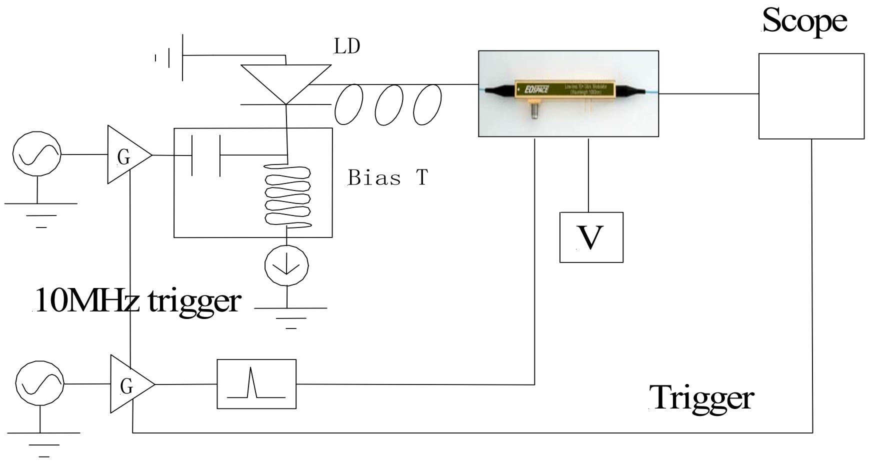
Laser seed: pulse length

Dependence of pulse length on rep. rate

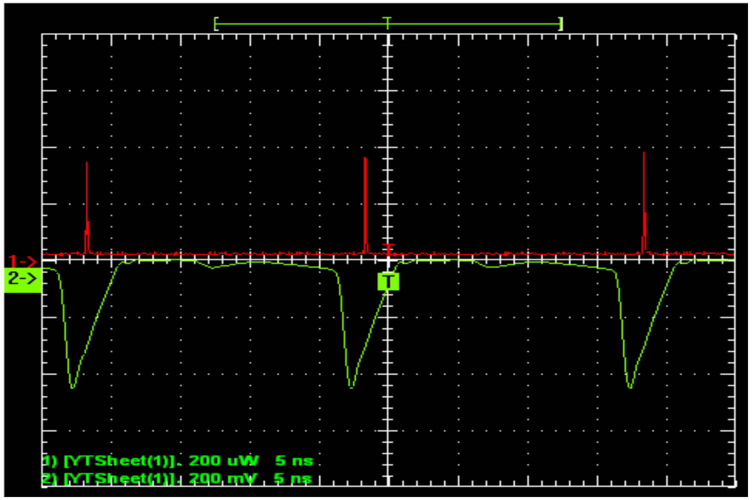
Rep. rate (MHz)	Power (mW)	T (ps, FWHM)	σ (ps)
125	0.108	60.230	25.630
250	0.224	53.956	22.960
300	0.265	51.446	21.892
400	0.464	50.192	21.358
499	0.738	46.427	19.756
600	1.176	46.427	19.756
700	1.318	46.427	19.756

Laser seed: pulse picking

Rep. rate < 100 MHz is useful for commissioning, measurements and some users



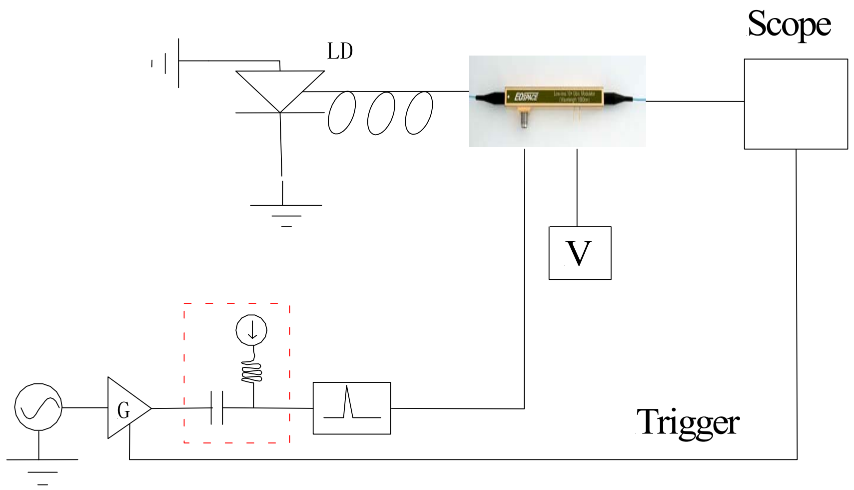
Schematic of pulse picking



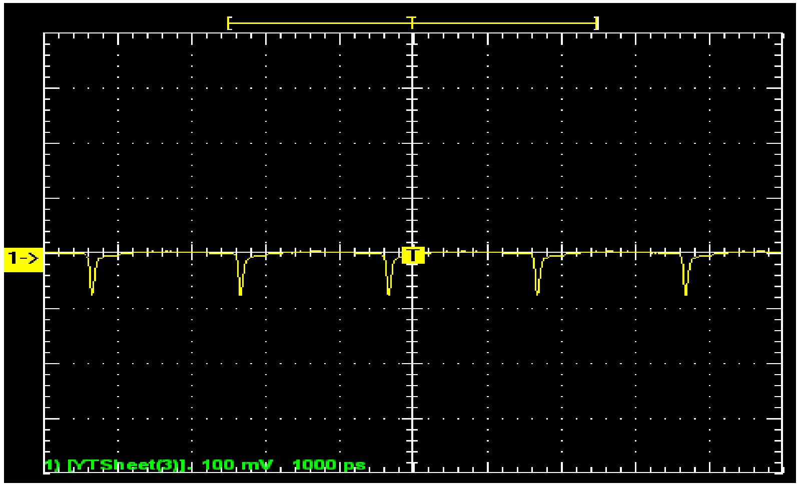
250MHz to 50MHz

1. Realize tunability of seed rep. rate with a convenient fiber coupled modulator
2. Faster than Pockels cell
3. Seed modulation, won't lose much power
4. Good feature for drive lasers.

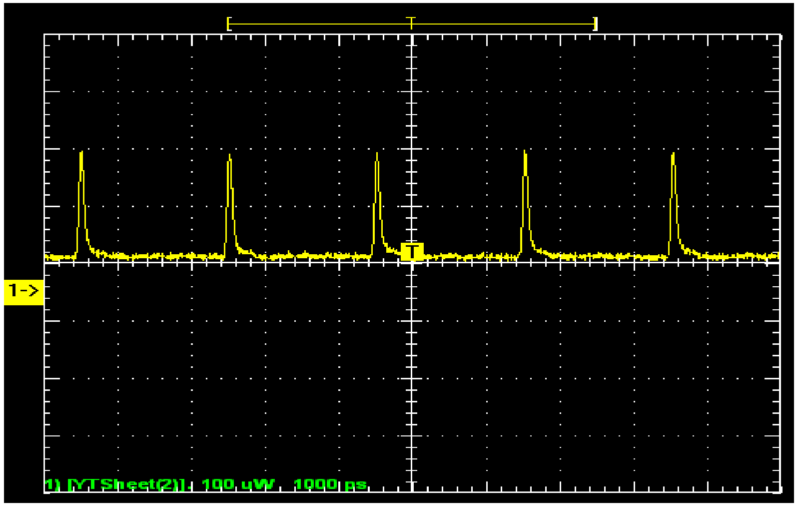
Laser seed: pulse forming



Schematic of pulse forming



Signal from step recovery diode



Laser train from pulse forming

1. New technique for producing ultra-short laser!
2. Nice single frequency and high coherence.
3. Possible shorter pulse than GS seed

Amplifier

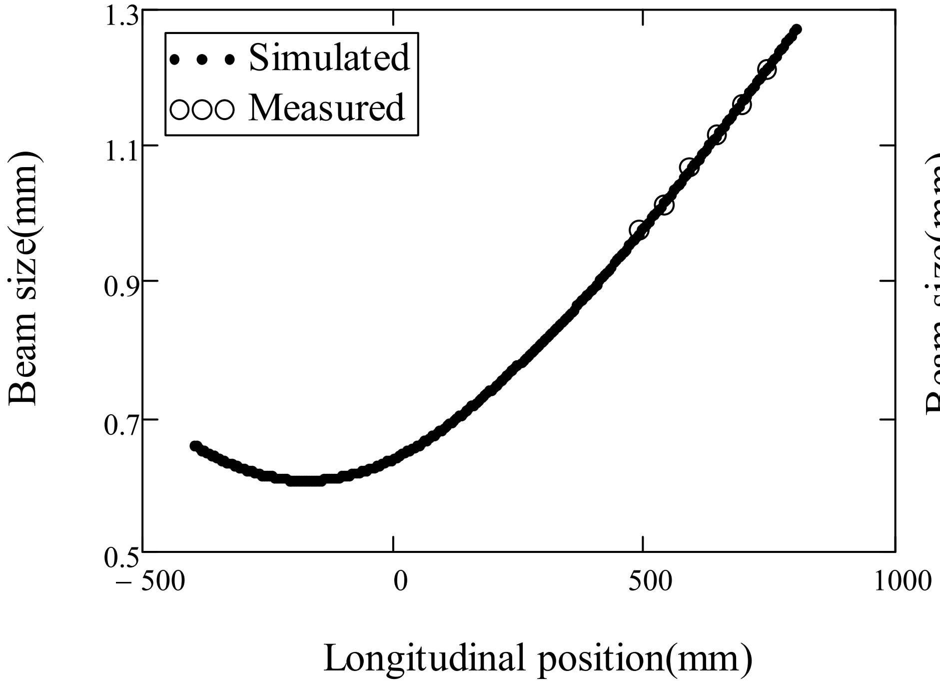
Available ultrafast amplifiers:

Fiber amplifier	Nice beam quality, relatively low damage threshold
Multipass bulk amplifier	High damage threshold, good quality, water cooling
Regenerative amplifier	High gain, low rep. rate
Optical parametric amplifier	Phase matching

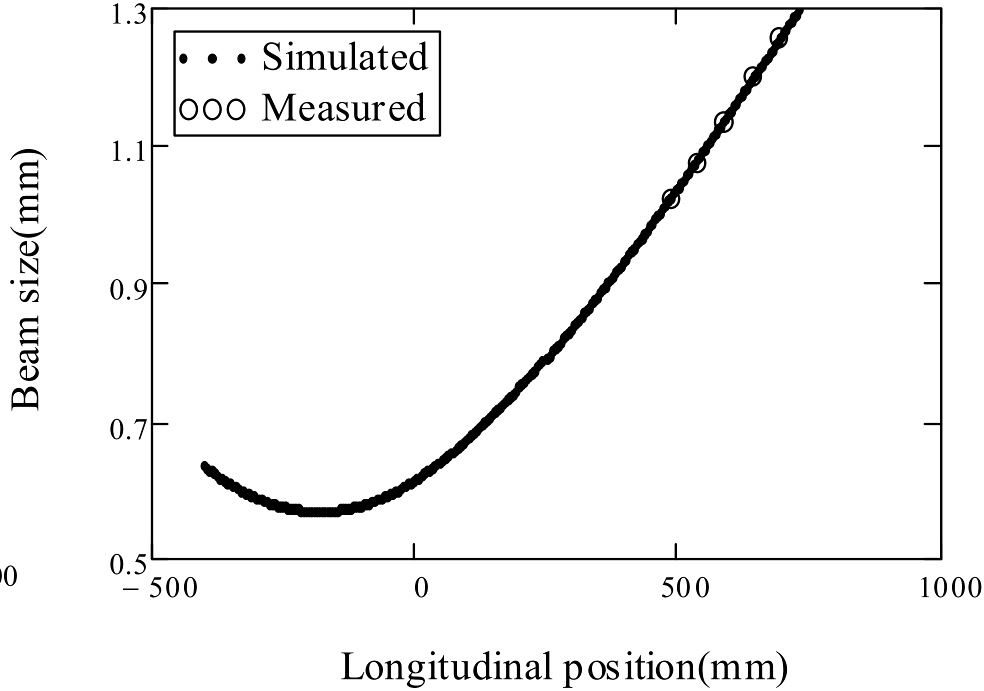
YFA from IPG

Parameters	Unit	YAR-5K-LP-SF
Polarization of output signal		linear
Operating wavelength range	nm	1050-1120
Operating bandwidth (FWHM)	nm	20
Central operating wavelength	nm	1064
Input power range	mW	1-30
Minimum input signal linewidth	MHz	0.01
Saturated output power (PIN=3 mW)	W	5
Output power tunability	%	10-100
Output power stability (over 8 hrs) (ACC)	%	2
Relative residual pump at input/output ports	dB	-30
Maximum power consumption (at 20°C)	W	75

M^2 (beam quality) measurement



Horizontal M^2 measurement



Vertical M^2 measurement

$$w_{0x} = 0.608mm \qquad M_x^2 = 1.03 \qquad z_{0x} = -176mm$$

$$w_{0y} = 0.58mm \qquad M_y^2 = 1.08 \qquad z_{0y} = -180mm$$

Frequency doubling

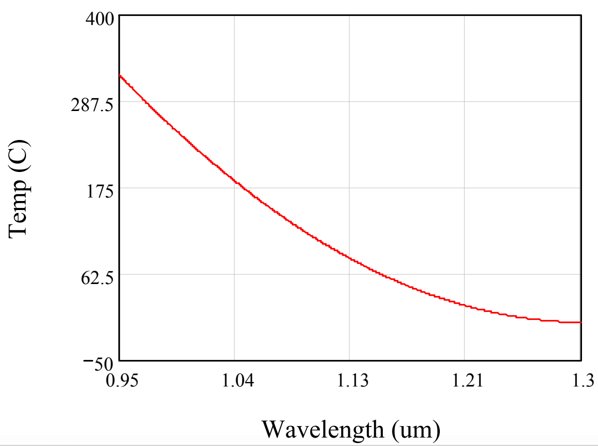
532 nm are needed and not available from laser transition,
so, nonlinear crystal is used for wavelength conversion

Available crystals for doubling 1064 nm: KDP, BBO, BIBO, LBO

Reasons for choosing LBO:

1. Relative large nonlinear coefficient
2. Good for non-critical phase matching: zero walk-off angle, ease of alignment
3. Large spectral acceptance
4. Large damage threshold

Nonlinear Optical Property Comparison			
Properties	BIBO	LBO	BBO
Length (mm)	10.4	10	8
Deff (pm/V)	3.3	0.81	2.0
Walk-Off (mrad)	40.7	11.3	60.3
Output Power (W)	2.8	1.52	2.1
Conversion Efficiency	63%	33%	47%



$T_1(1.064) = 149.256\ ^{o}C$

Improving efficiency

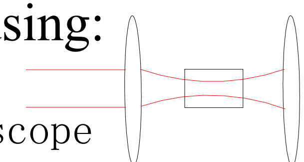
Doubling efficiency: $$\eta = P_{2\omega} / P_{\omega} = C \frac{d_{eff}^2 P_{\omega}}{A} \frac{\sin^2(\Delta k L/2)}{(\Delta k/2)^2}$$

Here, A is the beam area, $$\Delta k = k_2 - 2k_1 = \frac{2\pi}{\lambda_2} n(\omega_2) - 2\frac{2\pi}{\lambda_1} n(\omega_1) = \frac{4\pi}{\lambda_1}(n(\omega_2) - n(\omega_1))$$

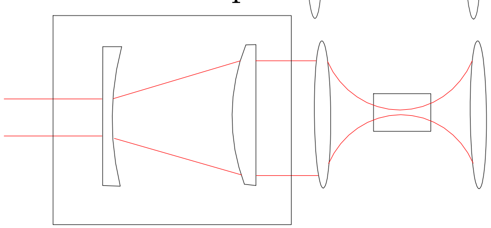
Three things that affect doubling efficiency:

1. Beam area/focusing
2. Peak power/ pulse width
3. Line width

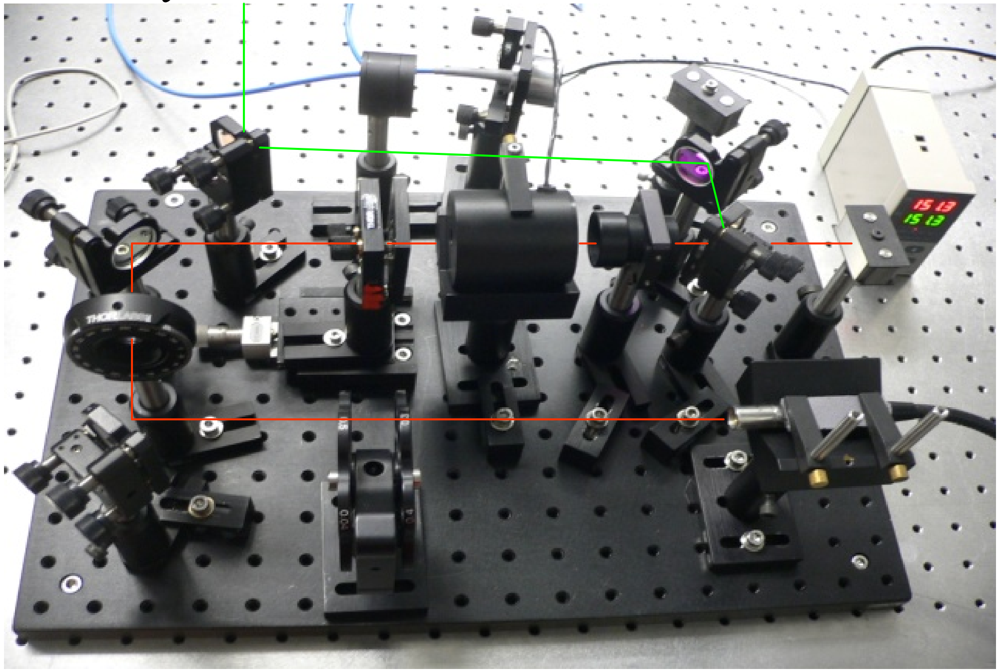
Better focusing:



Telescope

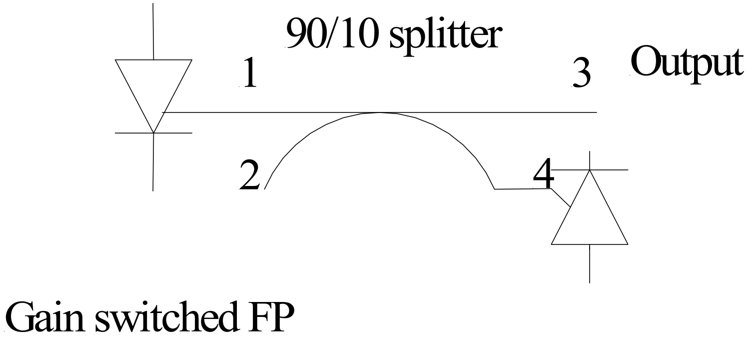


Telescope for better focusing

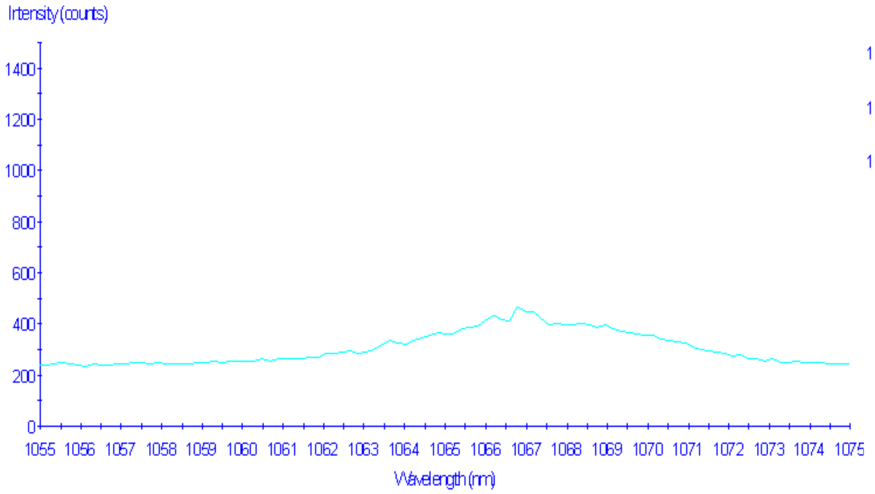


Optical feedback

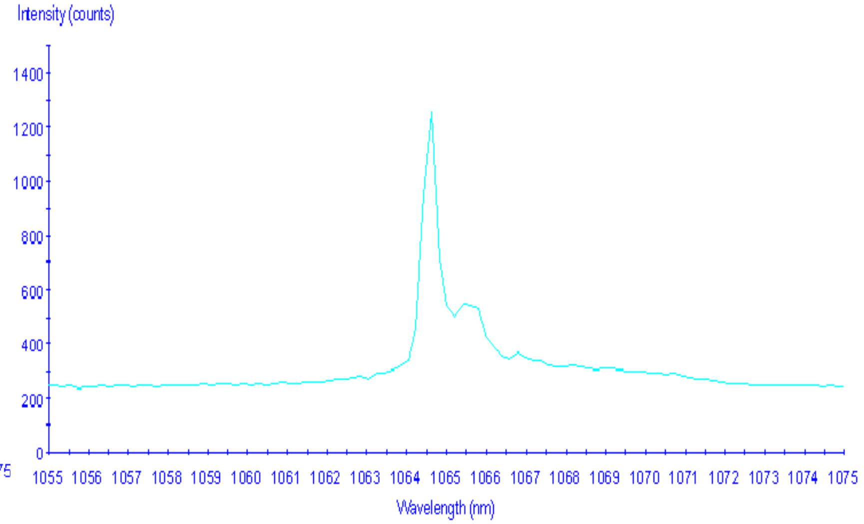
Narrower linewidth:



Optical feedback

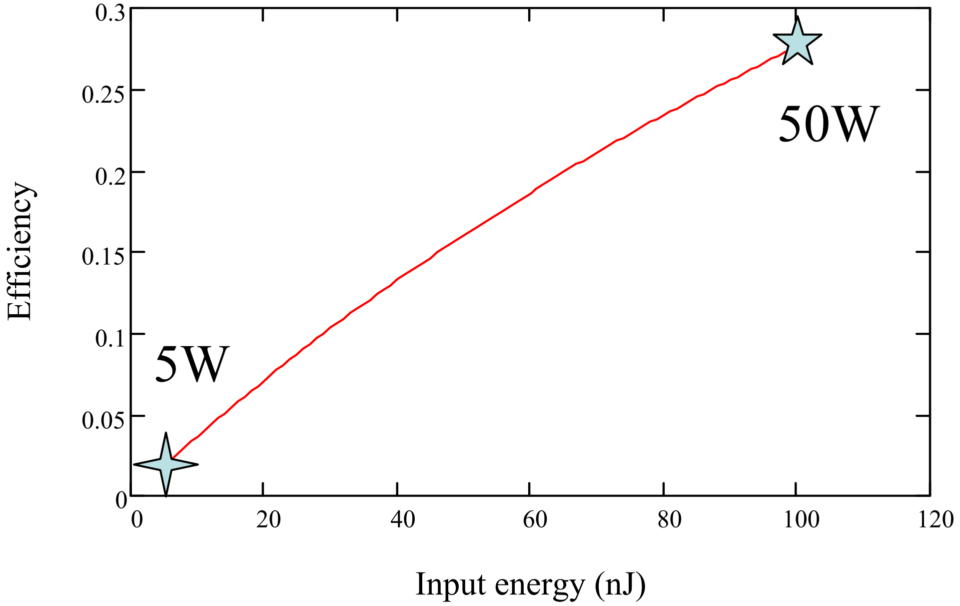


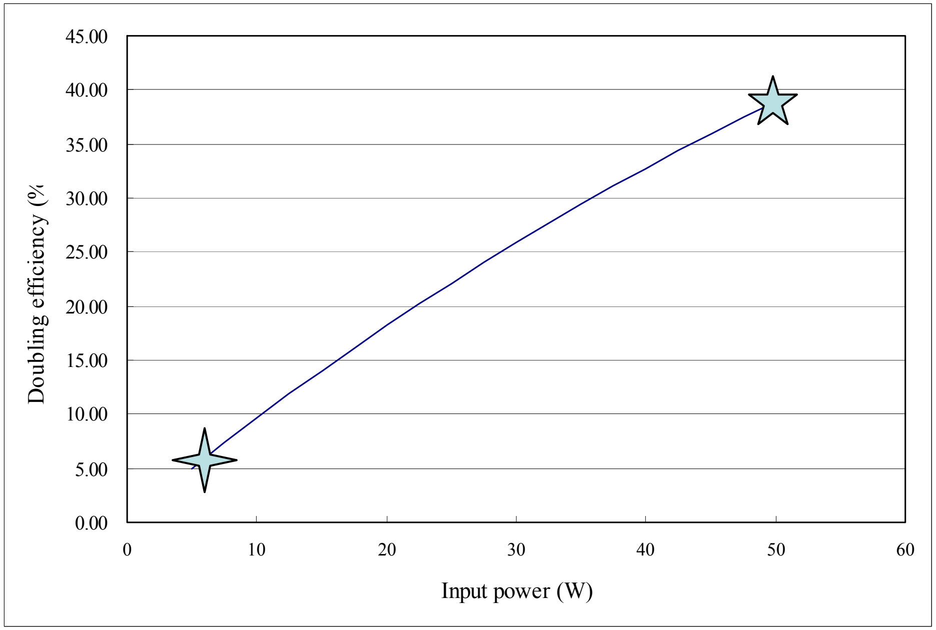
W/O Feedback



W Feedback

Efficiency evaluation





Efficiency calculated at 5 W IR agrees well with the experiment result, and predict ~30% efficiency when scaling power to 50 W.

[1] Haifeng Wang and Andrew M. Weiner Efficiency of Short-Pulse Type-I Second-Harmonic Generation With Simultaneous Spatial Walk-Off, Temporal Walk-Off, and Pump Depletion

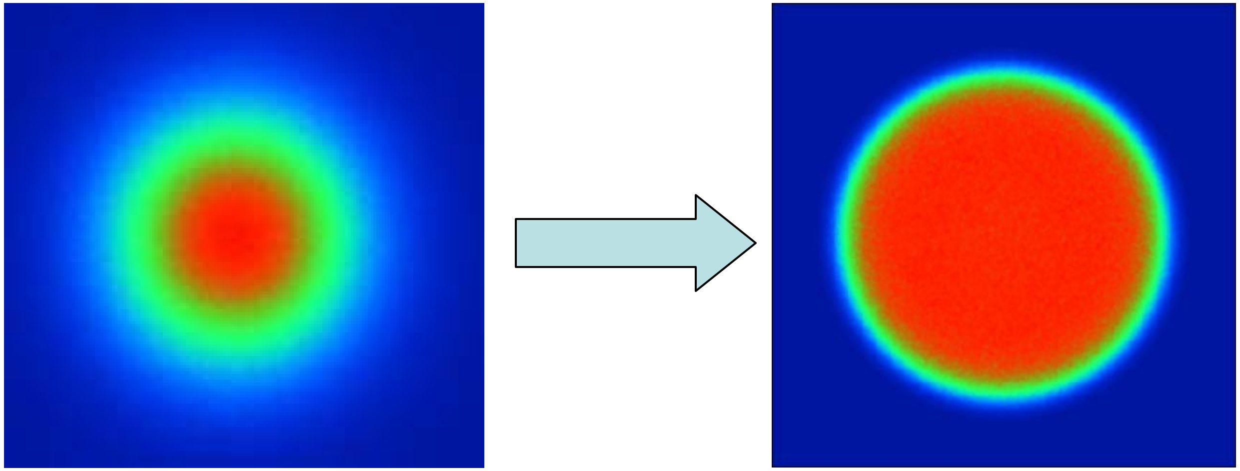
[2] Arlee V. Smith How to use SNLO nonlinear optics software to select nonlinear crystals and model their performance

Laser beam shaper

Definition: Optical element converting a usual Gaussian profile to a flat-top profile

Applications: material processing, lithography, medical applications, laser printing, optical data storage, micromachining, isotope separation, optical processing

Usage for us: Emittance growth from linear space charge force can be fully recovered by appropriate optics arrangement, and an uniform laser beam is needed to produce uniform electron beam



Shaper: typical designs

Design criteria for shaper:

1. energy conservation, the total beam energy remains constant from the input to the output, and
2. equal optical path, all rays passing through the shaper from input pupil to output pupil have zero optical path difference (OPD).

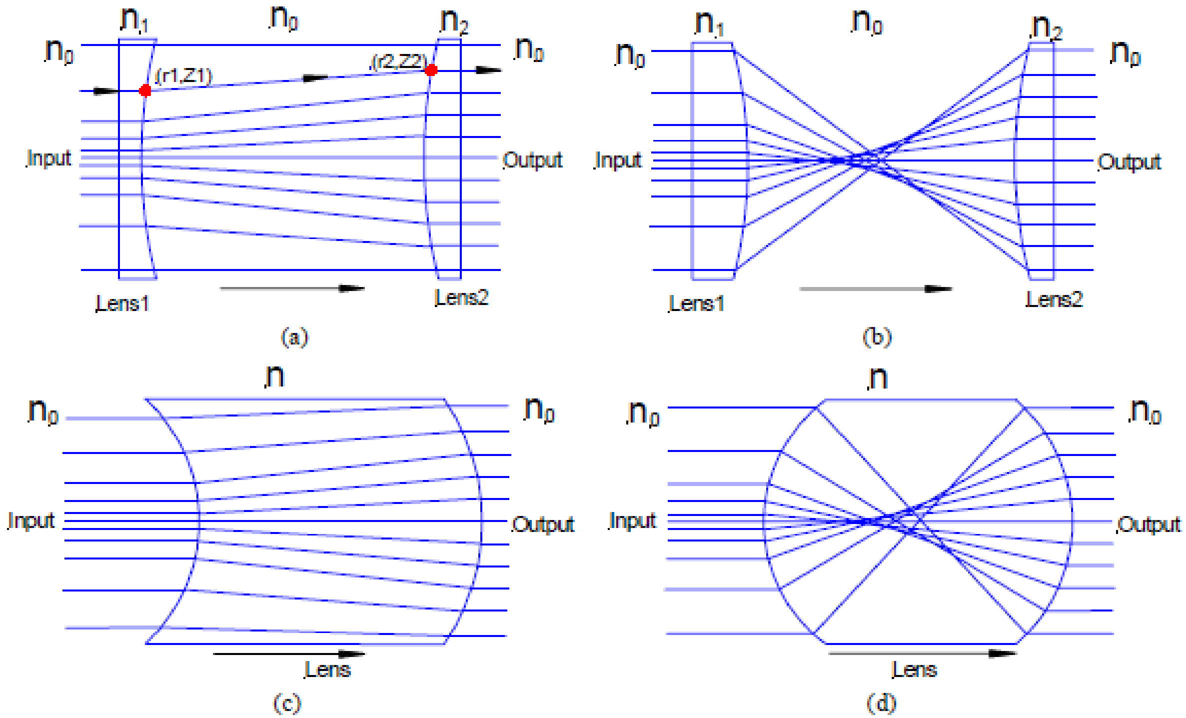


Fig. 1. Optical configurations of refractive laser beam shaper: (a) Galilean type, (b) Keplerian shaper, (c) Single-lens Galilean shaper, (d) Single-lens Keplerian shaper

C. Liu, S. Zhang, ***Study on singular radius and surface boundary constraint in refractive beam shaper design.*** Optics Express Vol. 16, No. 9 P.6675-6682 2008

Shaper: singular radius

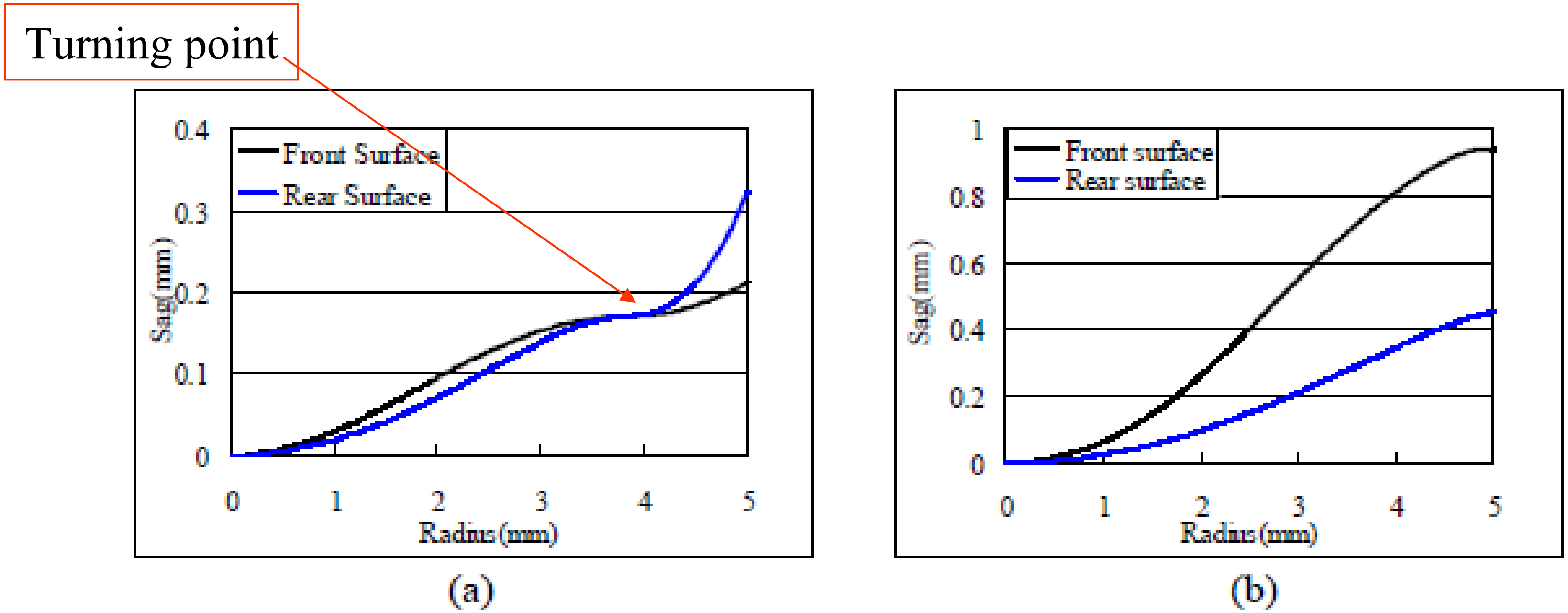


Fig. 2. Sag curves for the two single-lens beam shapers, (a) R=4mm, and (b) R=5mm.

Singular radius (the turning point) is where the input ray will pass straight through the optical material, is highly undesirable because it incurs unnecessary complication, adding particular difficulty in data processing and optical fabrication, only associated with type 1 and 3.

Shaper: singular radius

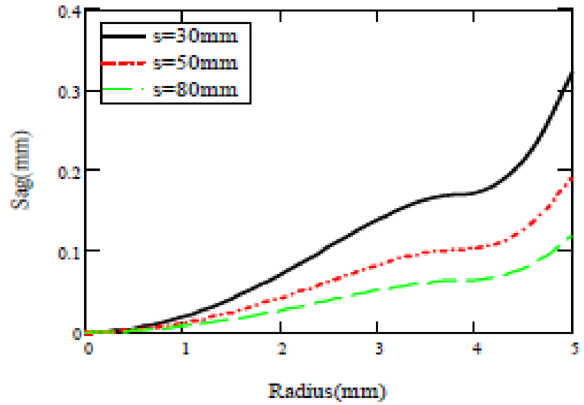


Fig. 6, Sag curves of rear surface for different lens thickness

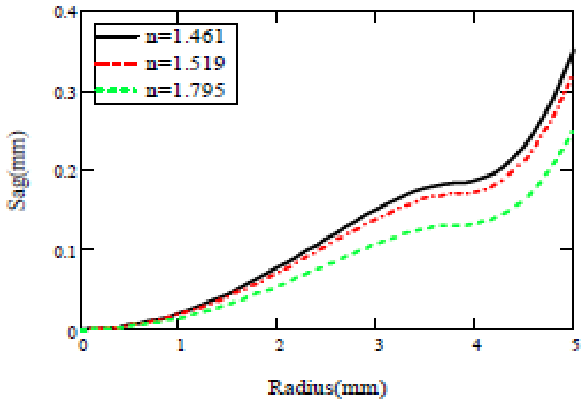


Fig. 7, Sag curves of rear surface for different index of refraction. *S* =30mm.

The curve becomes more monotonic as the lens thickness increases, however, refraction index won't make much difference.

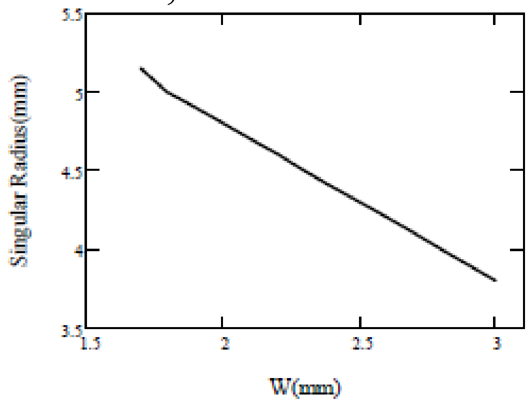


Fig. 5. Singular radius changes with initial beam size W

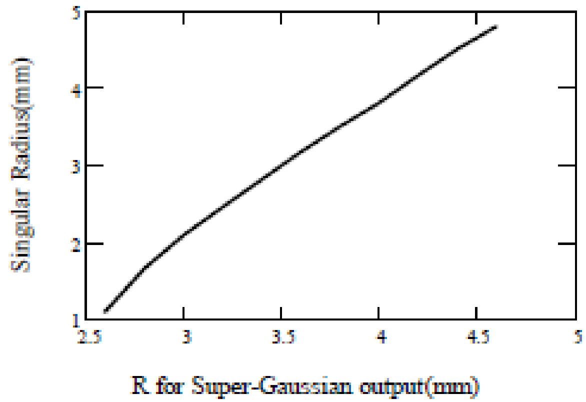


Fig. 8. Singular radius changes with output beam parameter R

Smaller input size and bigger output size move singular radius away from center

Shaper: surface boundary

The surface tends to bend more until it's parallel to the optical axis, this natural boundary happens for type 3 and 4

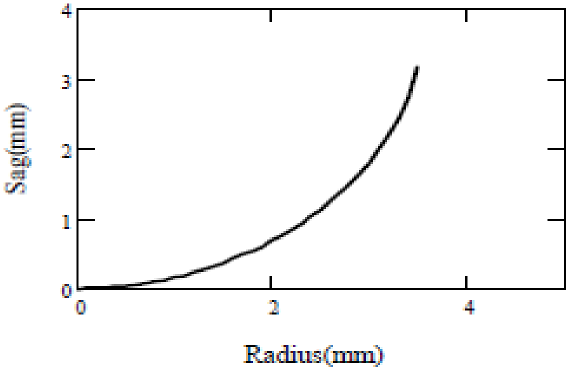


Fig. 9. Surface profile showing the boundary constraint for Type-4 shaper

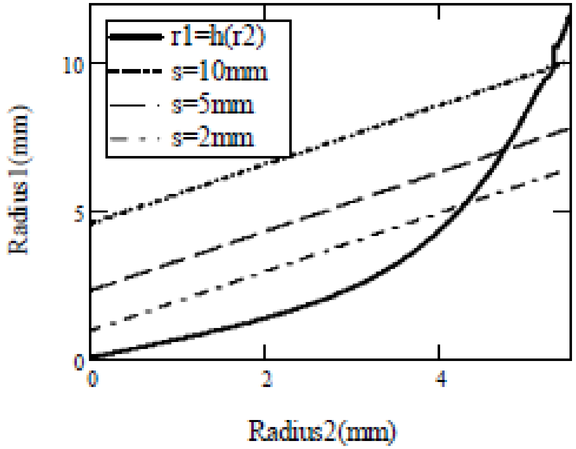


Fig. 10. Dependency of Type-3 beam shaper surface boundary on different lens thickness

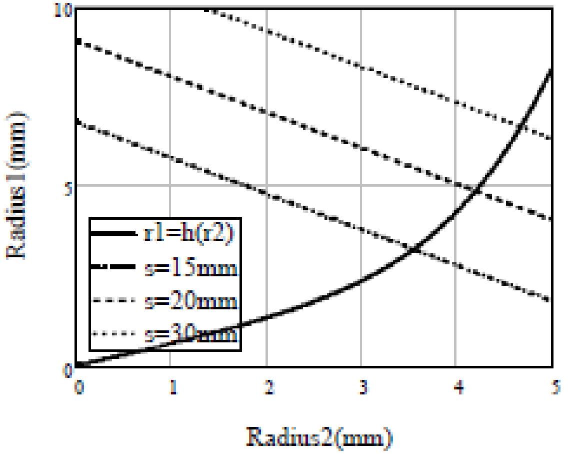
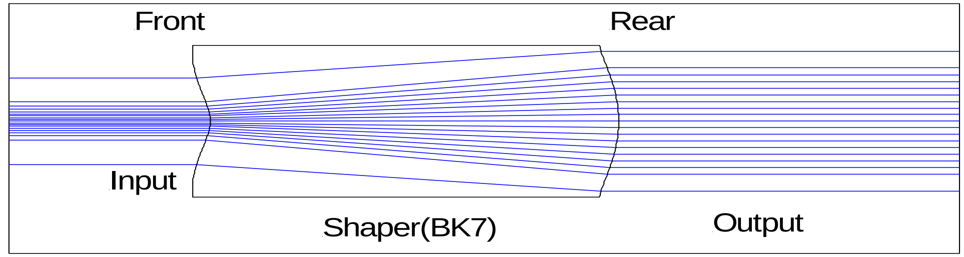


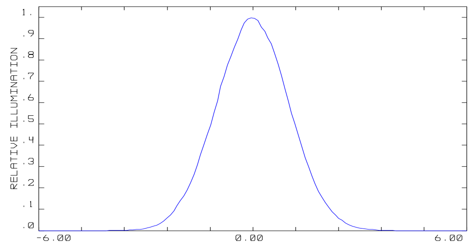
Fig. 11. Shaper surface boundary changes with lens thickness for Type-4 shaper

Longer shaper extends the boundary

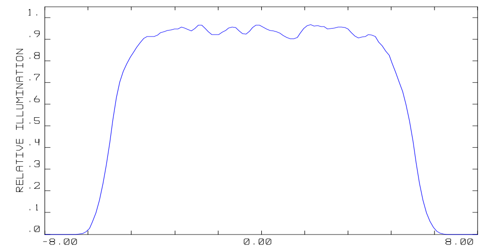
Shaper: a new single lens design

ZEMAX simulation:

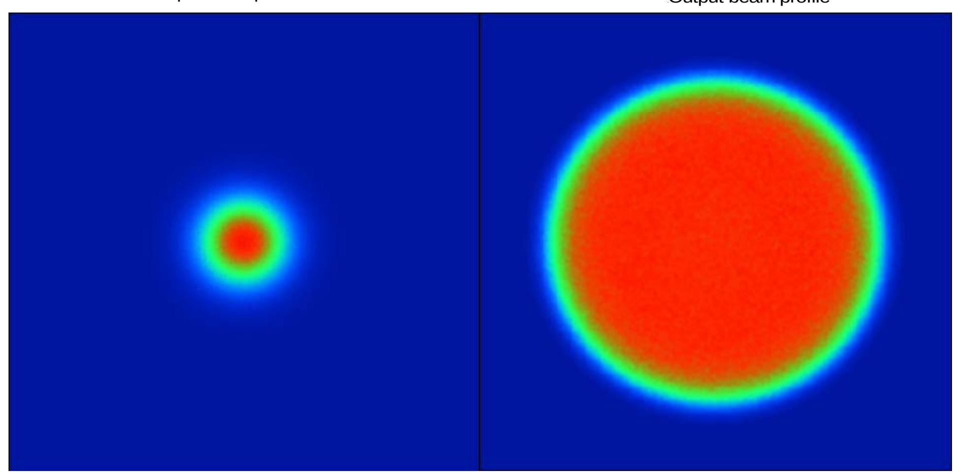




Input beam profile



Output beam profile



Newport shaper:

Not working for most cases

My single lens shaper:

Low loss

Easy to align

Relieving diffraction effects

From criteria 1:

$$r_1 = h(r_2) = \sqrt{-\frac{9}{2}\ln(1-2\pi\int_0^{r_2} I_2(r)rdr)}$$

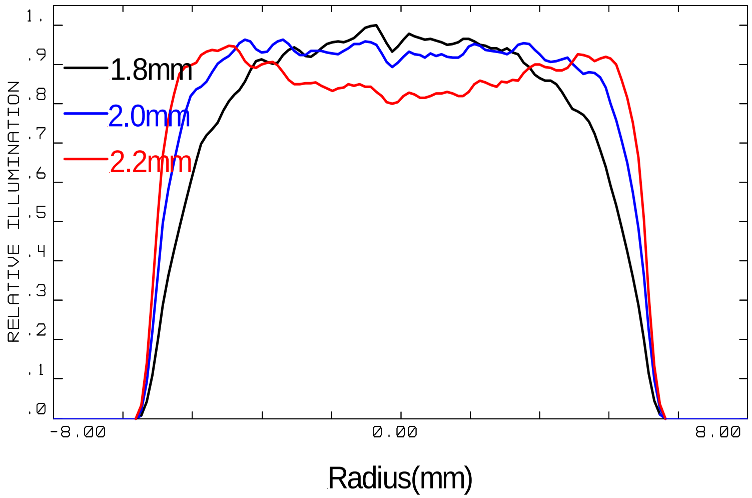
From criteria 2:

$$Z_1(r) = \int_0^r n[-(n^2-1)+(\frac{(n-1)s}{r_2-r_1})^2]^{-1/2}dr_1$$

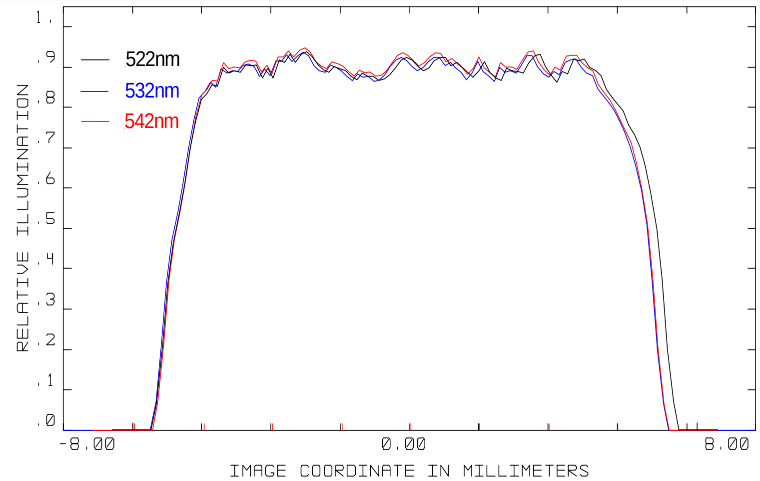
$$Z_1(r) = \int_0^r n[-(n^2-1)+(\frac{(n-1)s}{r_2-r_1})^2]^{-1/2}dr_2$$

5.7mm radius for diffraction effects relief and single element for easy alignment

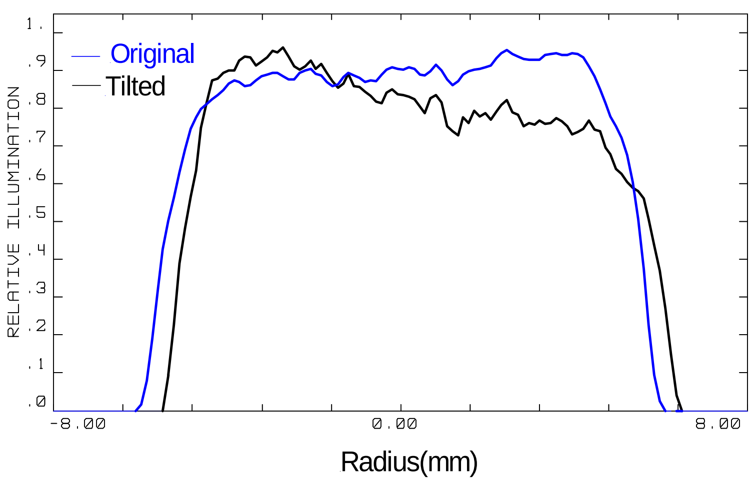
Shaper: performance analysis



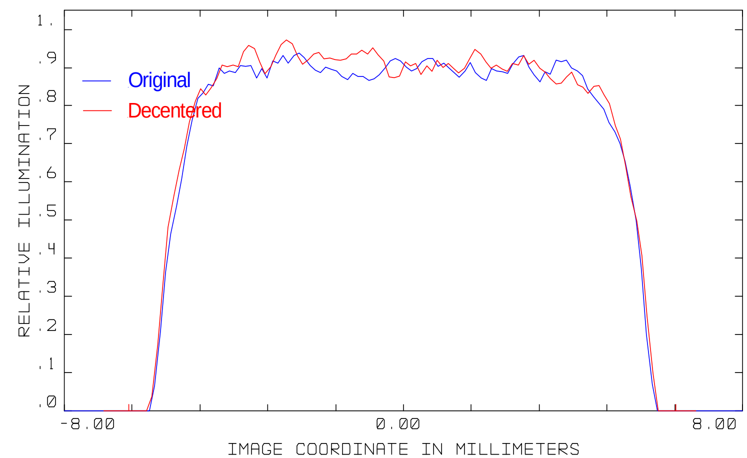
Output for different input radius



Output profiles for different wavelengths



Output of 1° tilted input beam

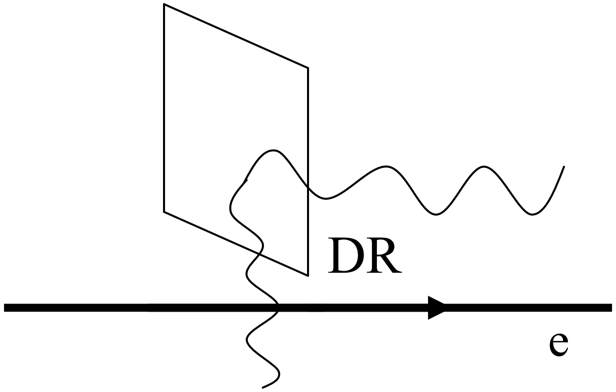


Output of input beam decentered by 0.1 mm

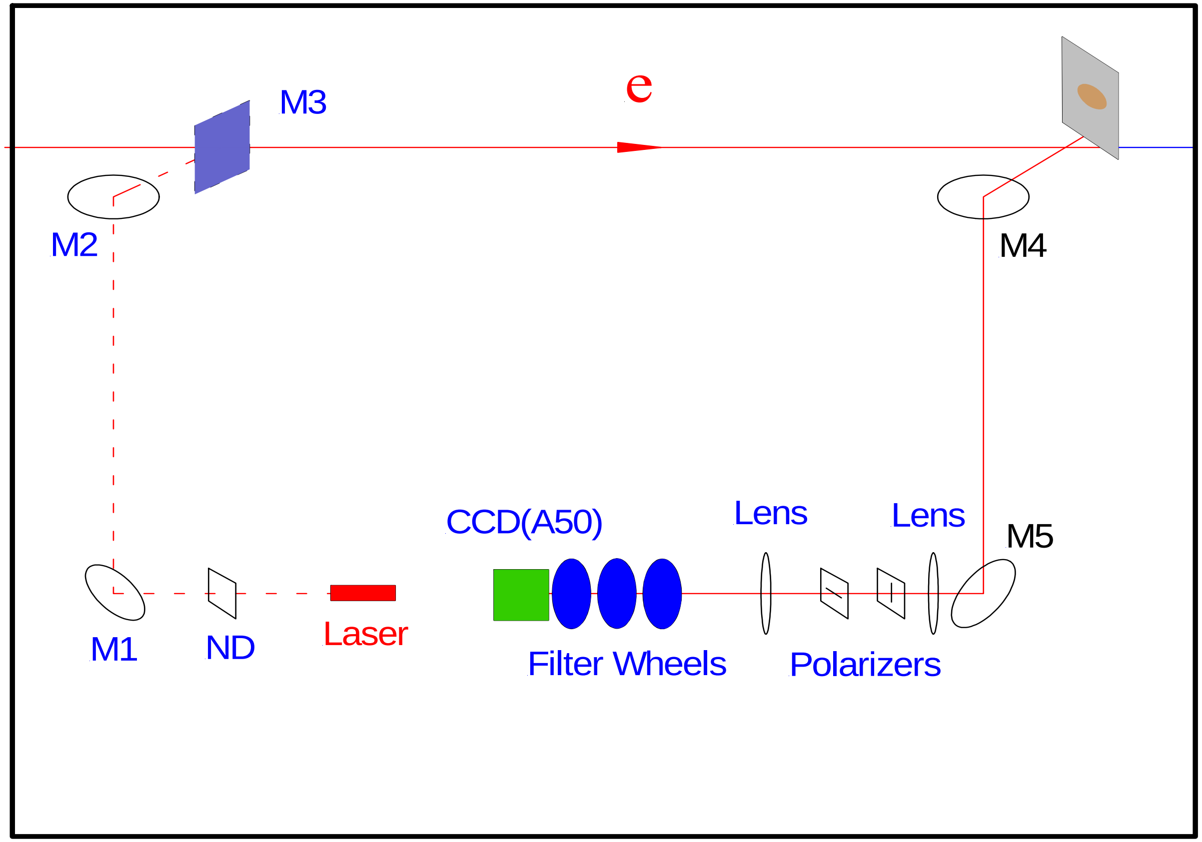
Optical diffraction radiation

- ODR: Wakefield generated by charged particle beam when it passes by an inhomogeniety, such as a circular hole, a slit on metal or the edge of a piece of metal

- ODR is potential to be a non-intercepting tool for measuring electron beam size between tens to hundreds μm



ODR setup



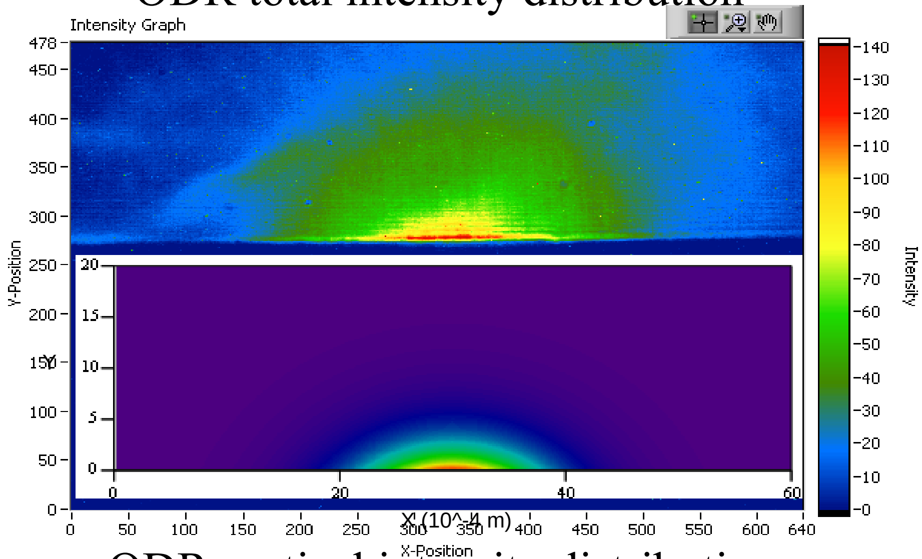
Schematic of ODR optics

OTR+ODR radiator

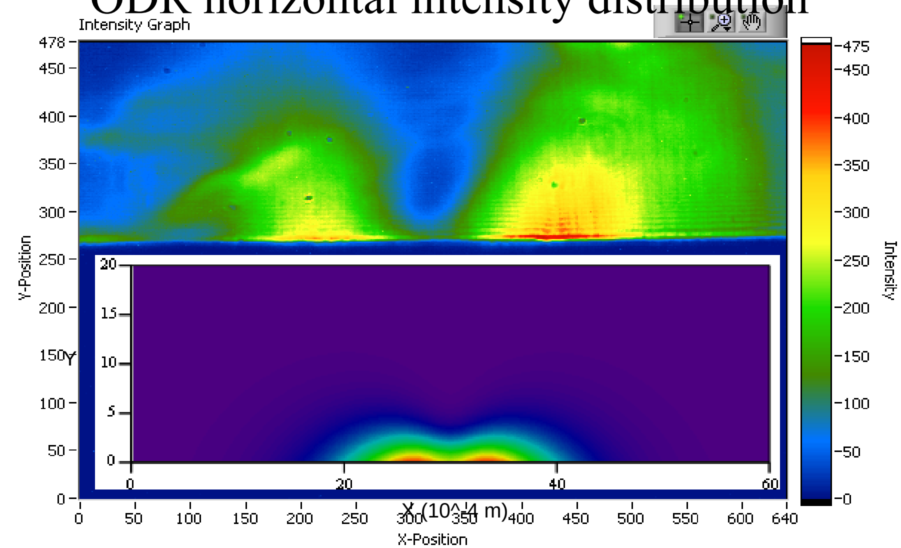
courtesy of P. Evtushenko and HyeKyoung Park

ODR measurements

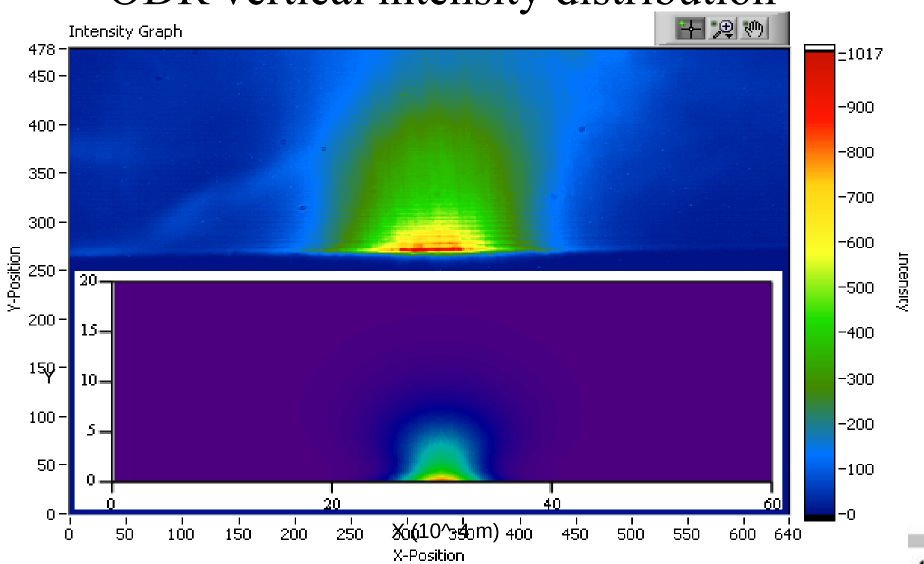
ODR total intensity distribution



ODR horizontal intensity distribution



ODR vertical intensity distribution



All three measured distributions agree with calculated ones except two things:

1. Asymmetry caused by non ideal horizontal polarizer
2. Radiation streak from edge radiation

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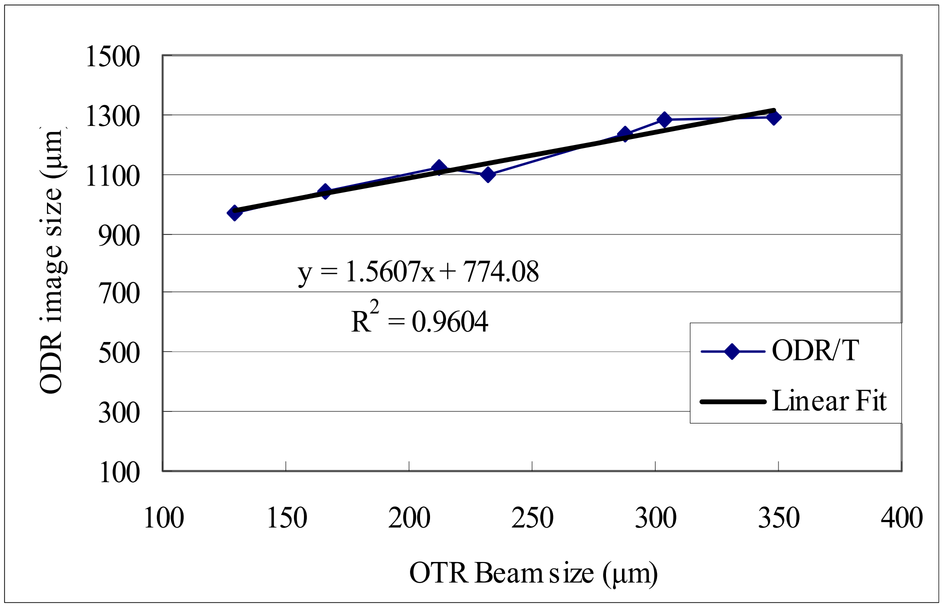
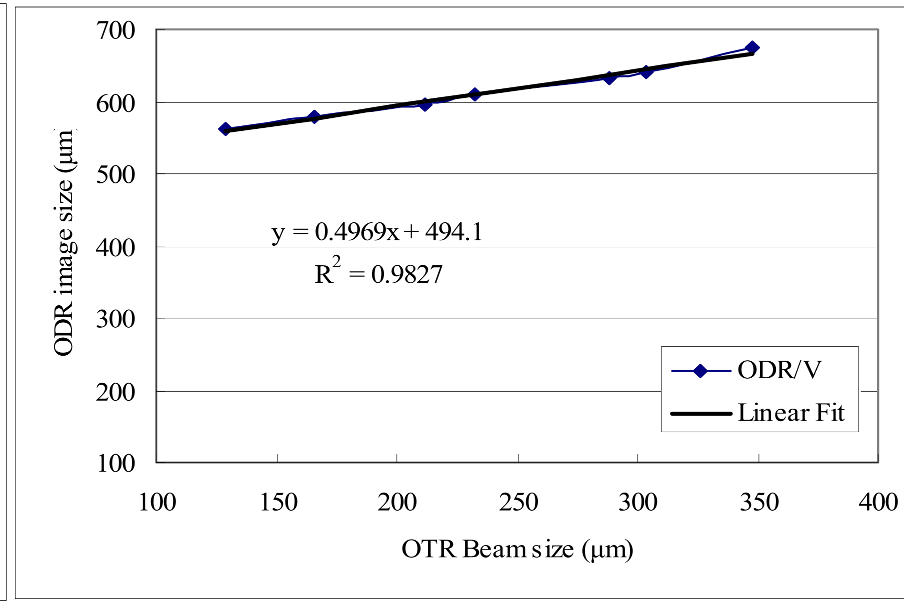
ODR vs. OTR





Close to linear relation

Better linear relation

Summary

- Gain-switched diode laser has been tested as a good seed
- Pulse picking and pulse forming was demonstrated
- 5 W laser system was established
- Issues on beam shaper were discussed and a new single lens design was presented
- ODR e^- beam size measurement is presented

Future plan on laser:

- Manipulate pulse length of gain-switched diode laser
- Reduce S/N ratio of pulse picking
- Temporal shaping

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