Pulse shape measurement issue

~ Pulse-stacker-based square pulse (>10ps) shaping system ~

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0. Intro. ~ Recent progress in UV-pulse (>10 ps) shaping ~
1. Macro-pulse (>10 ps) generation with UV-pulse stacker
2. Passive micro-pulse preparation
   - Prism-pair UV-stretcher + Pulse Stacker
3. Adaptive micro-pulse preparation
   - UV- & IR-DAZZLER feedback sys.+ Pulse Stacker
4. Summary for generation of >10-ps UV- Square laser pulse

O. ~10-ps pulse-shaping development in UV (~263 nm): In the year 2006, UV-shaping technologies are matured!

~ Pulse stacker-based shaping ~

1. Generally, UV-pulse stretcher is limited (up to 6 ps with nice shape).
   Prism-Pair, Meter-long silica rods, etc

2. UV-pulse stacker is the good tool to extend to >10-ps square pulse.
   We can combine with sub-10-ps shaping methods.

3. UV-Dazzler (AO) was completed (up to 5 ps) by Fastlite (L' Ecole poly-technique) and commercialized.

O. ~10-ps adaptive pulse- shaping development (SLM)

~ Arbitrary Laser Pulse Shaping ~

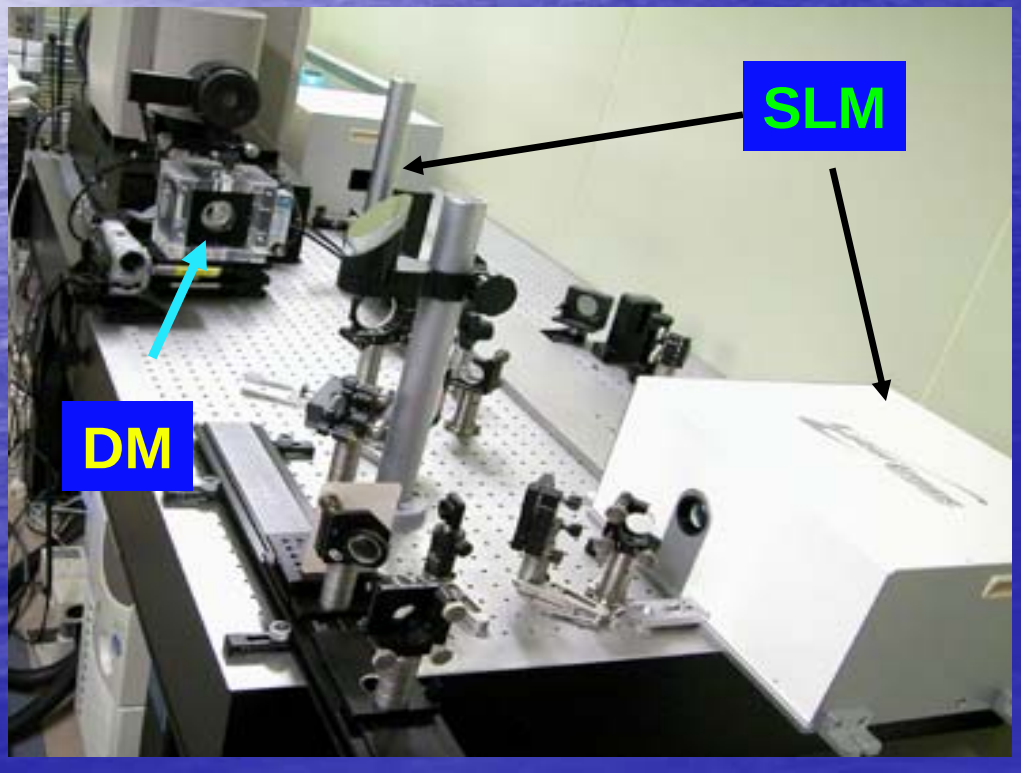
Possible to shape ~ms pulse train ~ However long-term drifting

A) Computer-aided **SLM (Spatial Light Modulator)**

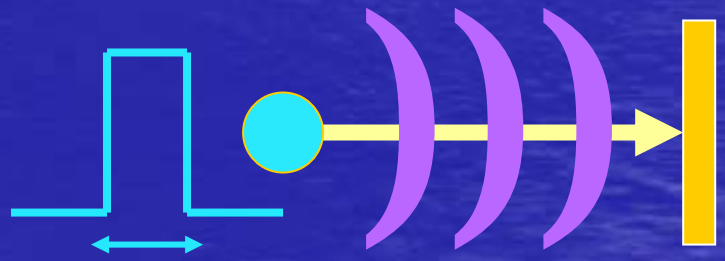
→ **Rectangular Pulse shaping (Arbitrary Shape)**

B) Computer-aided **DM (Deformable mirror)**

→ **Flattop spatial profile (Arbitrary Shape)**



Automatic Control Optics
- Spatial shaping (DM)
- Pulse shaping (SLM)
- Wave front Control (DM)



2 ~ 12 ps Fundamental

2 ~ 5 ps THG (263 nm)

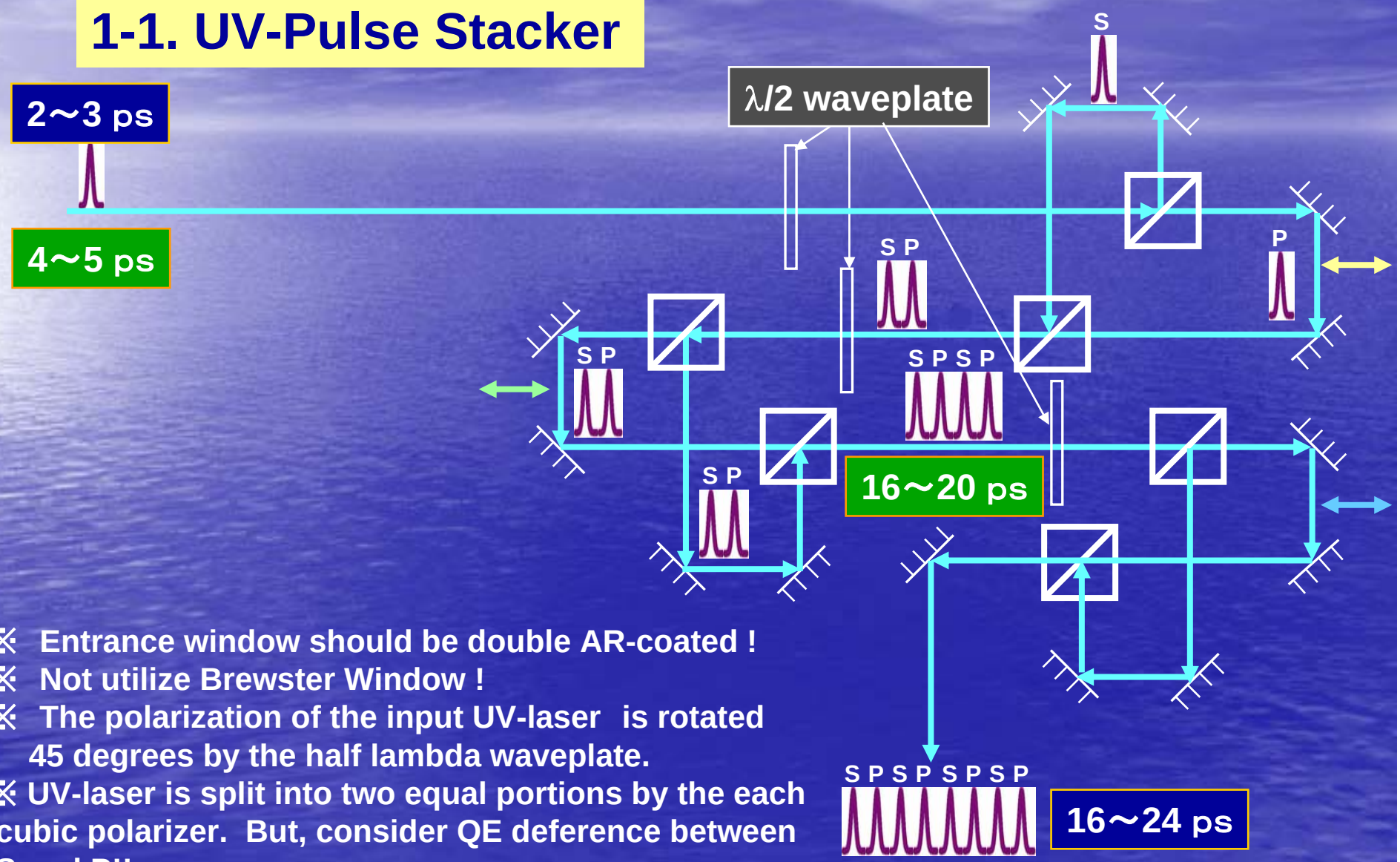
Compared with commercial equipments

Manufacturer Name (country)	APE (Germany)	APE (Germany)	Hamamatsu (Japan)	SWAMP (United State)
Type of measurement	SPIDER	Auto Correlator	Streak Camera	SHG-FROG (UPM-8-500)
Product Name	SPIDER	Mini	fesca-200	UPM-8-500
Wavelength Range	750～900nm	420～550 (1600) nm	250~850nm (Streak tube)	700～1100nm
Spectral Resolution Or Time Resolution	40 fs (0.3 nm@ spectrometer)	50 fs (< 20 fs)	200 fs (at 800 nm) 500 fs (at 400nm) 700 fs (at 250 nm)	0.05 (0.025)nm
Damage Threshold Requirement of measurement	> 8 mm < 400mW @80MHz, 80fs < 25μJ @1kHz, 35fs	< 400mW @80MHz, 80fs < 25μJ @1kHz, 35fs	To reduce space charge-pulse width broadening, light intensity should be weak possible	>400 μJ（2 mm）with 75 fs pulses
Single Shot Pulse	OK	Not available	OK (For accuracy, should be integrated)	OK
Measurable Pulse width	40～150fs	50fs ～3.5ps	700 fs～800 ps (in UV)	500 fs～10 ps (up to15ps ?)
others	Perfect characterization of temporal pulse	Just pulse width measurement	Direct measurement of temporal shape	Almost perfect characterization of temporal pulse

1. Macro-pulse (>10 ps) generator

(Pulse stacking to reach longer square pulse)

1-1. UV-Pulse Stacker



※ Entrance window should be double AR-coated !

※ Not utilize Brewster Window !

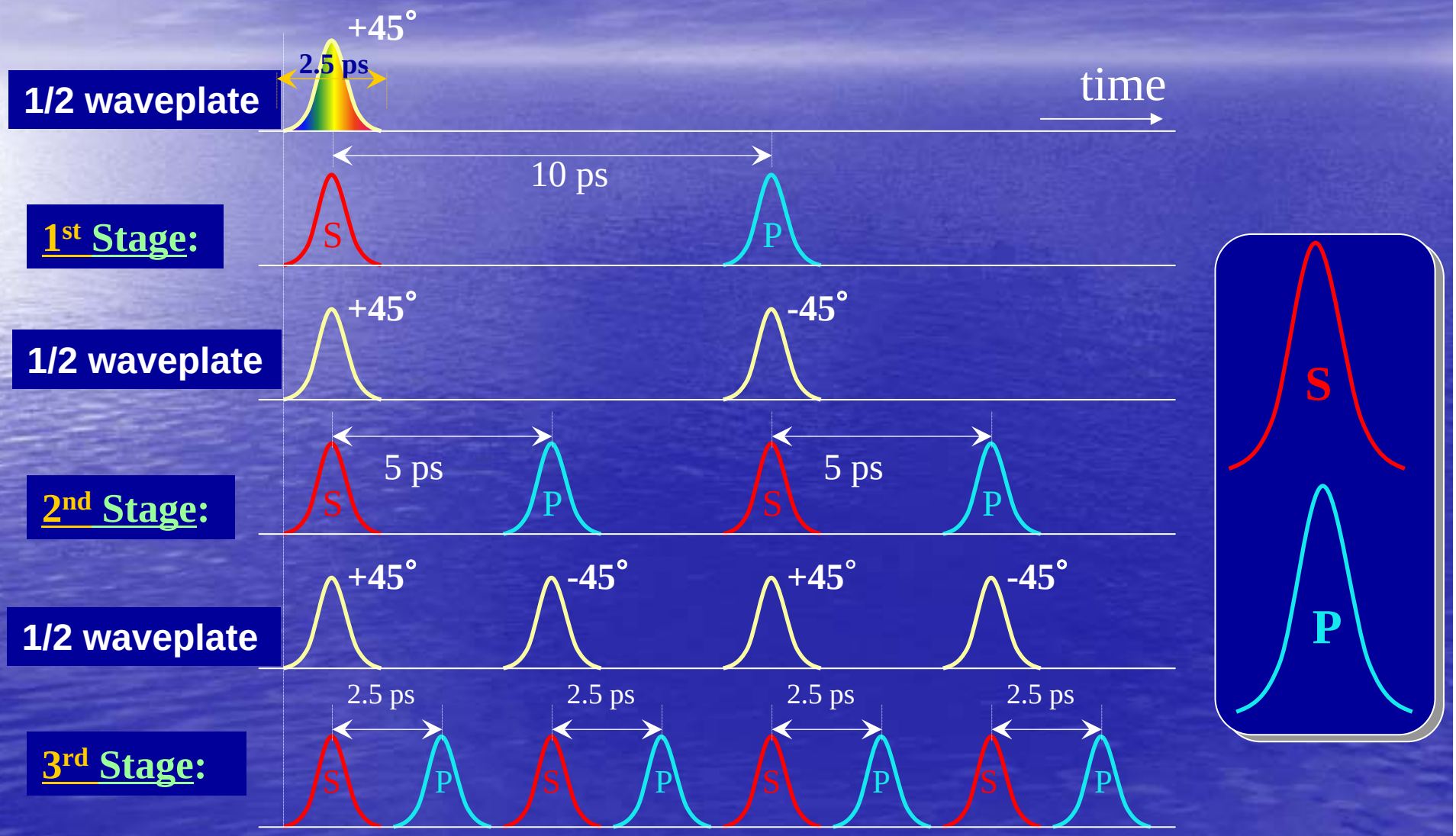
※ The polarization of the input UV-laser is rotated 45 degrees by the half lambda waveplate.

※ UV-laser is split into two equal portions by the each cubic polarizer. But, consider QE deference between S and P!!

1. Macro-pulse (15~20 ps) generator

1-2. Time chart of pulse stacking

3 stages for generation of 20 ps square pulse

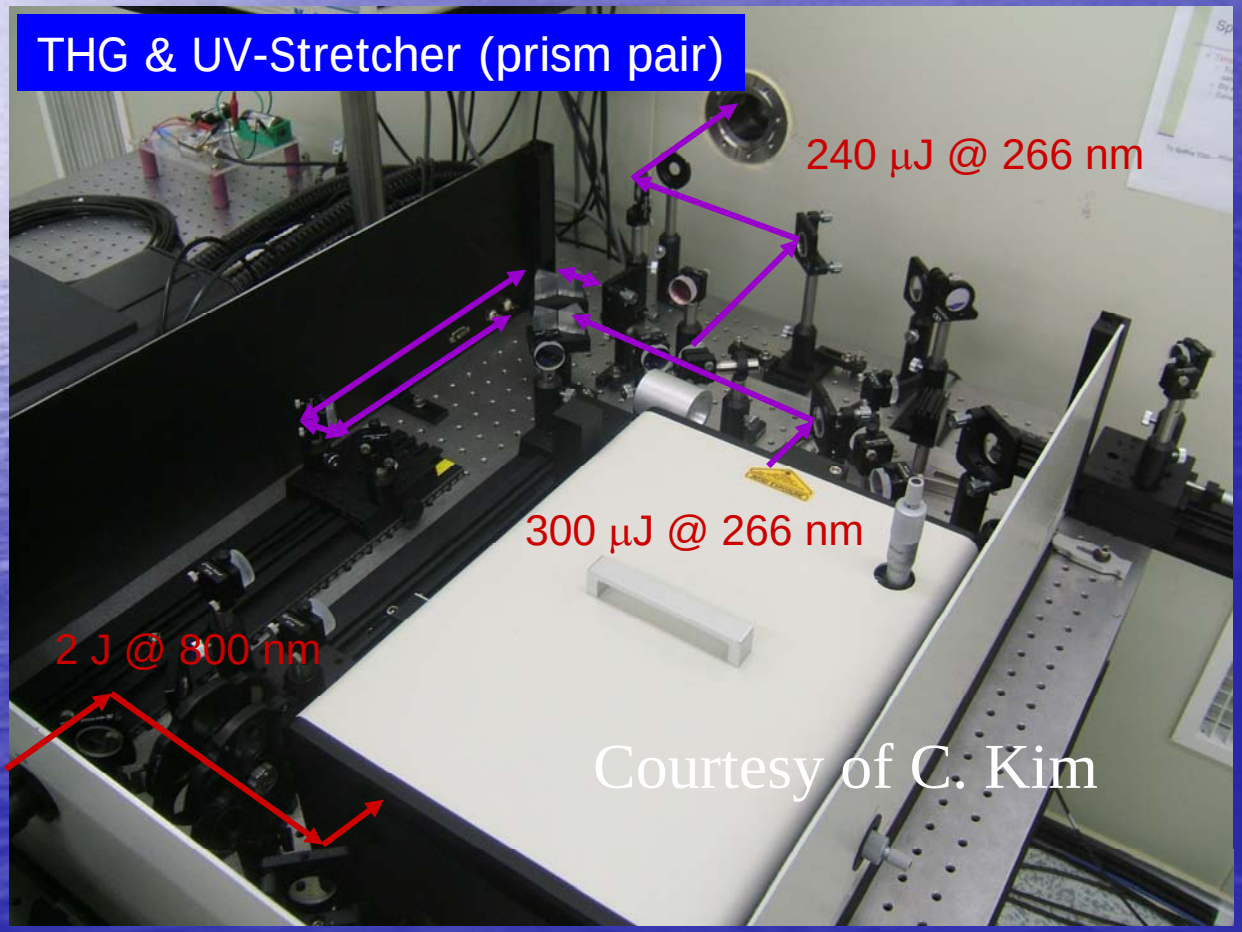


2. Passive micro-pulse preparation

- Prism-pair UV-stretcher + Pulse Stacker

2-1. THG-Stretching system

~ Combining with Pulse stacker,
it generates ideal square laser temporal pulse ~



2.5 mJ @ 800 nm

X 10% efficiency

=250 μJ @ 266 nm

X 50% Loss

=125 μJ

=>1 nC from Cathode with 10^{-5} Q.E.

2. Passive micro-pulse preparation

- Prism-pair UV-stretcher + Pulse Stacker

2-2. Prism-Pair Dispersion

- Prism pair has been traditionally designed to compensate the GVD in the laser cavity, and to compress the output pulse.
- Prism-pair produces a negative GVD

$$GVD = (\lambda^3/2\pi c^2) d^2P/d\lambda^2$$

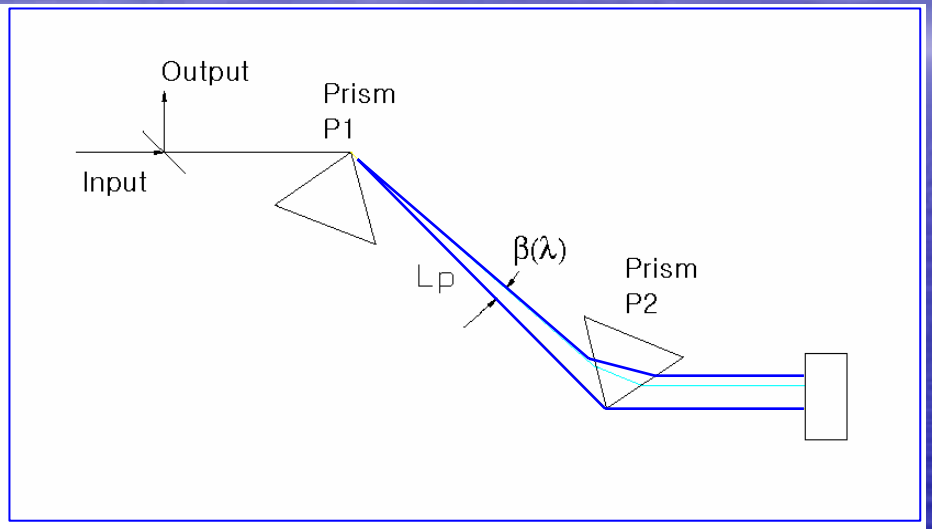
Path length $P = 2L_p \cos(\beta(\lambda))$

L_p = distance between P1 & P2

$$GVD \sim -(4\lambda^3 L_p/\pi c^2)(dn/d\lambda)^2$$

$$= -550 fs^2/cm \times L_p (cm)$$

for fused silica at 266nm



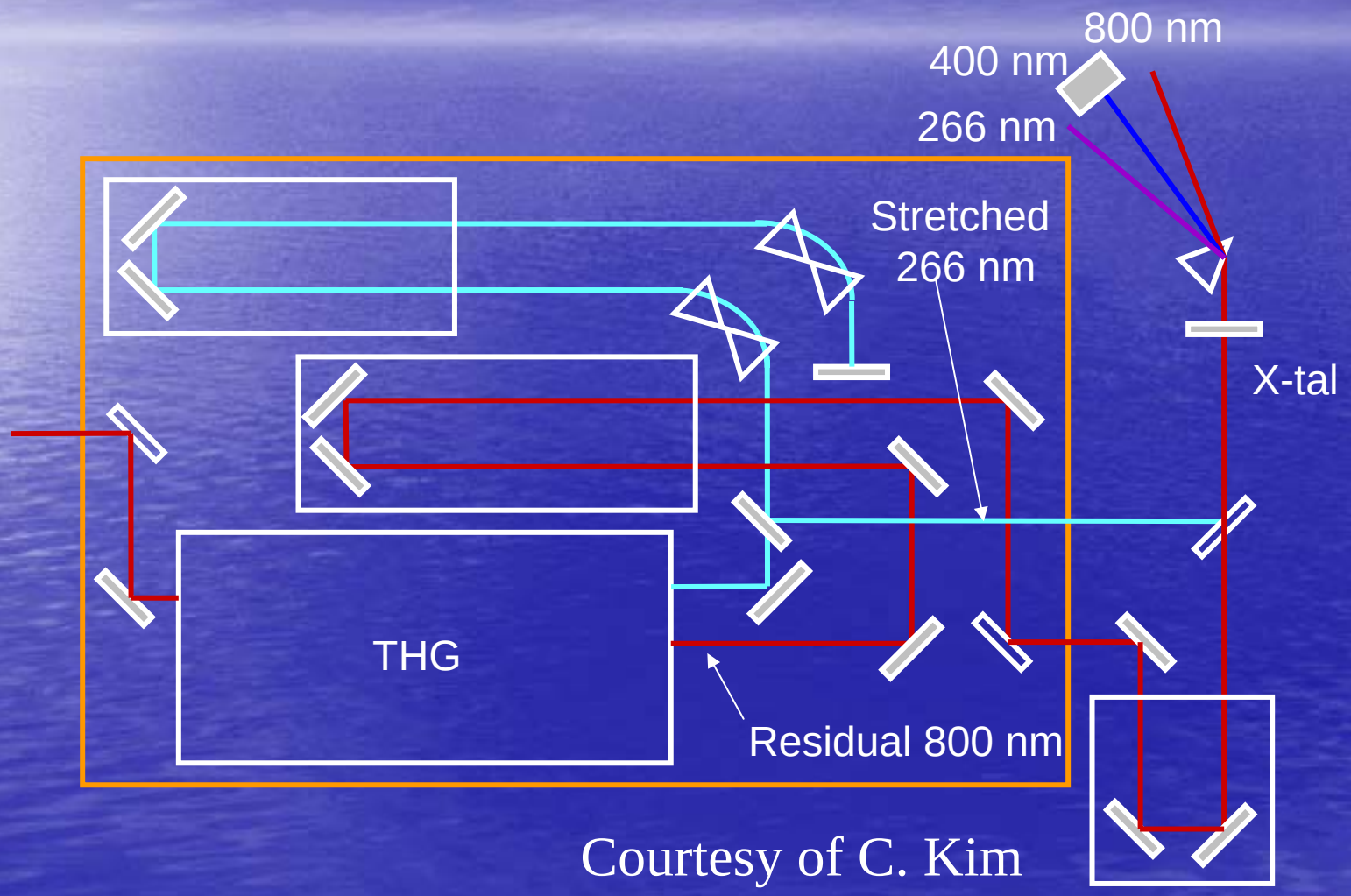
"Red" component of the pulse propagates in glass where group velocity is smaller than for the "blue" component

Courtesy of C. Kim

2. Passive micro-pulse preparation

- Prism-pair UV-stretcher + Pulse Stacker

2-3. UV-Stretcher (Prism-Pair)

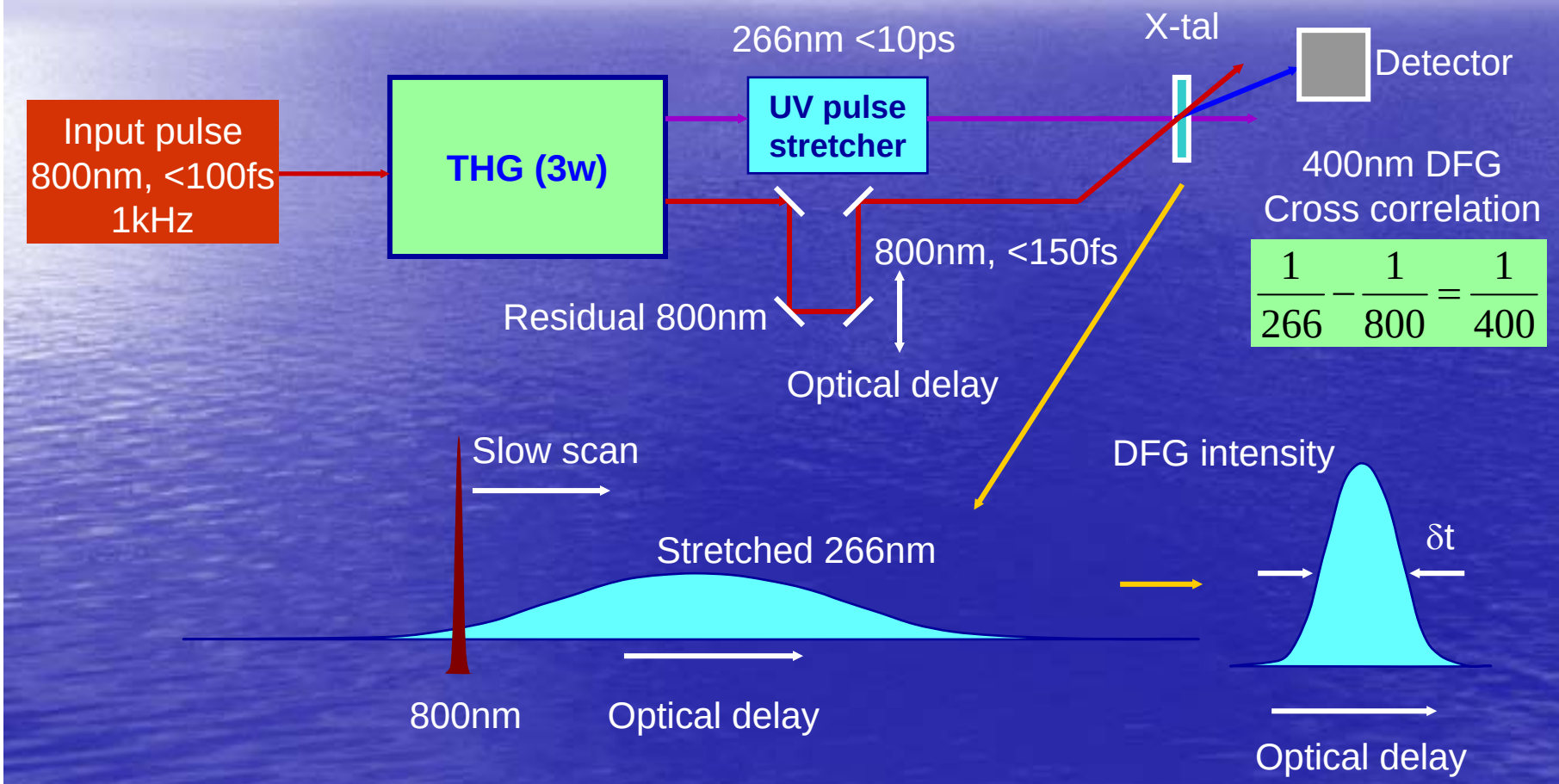


Courtesy of C. Kim

2. Passive micro-pulse preparation

- Prism-pair UV-stretcher + Pulse Stacker

2-4. UV-pulse measurement (Cross Correlator)



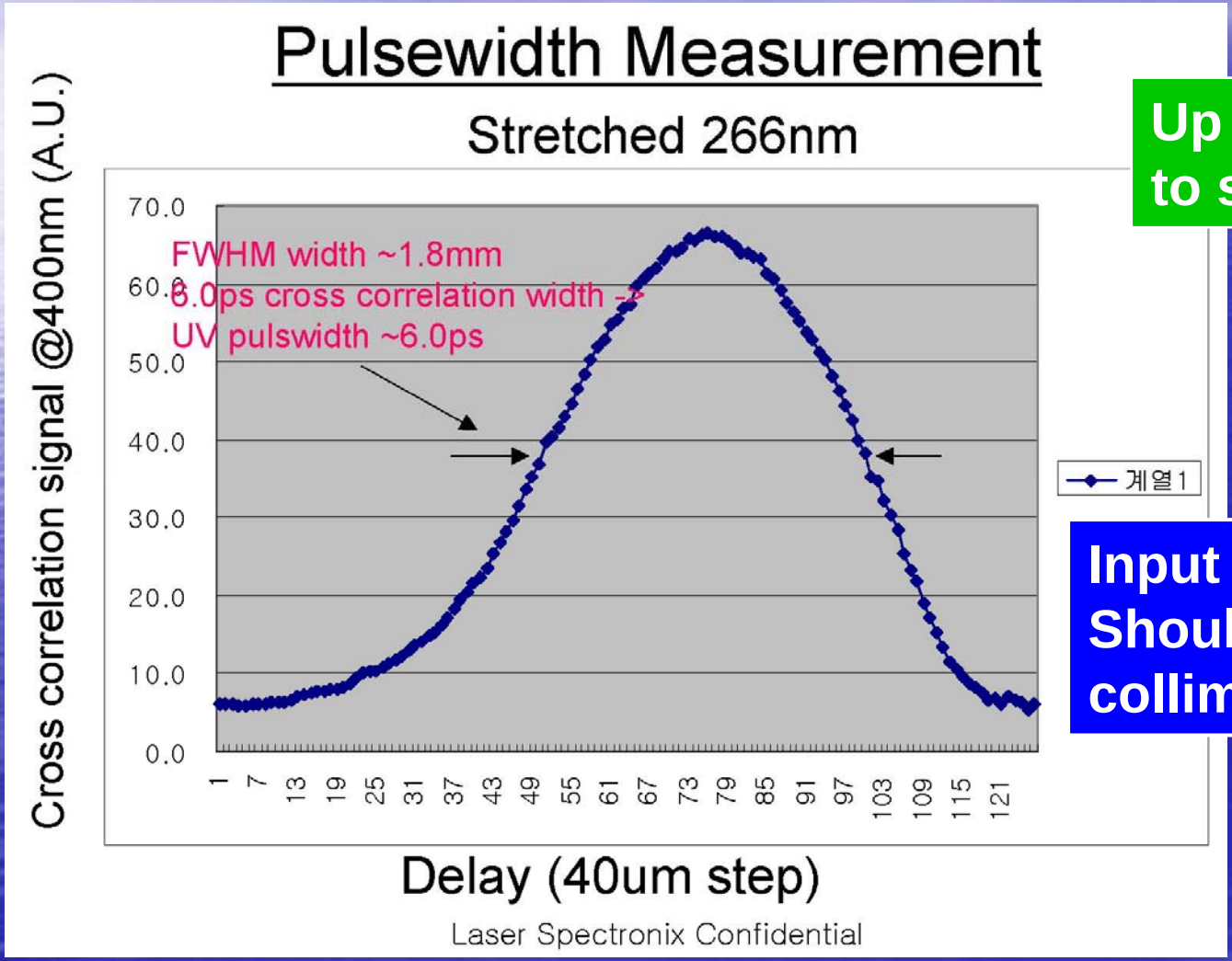
δt measurement -> UV 266nm pulsewidth calculation

Courtesy of C. Kim

2. Passive micro-pulse preparation

- Prism-pair UV-stretcher + Pulse Stacker

2-5. UV-pulse duration (with Cross Correlator)



Up to 6 ps, it possible to shape nicely.

Input UV-laser Should be perfectly collimated to prism-pair.

Courtesy of C. Kim

3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

3-1. Candidates of SLM for UV-Laser pulse shaping

3-1-1. DAZZLER (Acousto-optics)

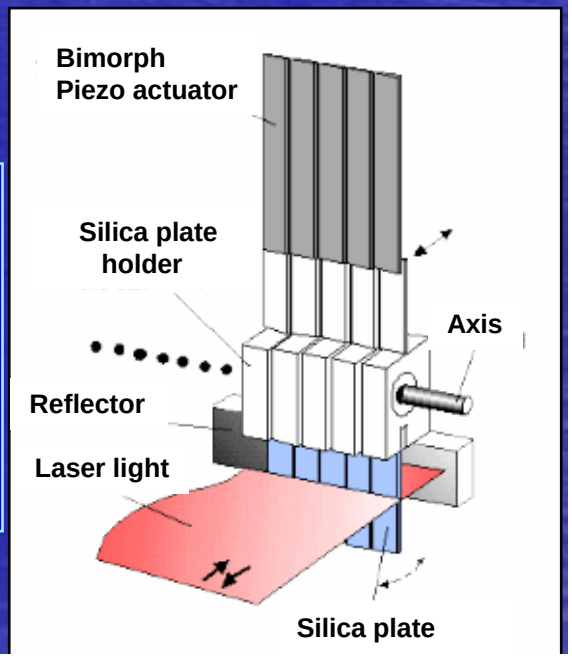
Simultaneously and independently performing both spectral Phase & Amplitude of ultrafast laser pulses. (*FASTLITE*)

3-1-2. Fused-silica based SLM

Utilizing silica plates

- Directly shaping for UV-Laser
- Higher Laser power threshold
- Possible to shape ~ms pulse train

~ However long-term drifting (At present status, very sensitive to temperature fluctuation) ~

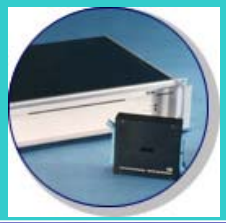


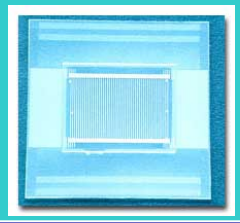
~ Computer-controllable silica plates complex ~

Simulated Annealing Algorisms (SA)

Compared with commercial SLM

Maker name	Cyber Laser Inc.	CRI	Meadlark	Jenoptik	Hamamatsu	FASTLITE
Product name	SP8 test-SLM	SLM-128	SSP -256 - λ	SLM640/12	X8267	T-UV200-300
wavelength	200 nm～ limited by gratings & optics	400 nm～	400 nm～	400 nm～	350 nm～	200~300nm
transparency	99%	94%	90%	95%	90% (Reflective)	50%
Total efficiency (0.1 nm/pixel)	20% in IR depends on input bandwidth (20 nm)	~ 40% in IR depends on input bandwidth (20 nm)	~ 70% in IR input bandwidth (< 26nm)	~ 70% in IR input bandwidth (< 64 nm)	~ 70% in IR input bandwidth (< 100 nm)	30-50% in UV depends on shaping
Damage threshold for amplified pulses (10 Hz)	1TW/cm^2 (100mJ/pulse)	500MW/cm^2 (50 μ J/ pulse)	500MW/cm^2 (50 μ J/ pulse)	2 GW/cm^2 (100 μ J/ pulse)	2GW/cm^2 (200 μ J/ pulse)	1GW/cm^2 (100 μ J/ pulse)
Operating speed	50ms	100 ms	100 ms	100 ms	500 ms	0.04ms
Pixel number	48	128	256	640	1024	None (No dead space)
others	Whole system is packaged	Only SLM	Only SLM	Only SLM	Only SLM	Whole system is packaged



Fused silica type: Mechanical control

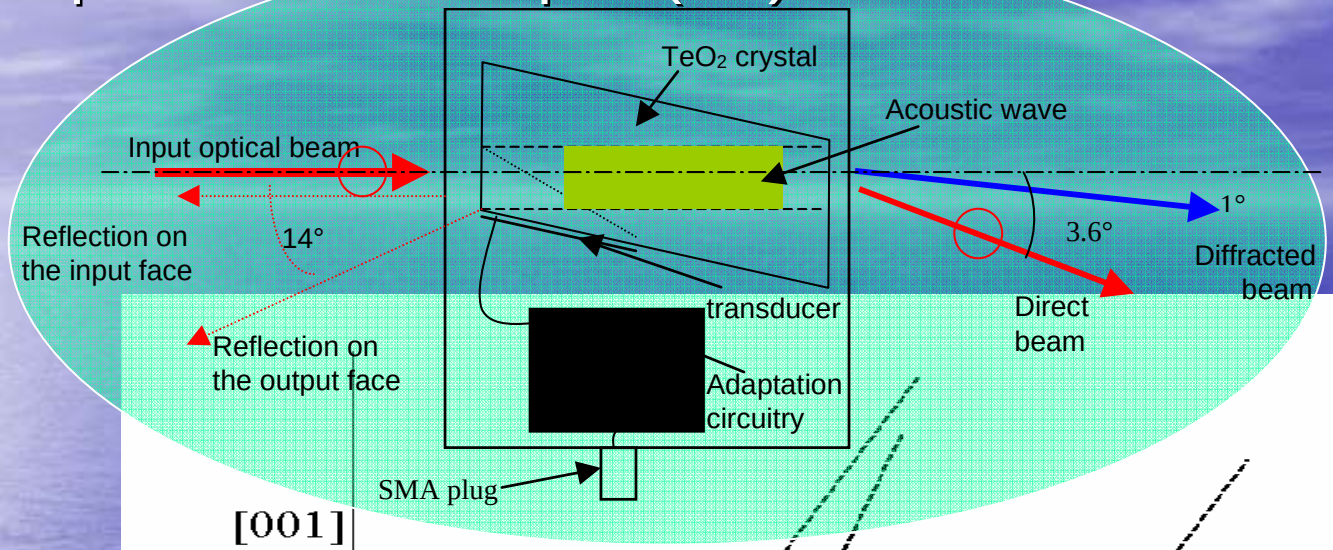
Liquid crystal type

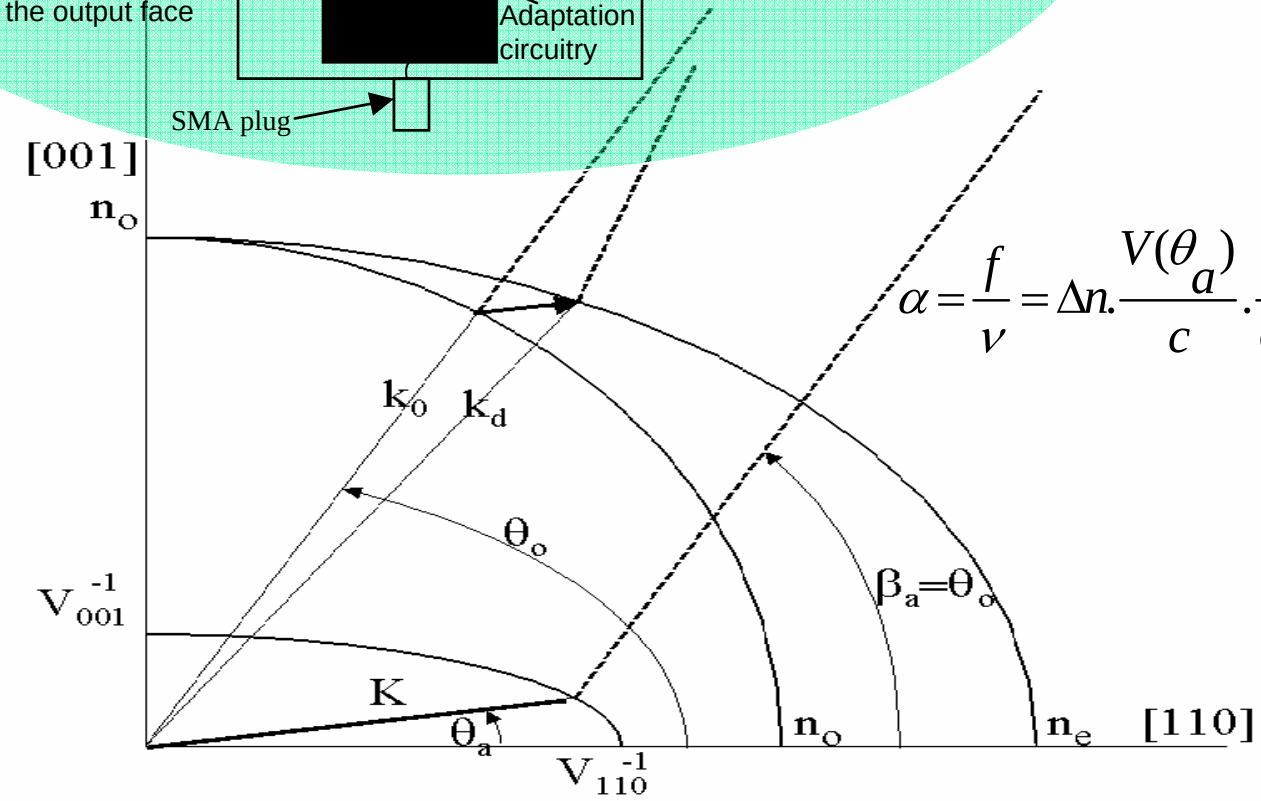
Electrical addressed type

AOPDF type

3-1-1. DAZZLER (Acousto-optics)

Principle of Acousto Optic (AO) ~ DAZZLER ~





$$\alpha = \frac{f}{v} = \Delta n . \frac{V(\theta_a)}{c} . \frac{\cos^2\theta_o}{\cos(\theta_o - \theta_a)}$$

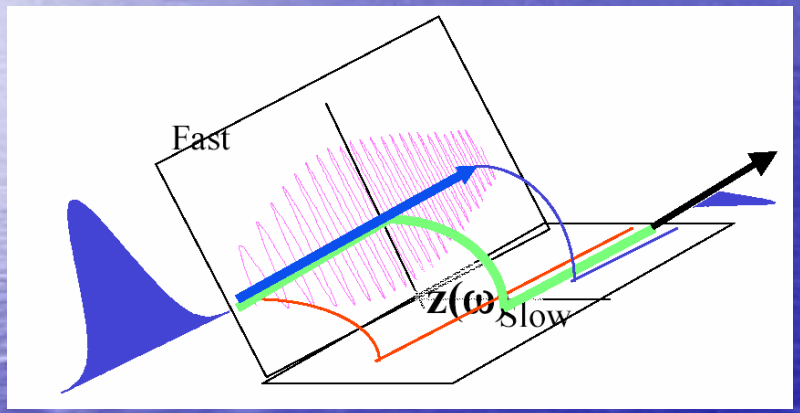
D.Kaplan and P.Tournois J.Phys.IV France **12** (2002) Pr5-69

3-1-1. DAZZLER (Acousto-optics)

Principle of AO Programmable Dispersive Filter: (UV-) DAZZLER

Courtesy of Fastlite

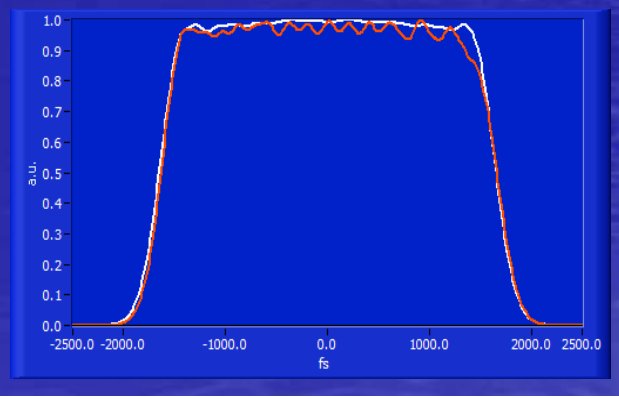
$$E_{out}(t) \propto S(t/\alpha) \otimes E_{in}(t) \quad \text{où} \quad \alpha = \frac{f_{ac}}{f_{opt}} \approx 10^{-7} \Rightarrow \boxed{E_{out}(\omega) \propto S(\alpha\omega) E_{in}(\omega)}$$



Transmitted pulse equals convolution of input pulse and acoustic wave:

- -single crystal design (few cm^3)
- -quantitative shaping in phase and amplitude
- -up to few ps shaping ability.
- -several wavelength available (from IR to UV)

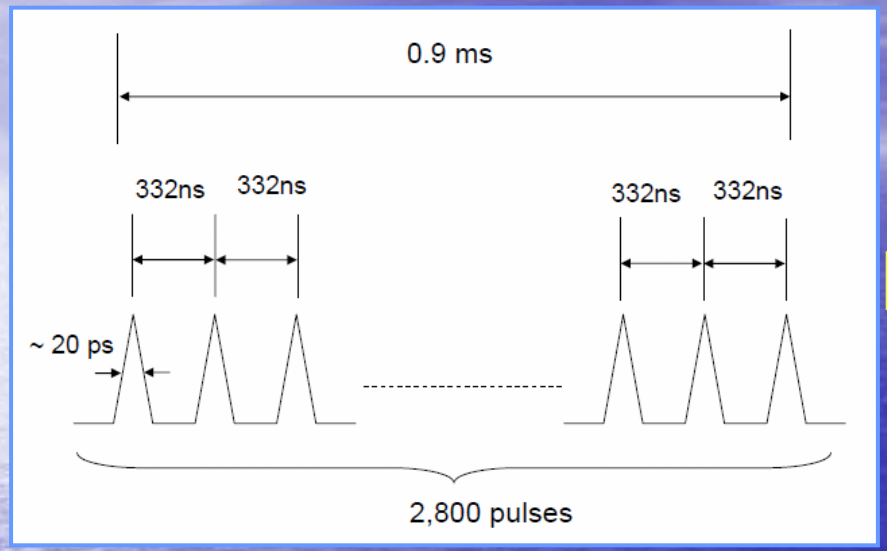
Example of 4ps square pulse made with UV DAZZLER

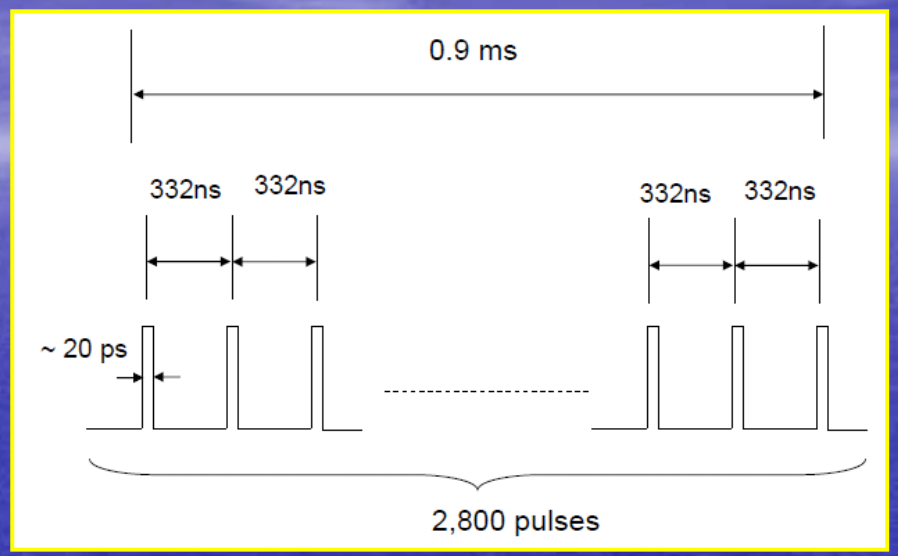


But Damage threshold problem In the UV!

3-1-2. Fused-silica based SLM

Multi-bunch beam with temporal shaping





Multi-bunch laser pulses **without shaping**

With squared shaping

	Others	Silica-plate SLM
Pulse energy	X (~0.1mJ/pulse)	O (~100mJ/pulse)
Repetition	X (~30kHz)	O (No refreshing time)

Silica-plate SLM sounds good for multi-bunch beam shaping! However it has difficulty of long-term mechanical stability & clipping loss for laser with broadband spectrum !!

3-1-2. Fused-silica based SLM

Pulse shape control with Silica-plate SLM

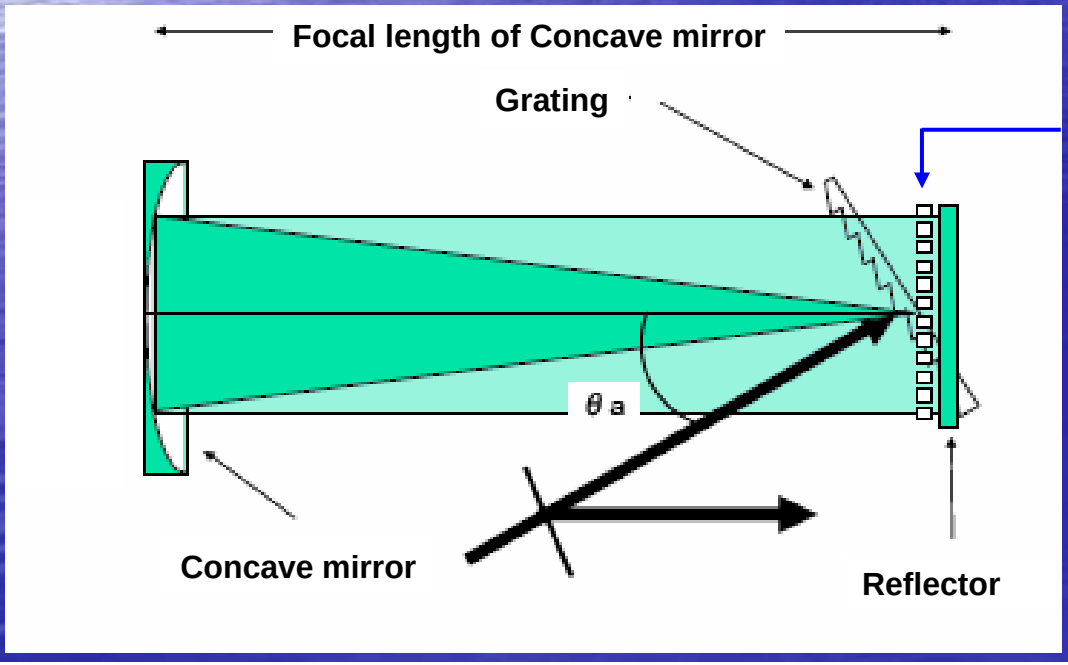
Short laser pulse

Grating breaks a light pulse into a spectrum
(Transform time distribution to spatial distribution)

SLM modulates phase distribution in spectrum

Grating transforms the spectrum into a light pulse

Shaped laser pulse



Utilizing silica plate modulator

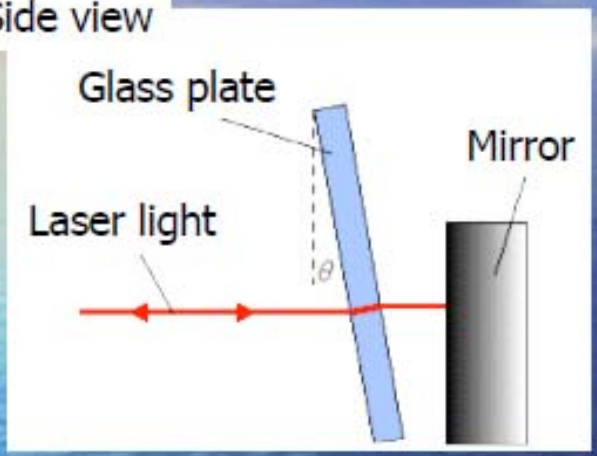
- Directly shaping for UV-Laser
- Higher Laser power threshold
  < 100 mJ/cm2

3-1-2. Fused-silica based SLM

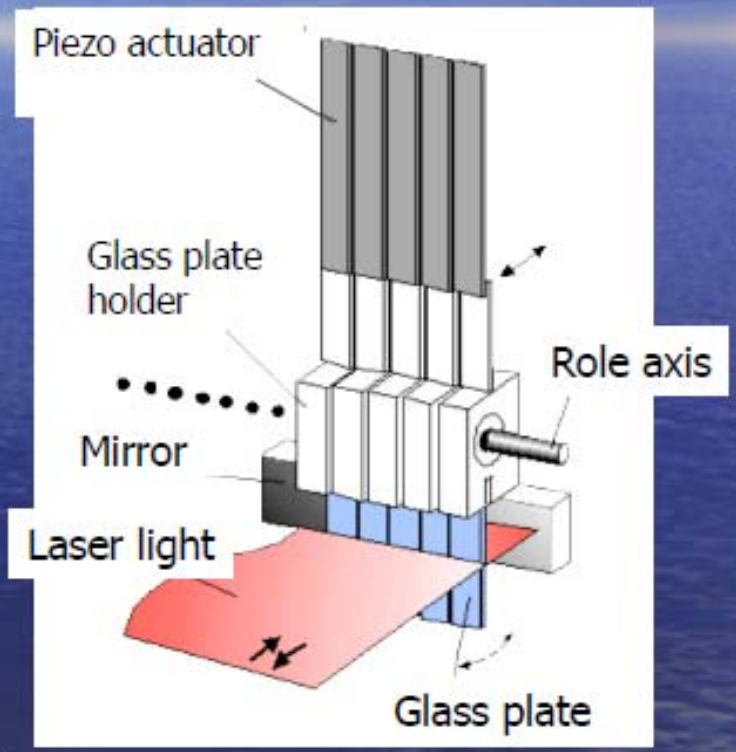
Changing angle of Silica-plate to modulate optical phase

Principle of glass plate type spatial light modulator

Side view



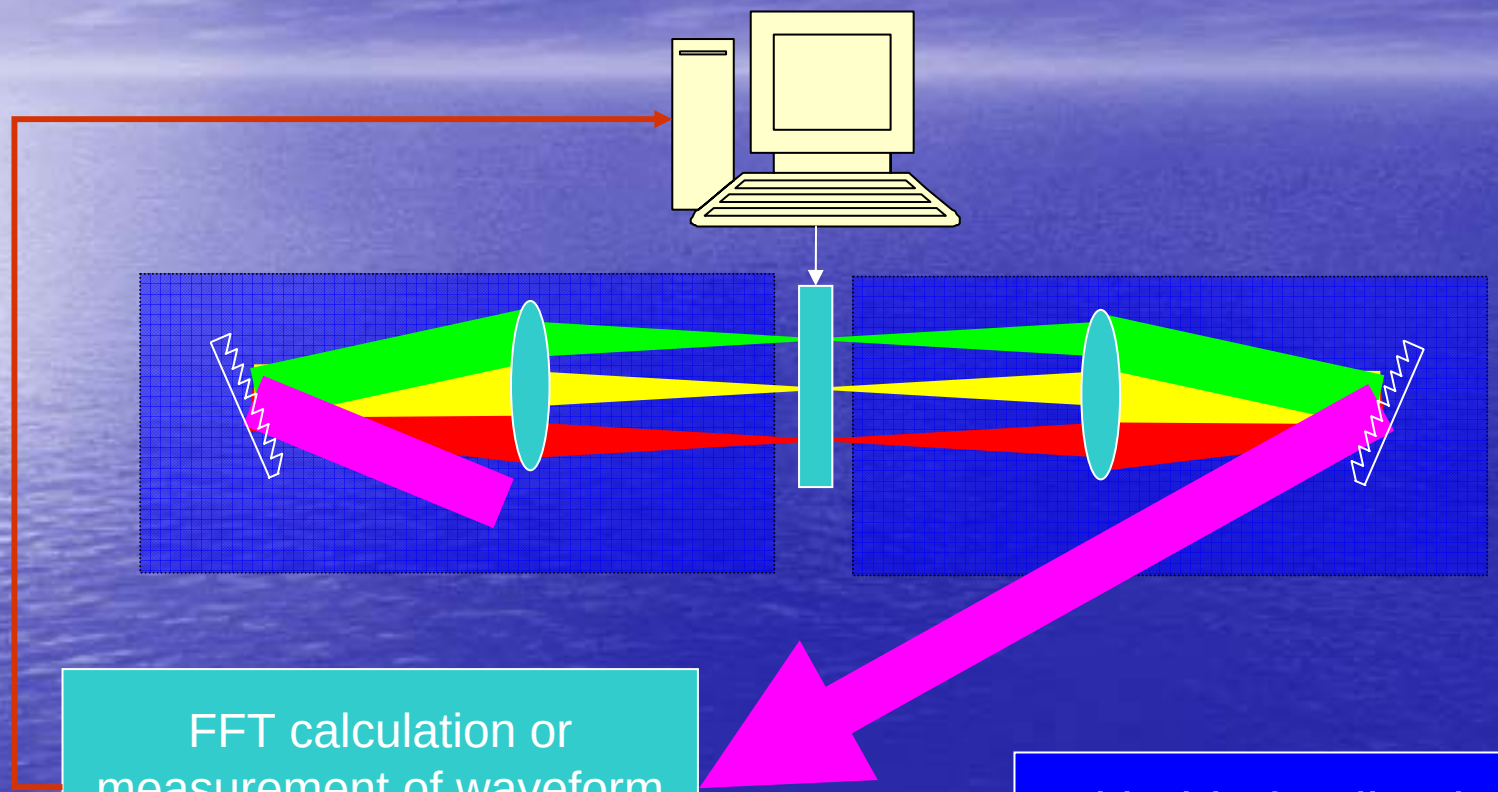
$$\phi(\theta) = \frac{2\pi d}{\lambda}\left(\sqrt{n_2^{\,2} - n_1^{\,2}\sin^2\theta} - n_1\cos\theta\right)$$



Phase of femtosecond pulses is retarded by tilting glass plate as shown in above equation.

3-1-2. Fused-silica based SLM

Schematic figure of waveform feedback control system



FFT calculation or measurement of waveform by streak camera

With this feedback system, pulse waveform will automatically optimize to desired one.

3-1-2. Fused-silica based SLM

Results of Pulse Shaping with SLM

A) First test for computer-aided **SLM** was done in **IR**

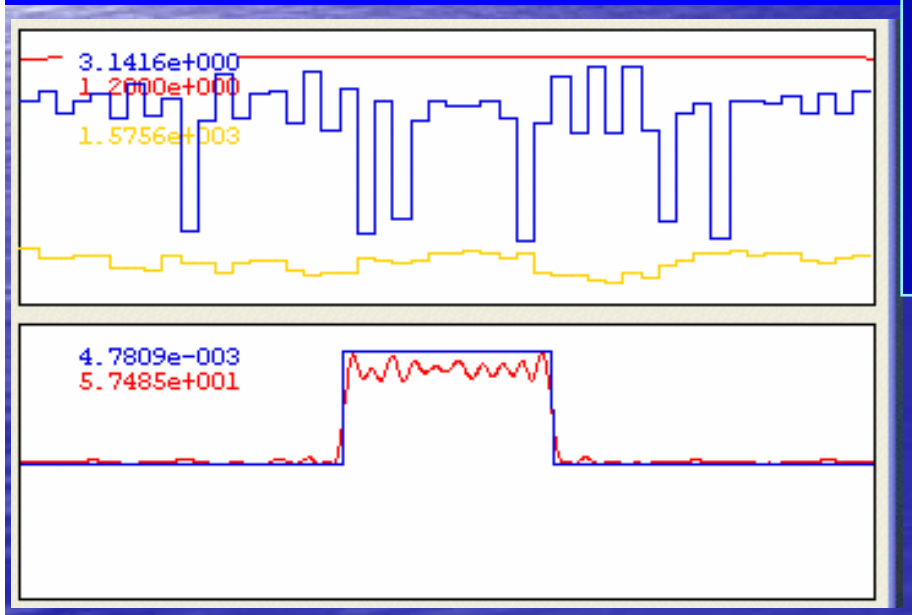
→ **Rectangular Pulse (width range: 2-12 ps)**

(rising-time: 800fs)

B) Computer-aided **SLM** in UV

→ **Size will be bigger (~5 times)**

Incident Pulse: Fourrier Transform Limit
Calculate Phase Spectra!



◆ **Possible to shape ~ms pulse train**

~ **However long-term drifting (At present status, very sensitive to temperature fluctuation)** ~

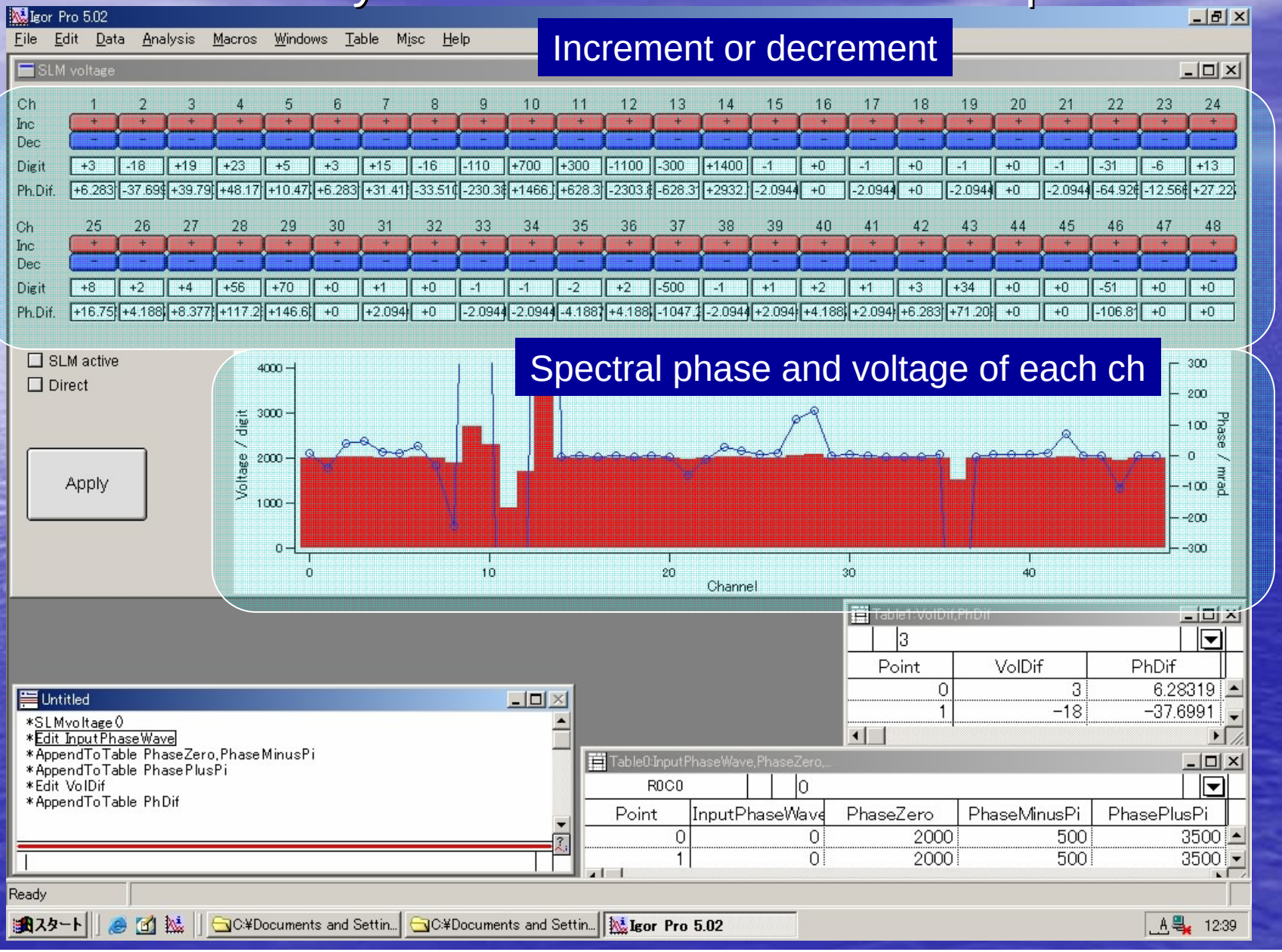
Short time fluctuation ：<0.1mrad（0.01π）
Temp. dependence ：<0.4mrad(0.04π)/℃
Long-term drift ：<0.5mrad(0.05π)/6 days

↓

Manually correction (every 2 weeks)

3-1-2. Fused-silica based SLM

Manually control software under development



3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

3-2. Difficulty of UV-Laser pulse measurements

3-2-1. Streak camera (Hamamatsu fesca-200)

In IR temporal resolution of 200 fs, but.....

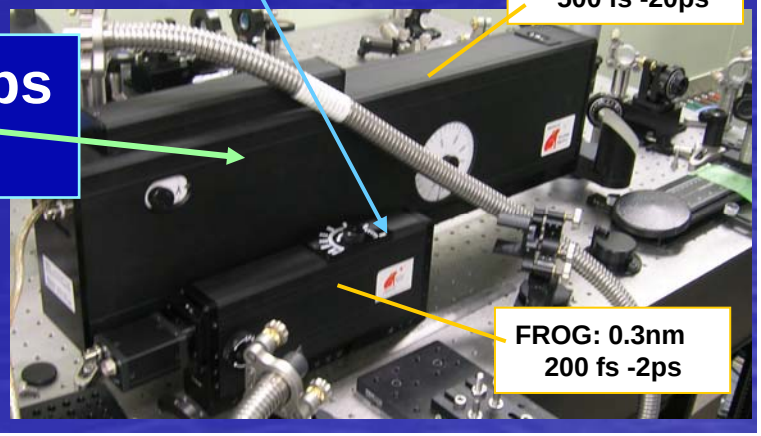
- Temporal resolution of 700 fs in UV
- Possible to measure up to 800 ps

3-2-2. FROG or SPIDER

Possible to measure just in IR (normally, <5 ps)

- Specially ordered FROG for 20 ps
- UV-Dazzler as FROG or SPIDER

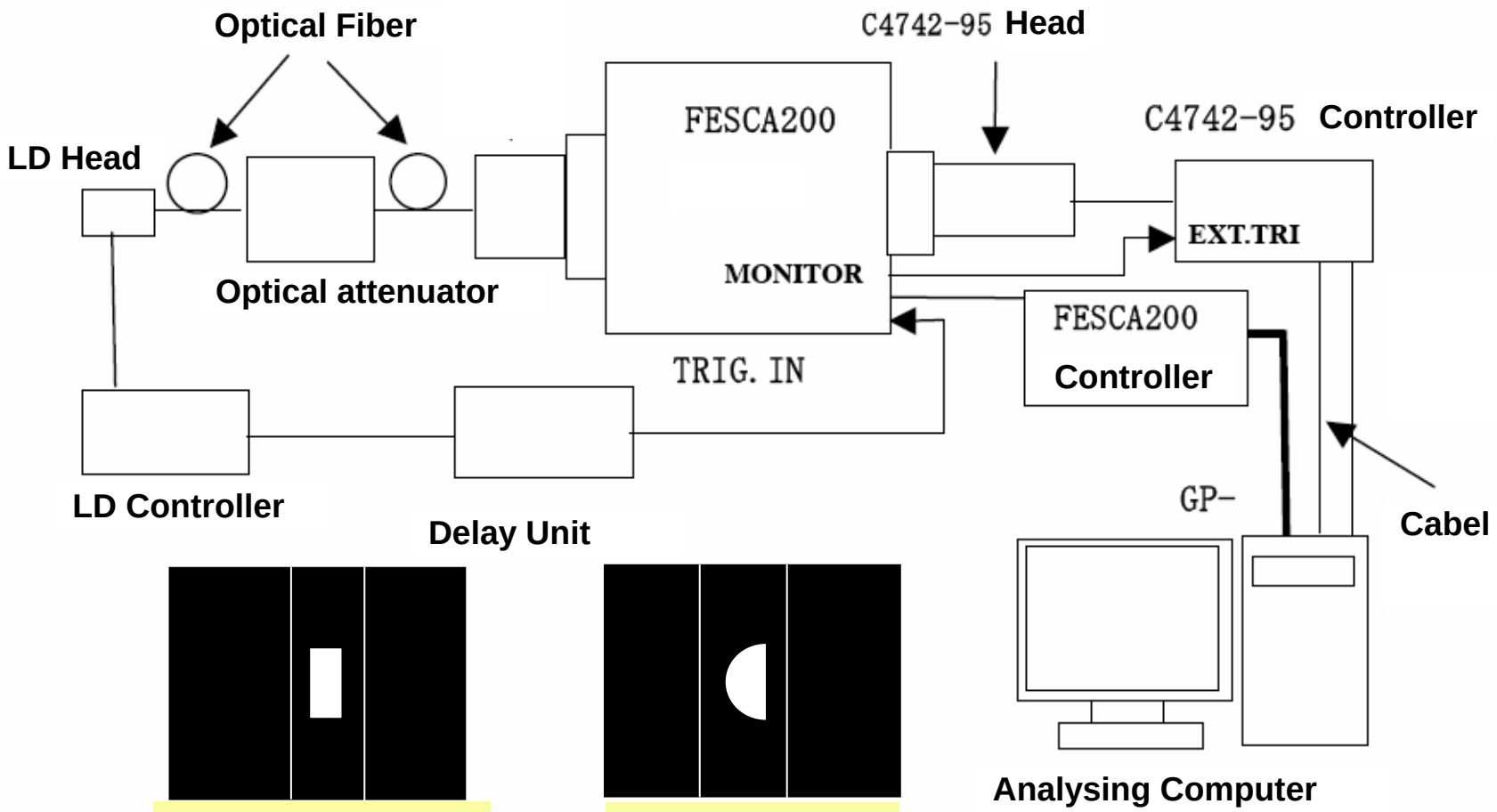
PHAZZLER (normally, <5 ps) can be one solution for micro-pulse measurement!



3-1-2. Fused-silica based SLM

Auto-pulse-evaluation system with Fesca-200

Feedback loop software is under development



Square Pulse

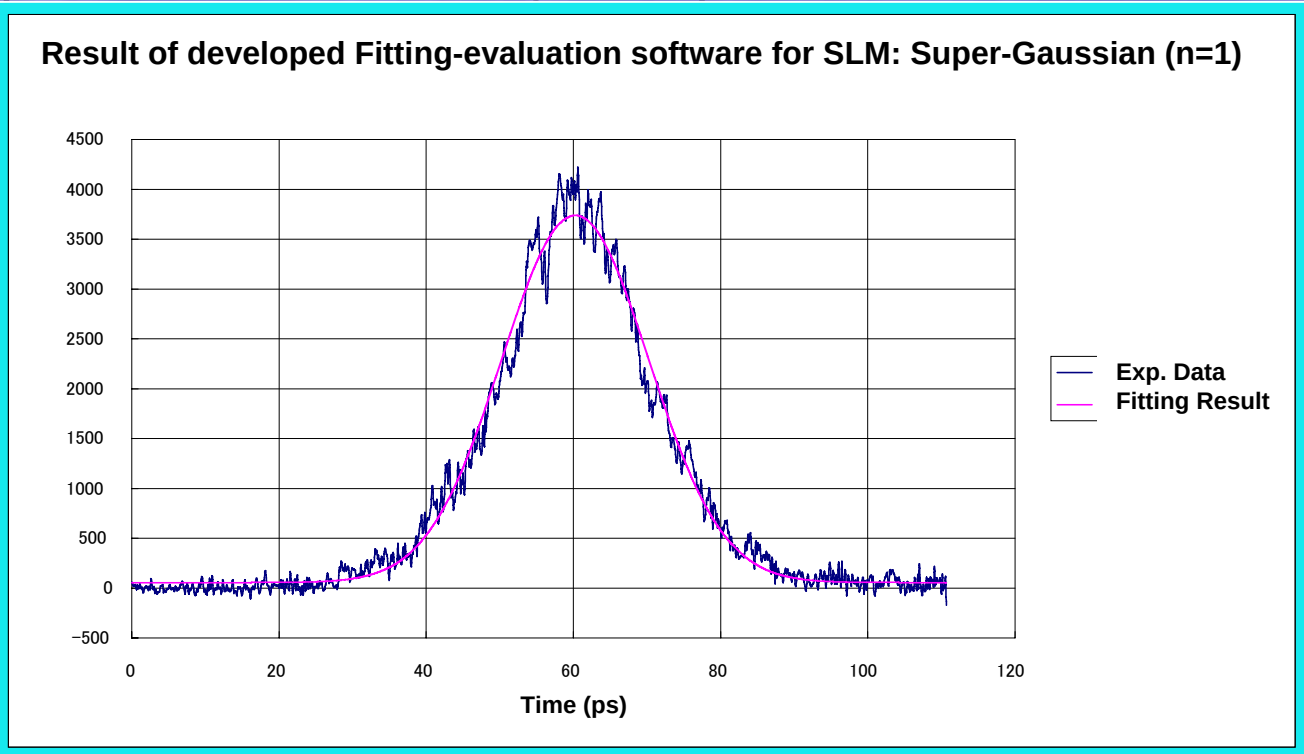
Ellipsoidal

3-1-2. Fused-silica based SLM

Auto-pulse-evaluation system with Fesca-200

Test for Gaussian temporal profile

(Super-Gaussian fitting: n=1)



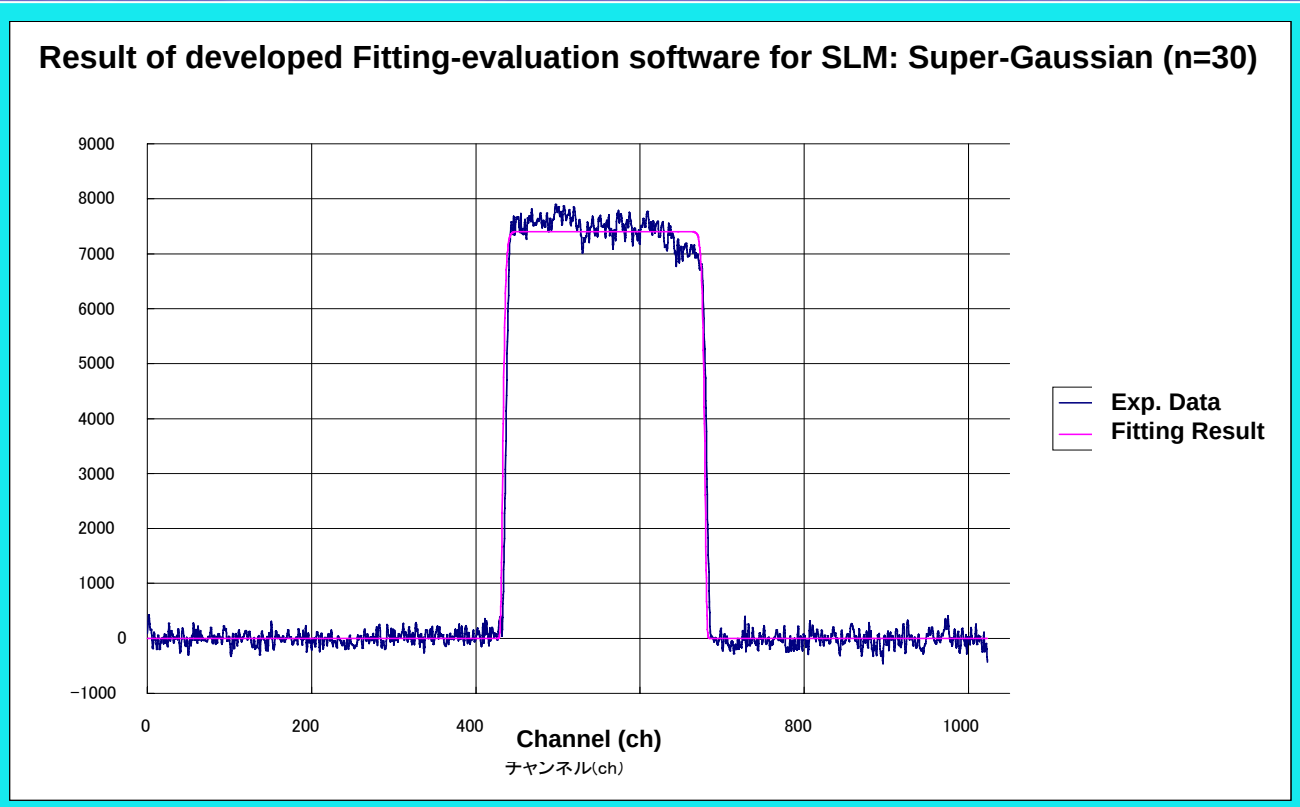
[OutputParameter]		unit
① Square mean (Error)	21169.075	count
② Offset of intensity: C	55.5431	count
③ FWHM of fitting pulse	23.9149	ps
④ Setting (aimed) FWHM	20	ps
⑥ FWHM of raw data	18.9993	ps
⑦ Rising time of raw data	20.2268	ps

3-1-2. Fused-silica based SLM

Auto-pulse-evaluation system with Fesca-200

Test for Square temporal profile

(Super-Gaussian fitting: n=30)



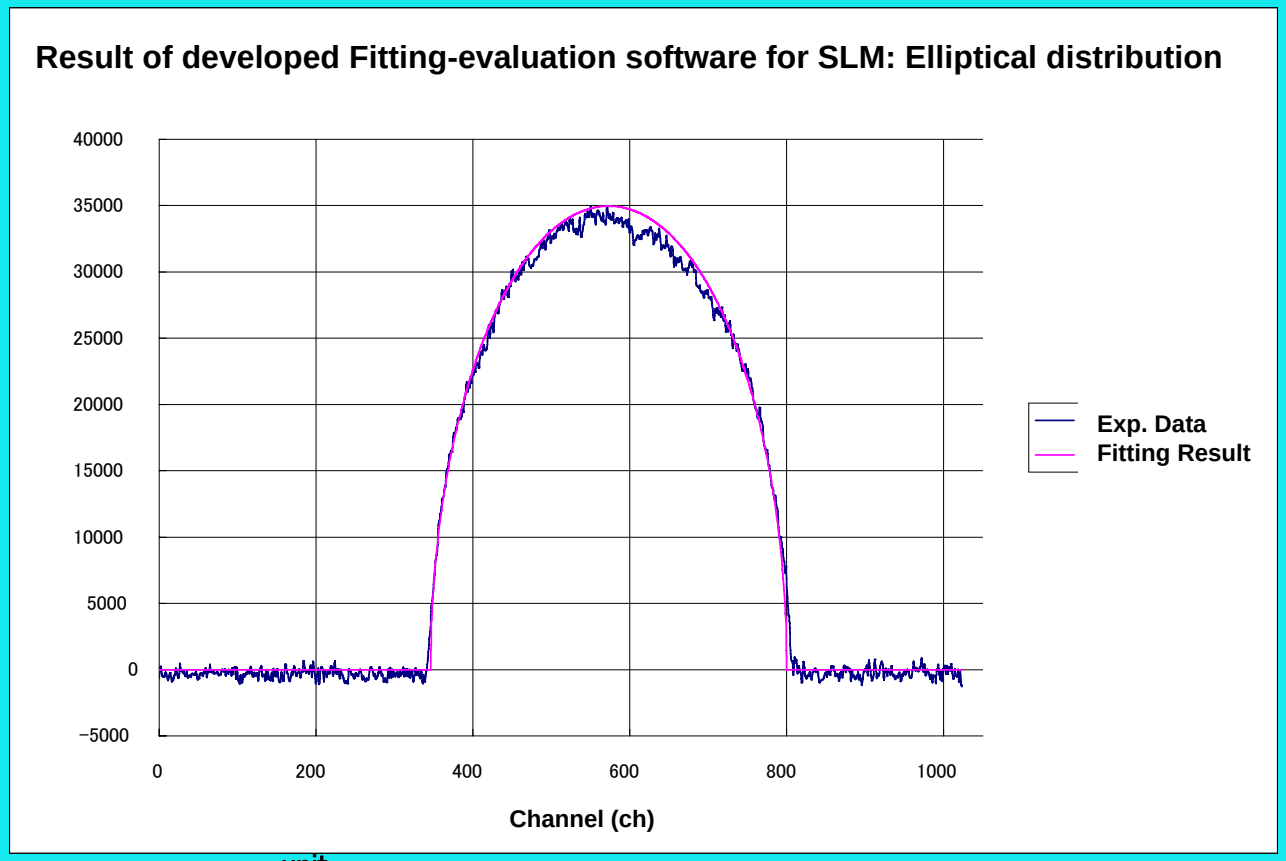
[OutputParameter]

①	Square mean (Error)	111334.4	count
②	Offset of intensity: C	1.132	count
③	FWHM of fitting pulse	245.6487	ch
④	Setting (aimed) FWHM	244	ch
⑥	FWHM of raw data	243.9206	ch
⑦	Rising time of raw data	7	ch

3-1-2. Fused-silica based SLM

Auto-pulse-evaluation system with Fesca-200

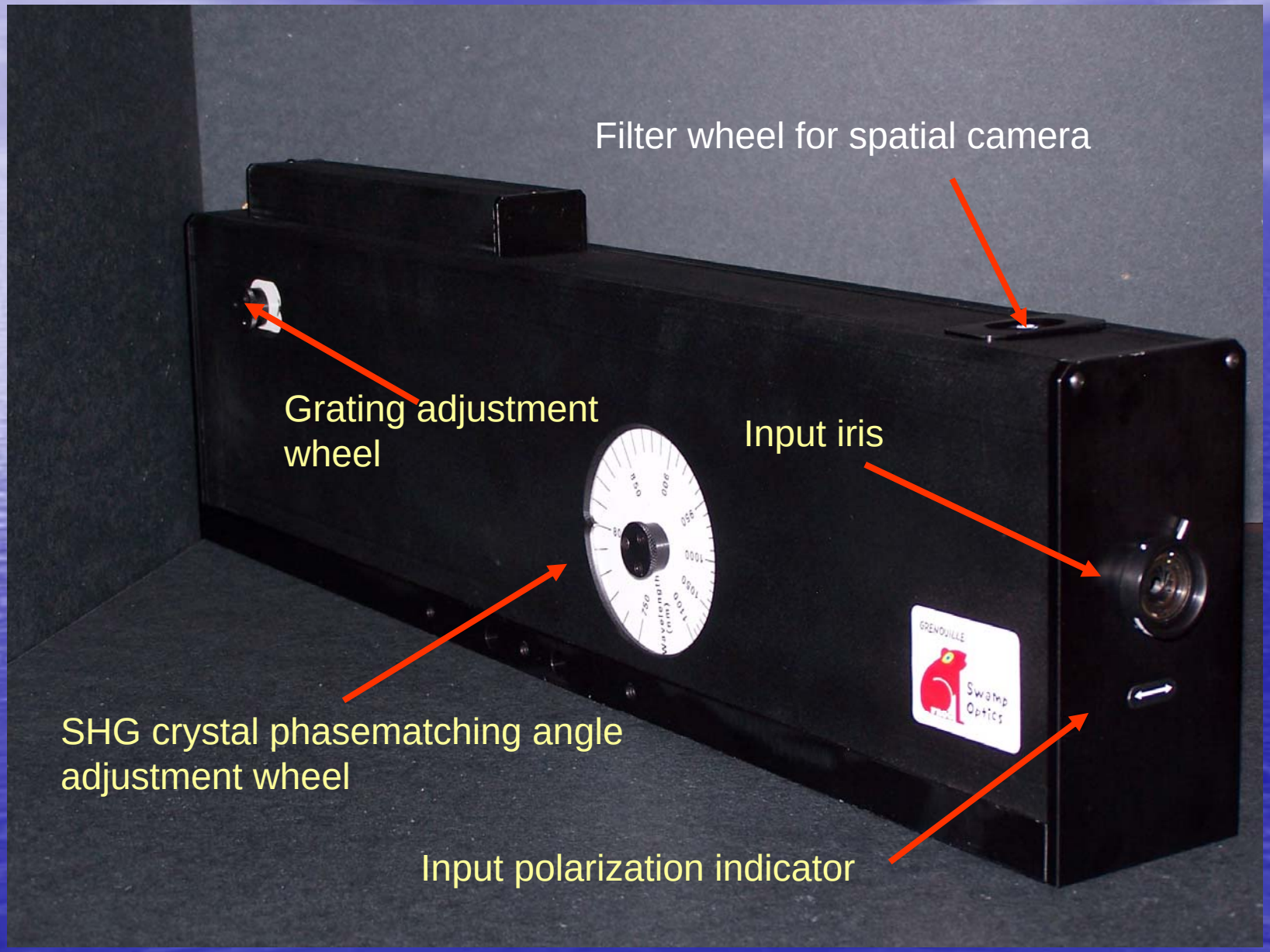
Test for ellipsoidal temporal profile



[OutputParameter]		unit
① Square mean (Error)	618409.9	count
② Offset of intensity: C	0	count
③ FWHM of fitting pulse	393.4975	ch
④ Setting (aimed) FWHM	393	ch
⑥ FWHM of raw data	395.8878	ch
⑦ Rising time of raw data	139	ch

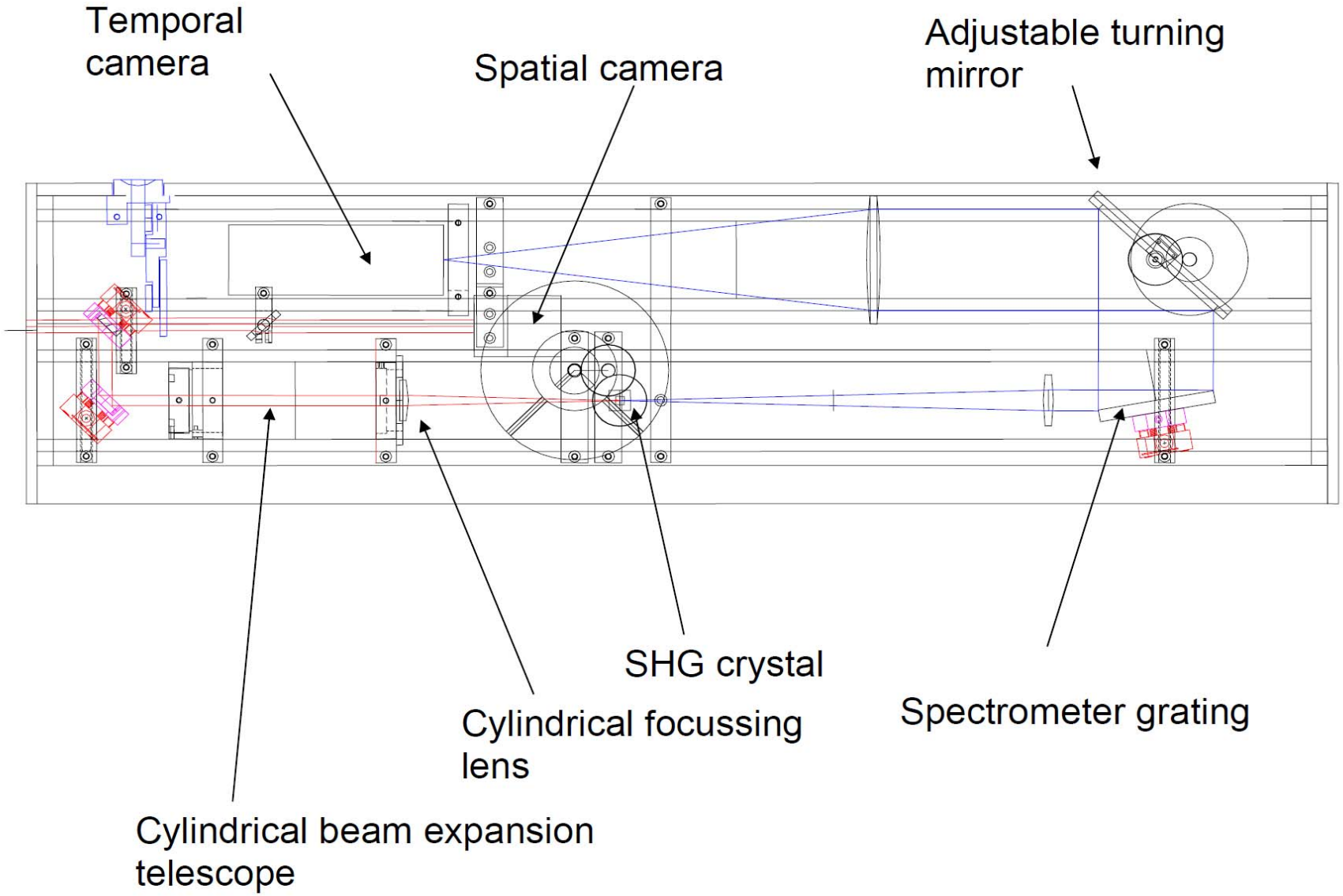
3-2-3. GRENOUILLE/FROG: specially ordered by SP8

The information about GRENOUILLE model UPM 8-500



3-2-3. GRENOUILLE/FROG: specially ordered by SP8

Inside of model UPM 8-500



3-2-3. GRENOUILLE/FROG: specially ordered by SP8

This UPM 8-500 vs. next series 8-200

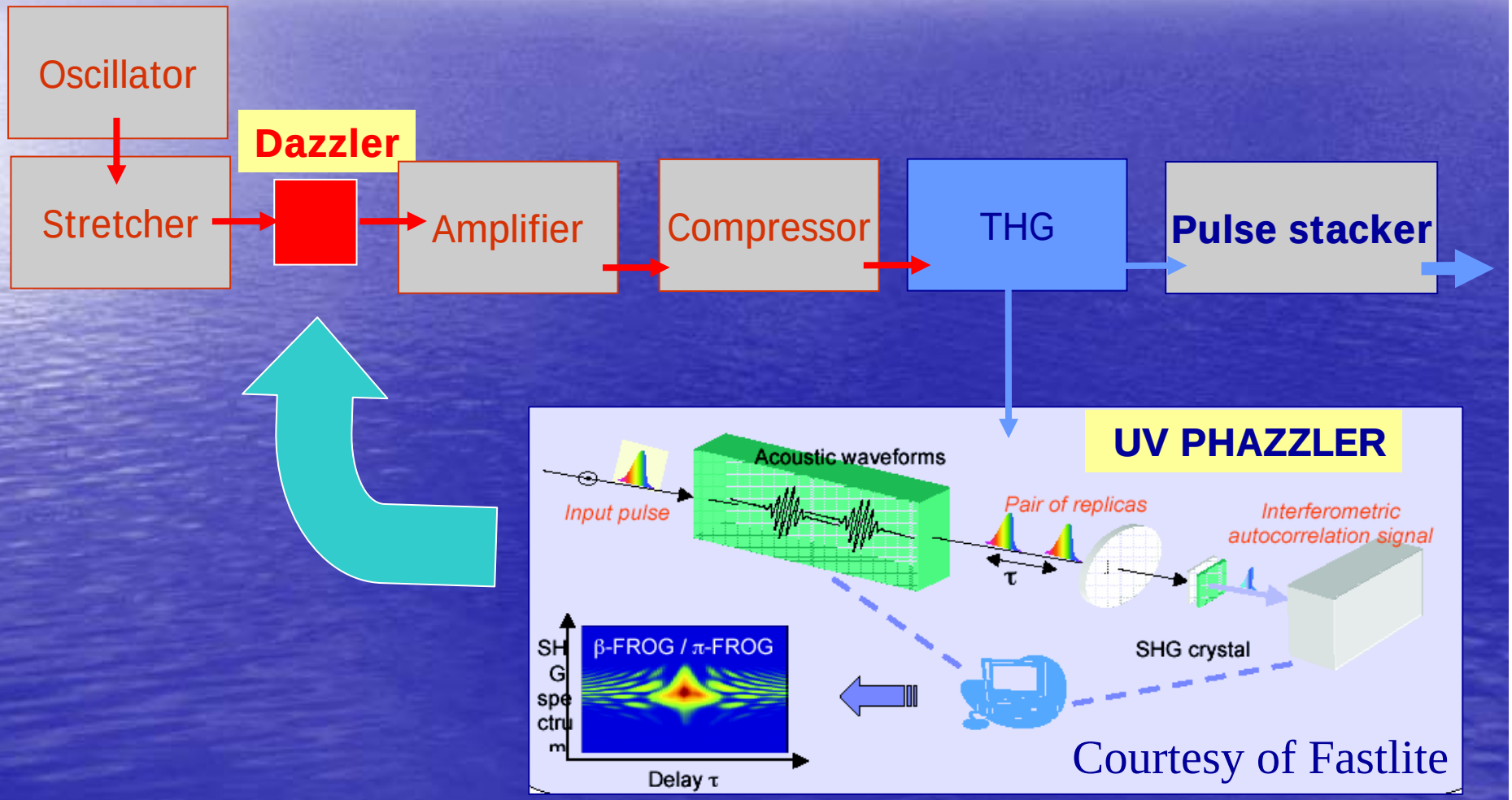
	UPM 8-200	UPM 8-500*
Pulse Length Range	150 fs - 2 ps	500 fs – 10 ps
Max. Pulse Bandwidth	20 nm	12 nm
Spectral Resolution	0.23 nm	0.05 nm

- So, better spectral resolution will allow the ability to resolve fine features in the temporal and spectral domains of the measured pulse. This contributes to a more accurate measurement of the pulse parameters.

3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

3-3. Combination with DAZZLER shaping in IR, and UV pulse measurement with feedback loop.



Courtesy of Fastlite

3. Adaptive micro-pulse preparation

3-4. Features of PHAZZLER MEASUREMENTS

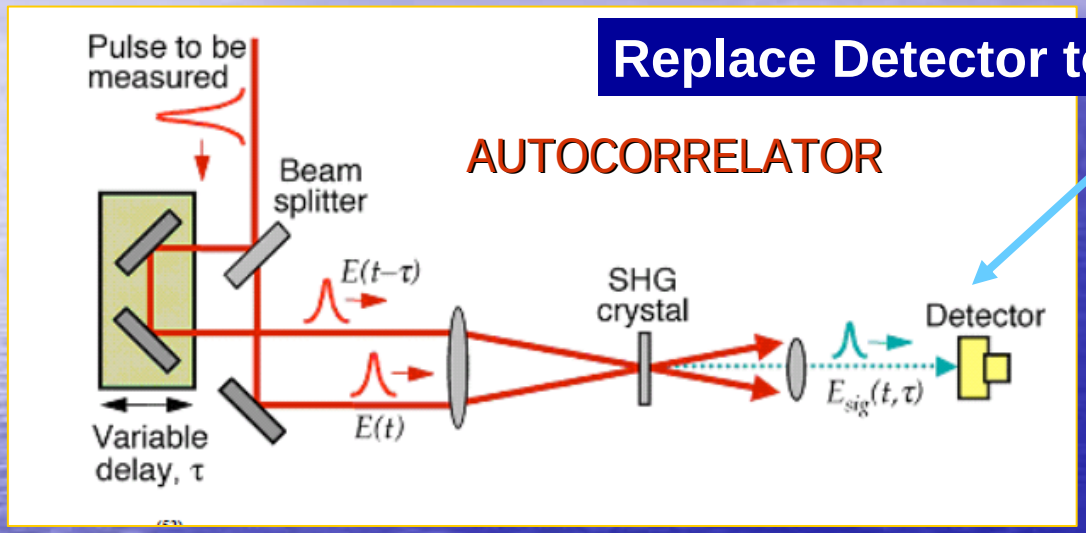
- Design based on a single beam geometry
  - Exceptional stability, reproducible results, user independent
  - Extreme ease of use (no calibration, very straightforward alignment procedure)
- FROG, SPIDER, AUTOCORRELATION within the same instrument by simply flipping a computer switch
  - Single shot, non iterative spectral phase and amplitude characterization with the SPIDER method
  - FROG (Intensimetric and Interferometric available) traces for complex pulse shapes (multiple pulses, large Time Bandwidth products)
  - Interferometric AutoCorrelation and Intensimetric Autocorrelation available
- Tunable wavelength range

3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

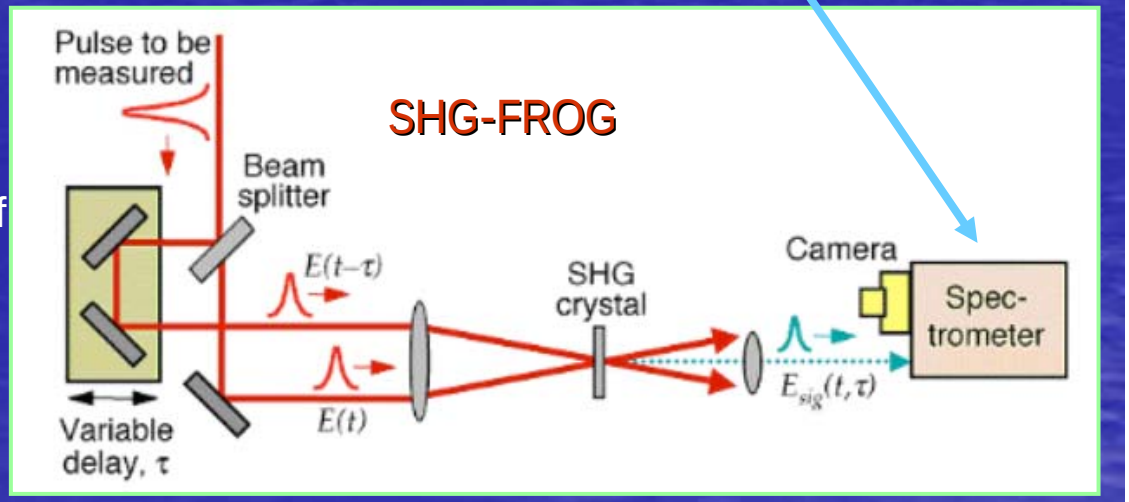
3-4-1. Conventional AUTOCORRELATOR & SHG－FROG

Replace Detector to Spectrometer for FROG



http://www.physics.gatech.edu/gcuo/images/others/

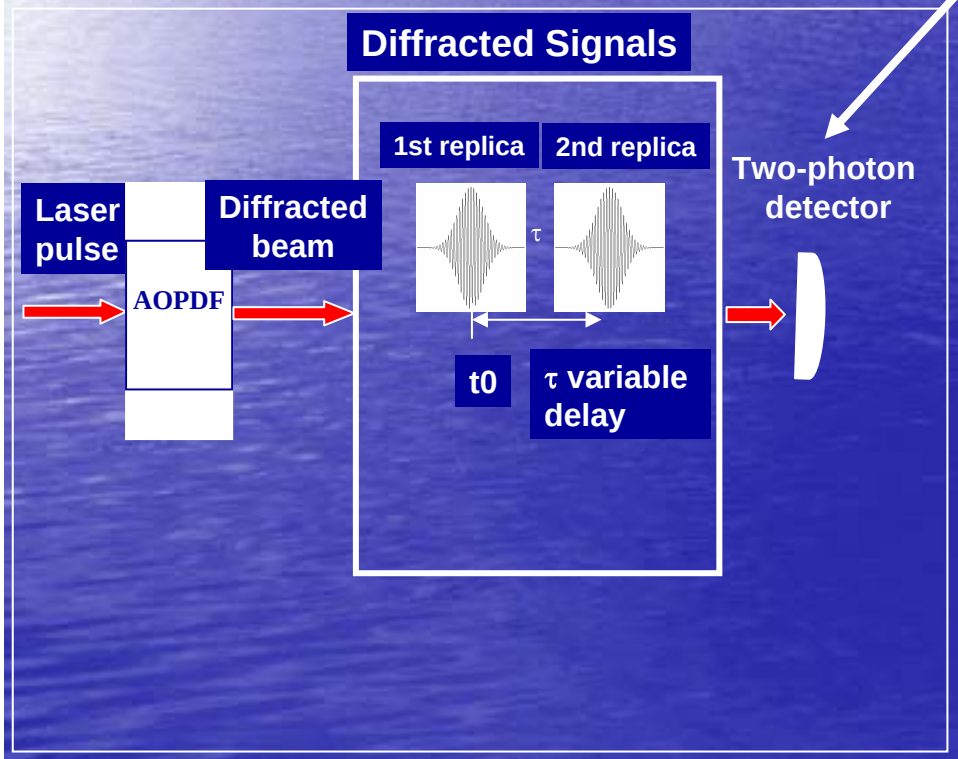
AC_fig01.gif ; FROG_fig05.gif



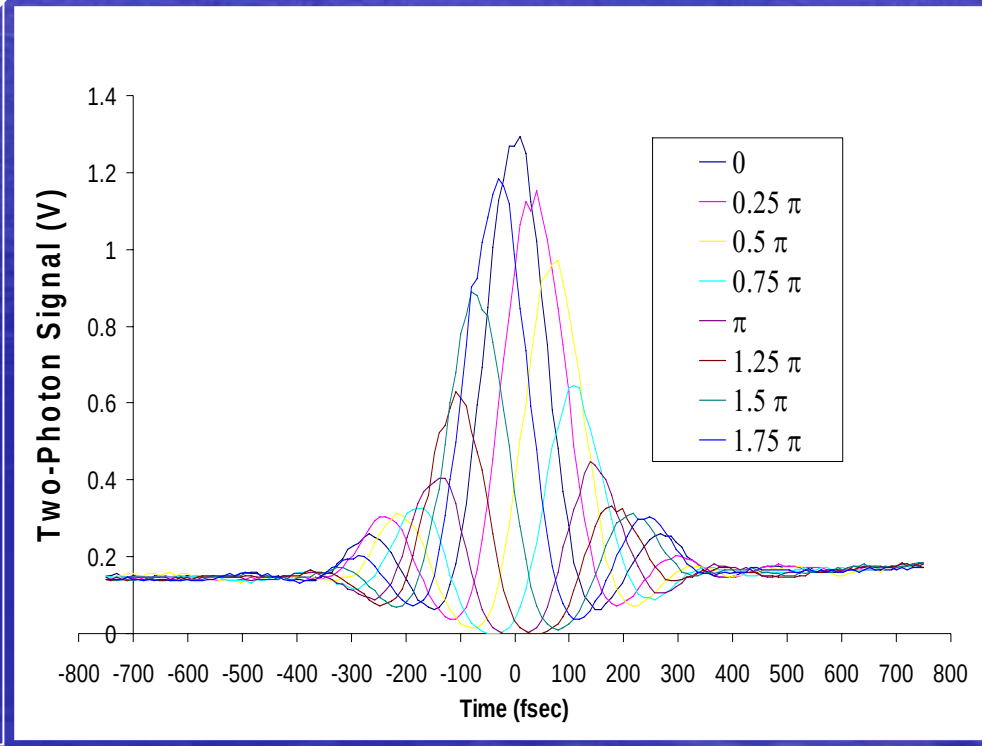
3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

3-4-2. BASEBAND INTERFEROMETRIC AUTOCORRELATION PULSE MEASUREMENTS with DAZZLER ~ PHAZZLER ~



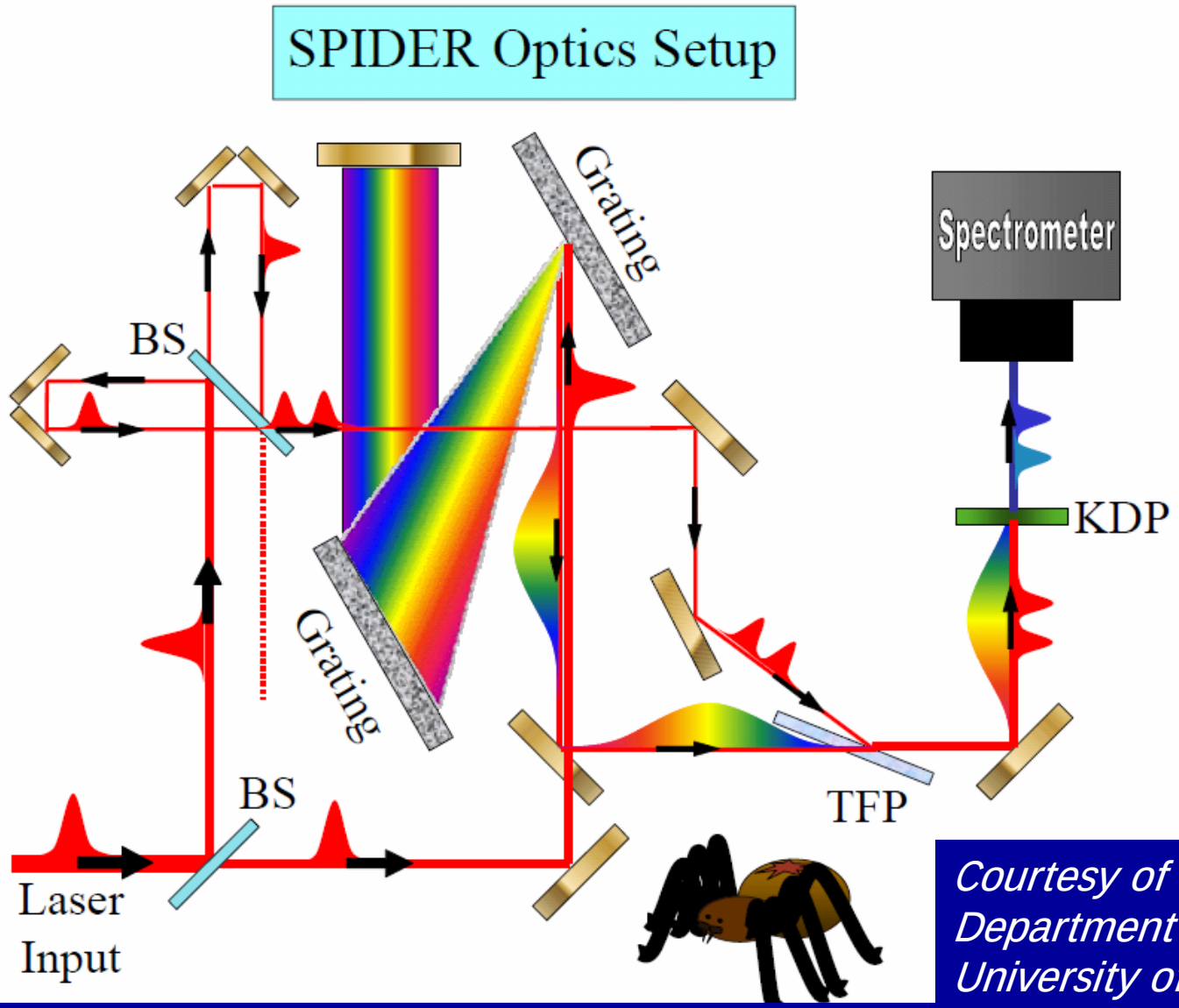
Spectrometer for FROG



Courtesy of Fastlite

3-4-3. SPIDER as a perfect pulse characterization

~ Conventional SPIDER CONFIGRATION ~



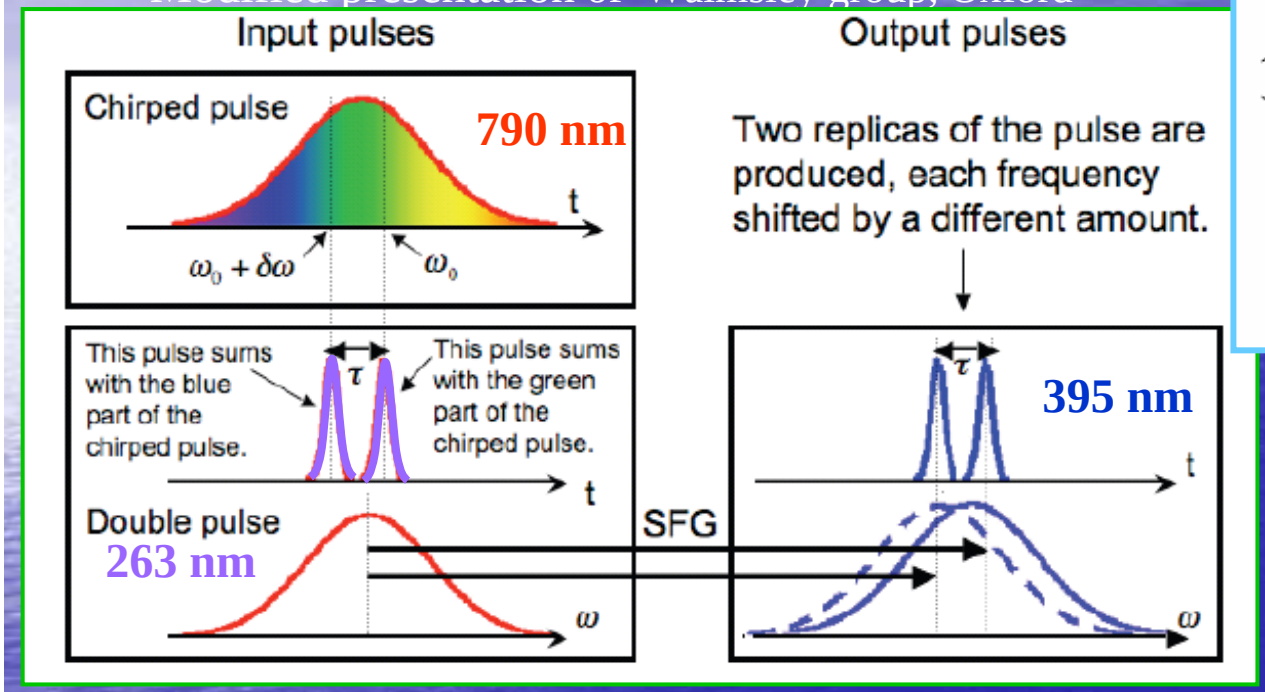
Courtesy of N.H. Matlis
Department of Physics
University of Texas

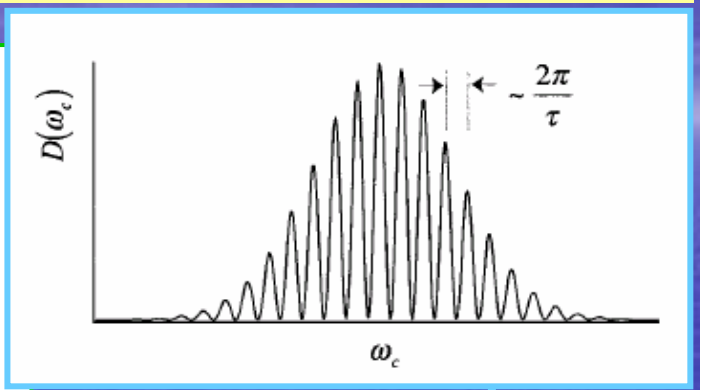
*Based on work by C. Iaconis & I.A. Walmsley (Opt.Let. /Vol. 23 No.10/May 15 1998)

3-4-4. SPIDER for characterization of macro-pulse (stacked pulse train) & micro-pulse (SP8-future plan)

~ Measuring the spectral phase: Down conversion SPIDER ~

Modified presentation of Walmsley group, Oxford





Feed backing with SPIDER, Pulse stacking can be optimized!

$$S(\omega_c) = \left|\tilde{E}(\omega_c)\right|^2 + \left|\tilde{E}(\omega_c+\Omega)\right|^2 + \left|\tilde{E}(\omega_c)\tilde{E}(\omega_c+\Omega)\right|\cos\left[\phi_\omega(\omega_c+\Omega) - \phi_\omega(\omega_c) + \omega_c\tau\right]$$

Spectrum of Pulse 1

Spectrum of Pulse 2

Spectral Phase of Pulse 1

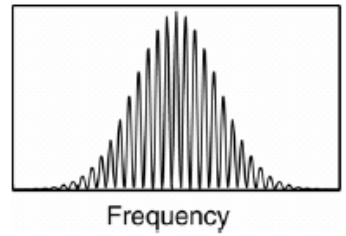
Spectral Phase of Pulse 2

Time Delay

Interference term

3-4-4-1. SPIDER for characterization of macro-pulse (stacked pulse train)

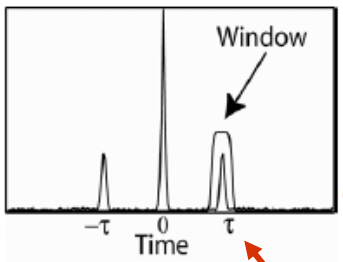
~ more precise than measurements with electron bunch ~



$$S(\omega) = \left|\tilde{E}_1(\omega)\right|^2 + \left|\tilde{E}_2(\omega)\right|^2 + 2\left|\tilde{E}_1(\omega)\right|\left|\tilde{E}_2(\omega)\right|^* \cos(\phi_t(\omega) + \omega\tau)$$

Fourier Transform

$$S(\omega) = A_1(\omega) + \left|\tilde{E}_1(\omega)\right|\left|\tilde{E}_2(\omega)\right|^* e^{i\phi_t(\omega)} e^{i\omega\tau} + \left|\tilde{E}_1(\omega)\right|^* \left|\tilde{E}_2(\omega)\right| e^{-i\phi_t(\omega)} e^{-i\omega\tau}$$



$$S(\omega) = A_{DC}(\omega) + A_{AC}(\omega)e^{i\omega\tau} + A^*_{AC}(\omega)e^{-i\omega\tau}$$

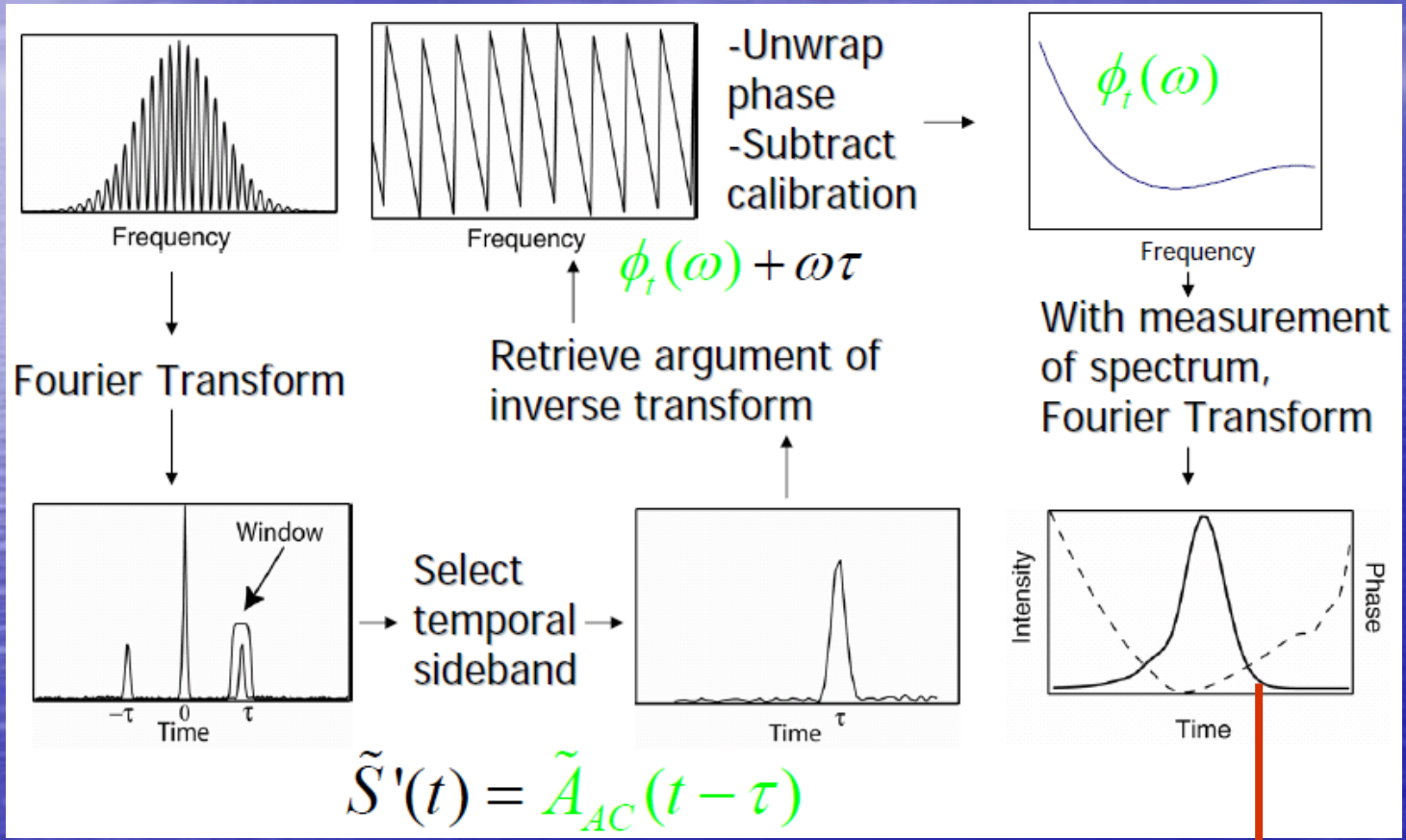
$$\tilde{S}(t) = \tilde{A}_{DC}(t) + \tilde{A}_{AC}(t-\tau) + \tilde{A}^*_{AC}(t+\tau)$$

Pulse interval in stacked pulse

3-4-4-2. SPIDER for characterization of micro-pulse

(SP8-future plan)

~ Perfect characterization of micro pulse shape ~



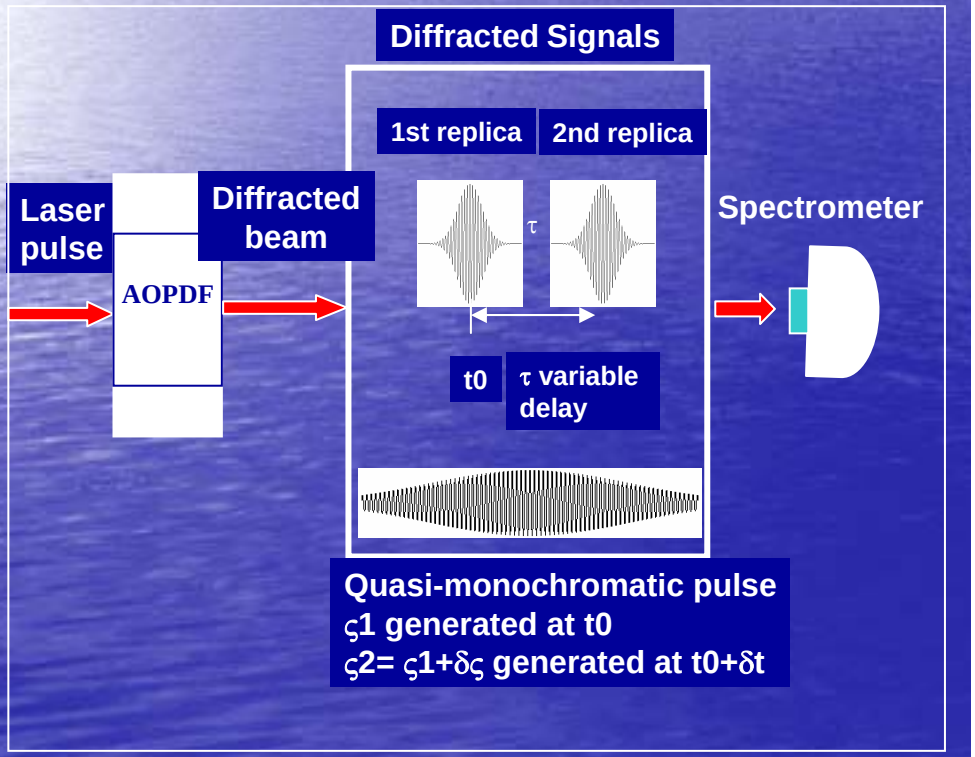
Feedback to SLM

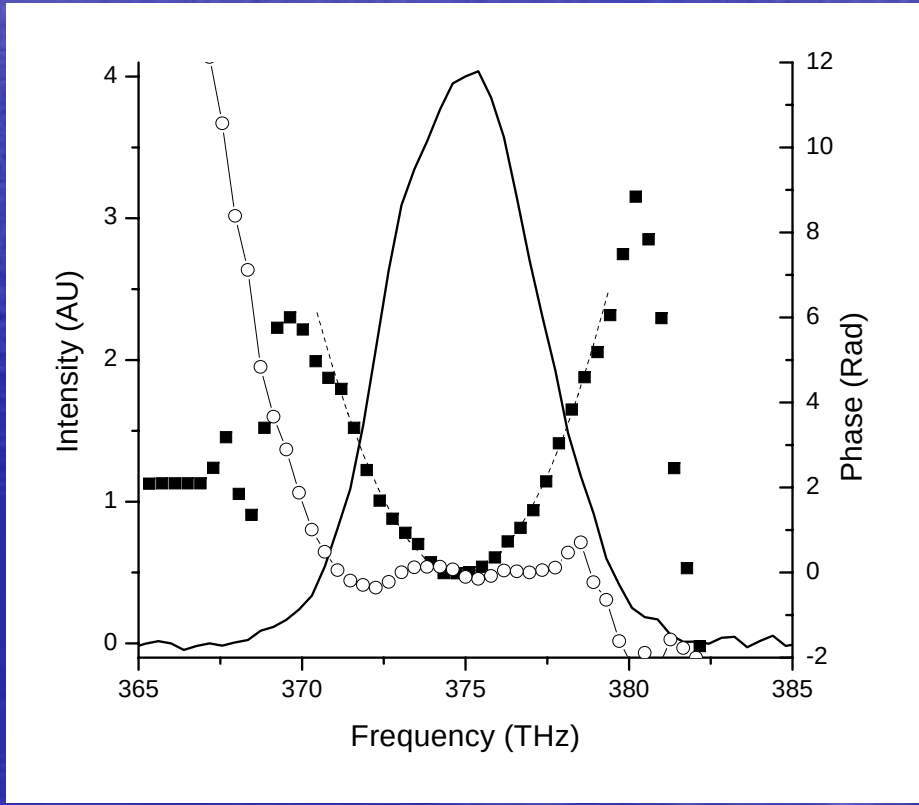
3. Adaptive micro-pulse preparation

- UV- & IR-DAZZLER feedback sys.+ Pulse Stacker

3-4-5. TIME DOMAIN SPIDER MEASUREMENTS with DAZZLER

~ PHAZZLER ~





A.Monmayrant et al. Optics Letters, 28, 4, p278-280 (Feb. 15, 2003)

4. Summary for generation of >10-ps UV- Square laser pulse

- Pulse Stacker (Macro-pulse) + Micro-pulse preparation

- 10~20-ps temporal shaping with pulse stacking could generate Square pulse!! Its flatness of the plateau depends on optimization of micro pulses!!
- Preparation & Characterization of micro-pulse (2~5 ps) It's very fine to shape : You have to exactly measure the shape of aimed laser pulse.
  - Grating compressor: It's characterized by SPIDER (SP8).
  - Prism-pair: It's characterized by Cross Correlator (PAL).
  - Adaptive DAZZLER(AO): It's characterized by itself (Fastlite).
- For 3D-laser pulse shaping, the complex system with adaptive DAZZLER & adaptive Deformable Mirror might have a lot of possibilities with fine tuning.

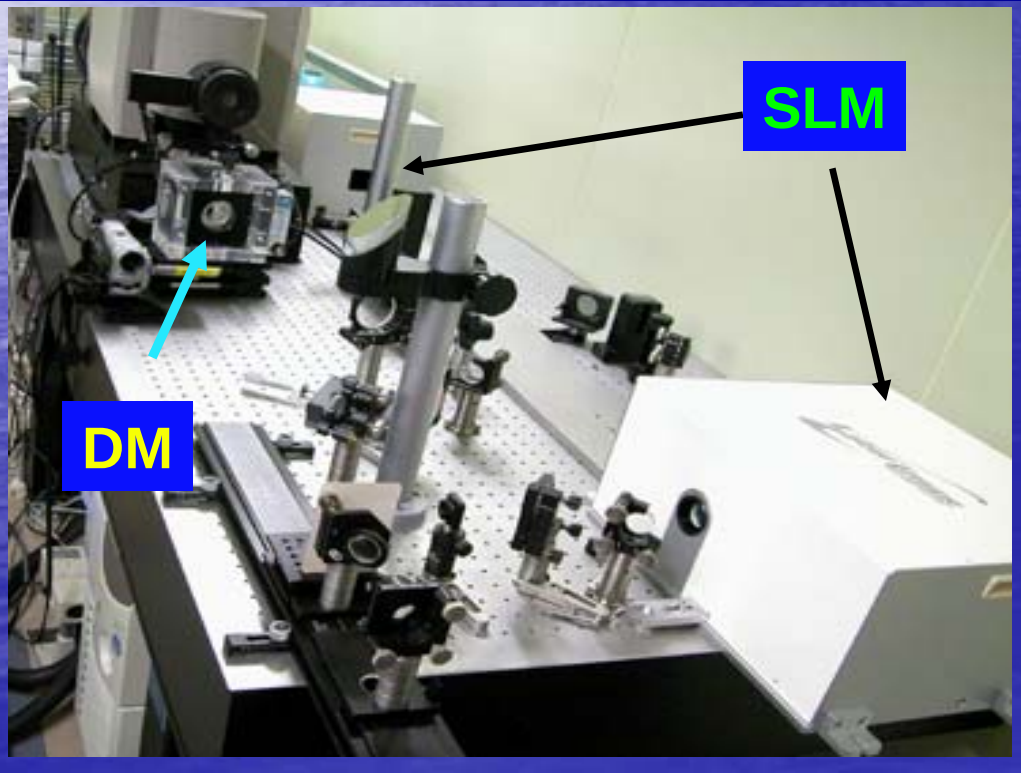
- For arbitrary 3D-laser pulse shaping, the complex system with adaptive Silica-SLM & adaptive DM should be the goal for any case. Especially, It can be utilized for multi-bunch beam shaping.

A) Computer-aided **Silica-SLM (Spatial Light Modulator)**

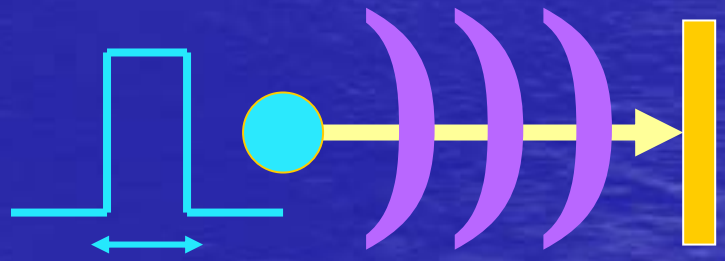
→ **Rectangular Pulse shaping (Arbitrary Shape)**

B) Computer-aided **DM (Deformable mirror)**

→ **Flattop spatial profile (Arbitrary Shape)**



Automatic Control Optics
- **Spatial shaping (DM)**
- **Pulse shaping (SLM)**
- **Wave front Control (DM)**



2 ~ 12 ps Fundamental

2 ~ 5 ps THG (263 nm)

A. UV-Pulse Stacker for quasi-ellipsoidal shaping?