Use of Fringe-Resolved Autocorrelation for the Diagnosis of the Wavelength Stability of KU-FEL

and single-shot measurement of mid-IR laser spectra

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Outline

- **Introduction**
- **Autocorrelation**

  intensity autocorrelation (IAC)
  fringe-resolved autocorrelation (FRAC)

- **Idea to estimate the shot-to-shot change of laser wavelength**

  spectrally unresolved method using IAC and FRAC

  WEPD37 by Mr. Qin

- **Single-shot measurement of mid-IR FEL spectra**

  sum-frequency mixing

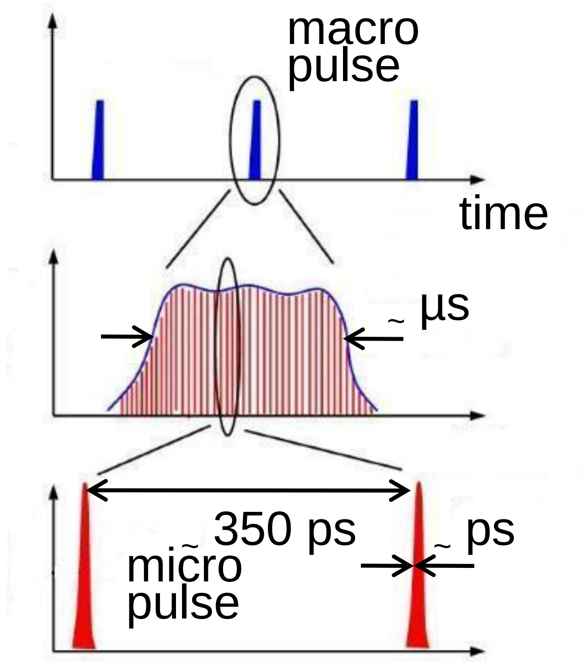
  WEPD36 by Dr. Wang

- **Summary**

Introduction

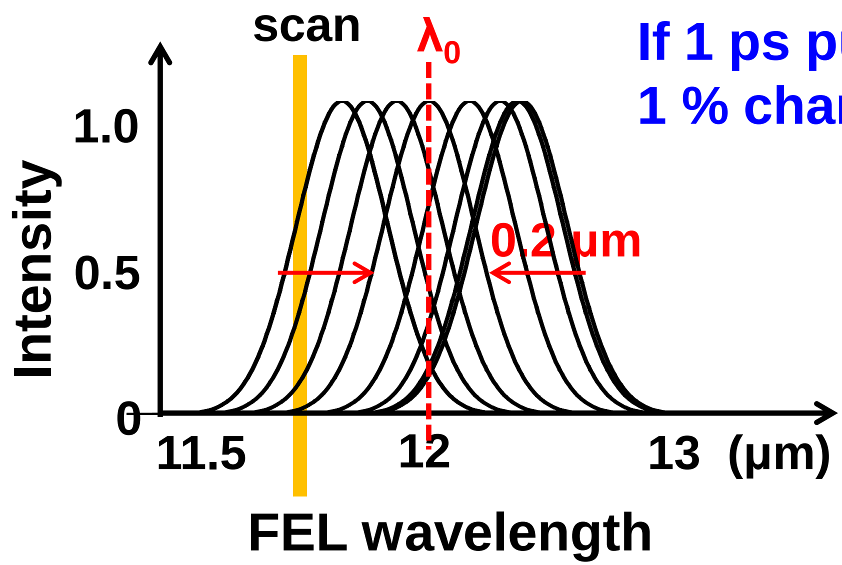
KU-FEL: Oscillator-type FEL for the mid-IR (5-14 μm)

pulse structure of KU-FEL



different macropulse
different micropulse

Shot-to-shot change of laser wavelength



If 1 ps pulse and 1 % change of λ_0

For the detection of single-micropulse spectra

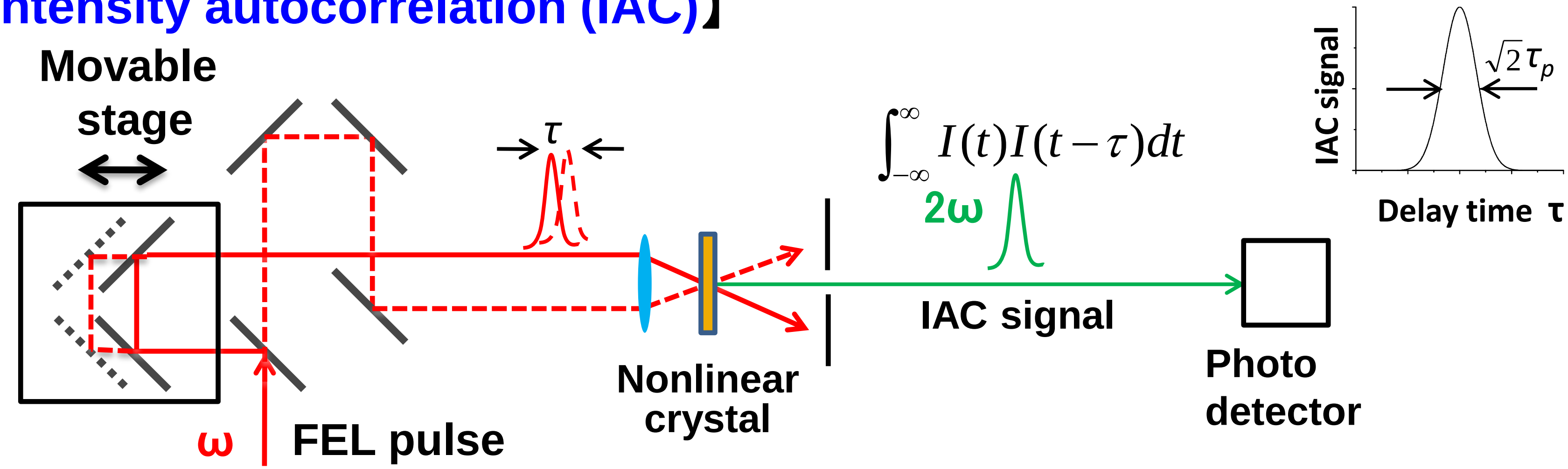
~~scanning-type spectrometer~~

~~array-type mid-IR photodetector~~

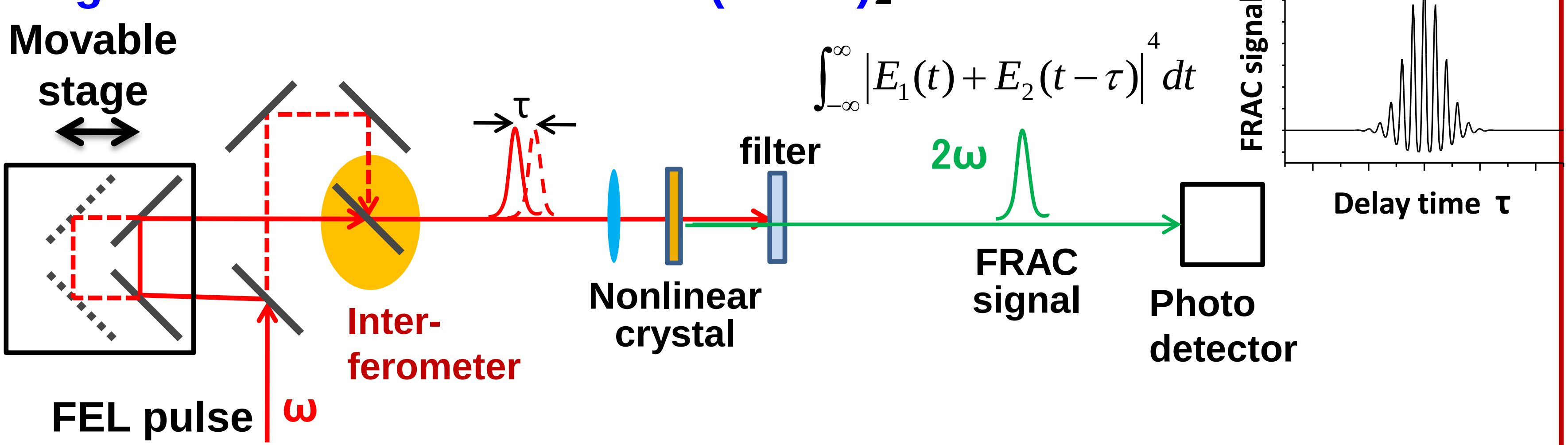
Autocorrelation methods

Techniques to measure the ps~fs pulse duration

【Intensity autocorrelation (IAC)】



【Fringe-resolved autocorrelation (FRAC)】

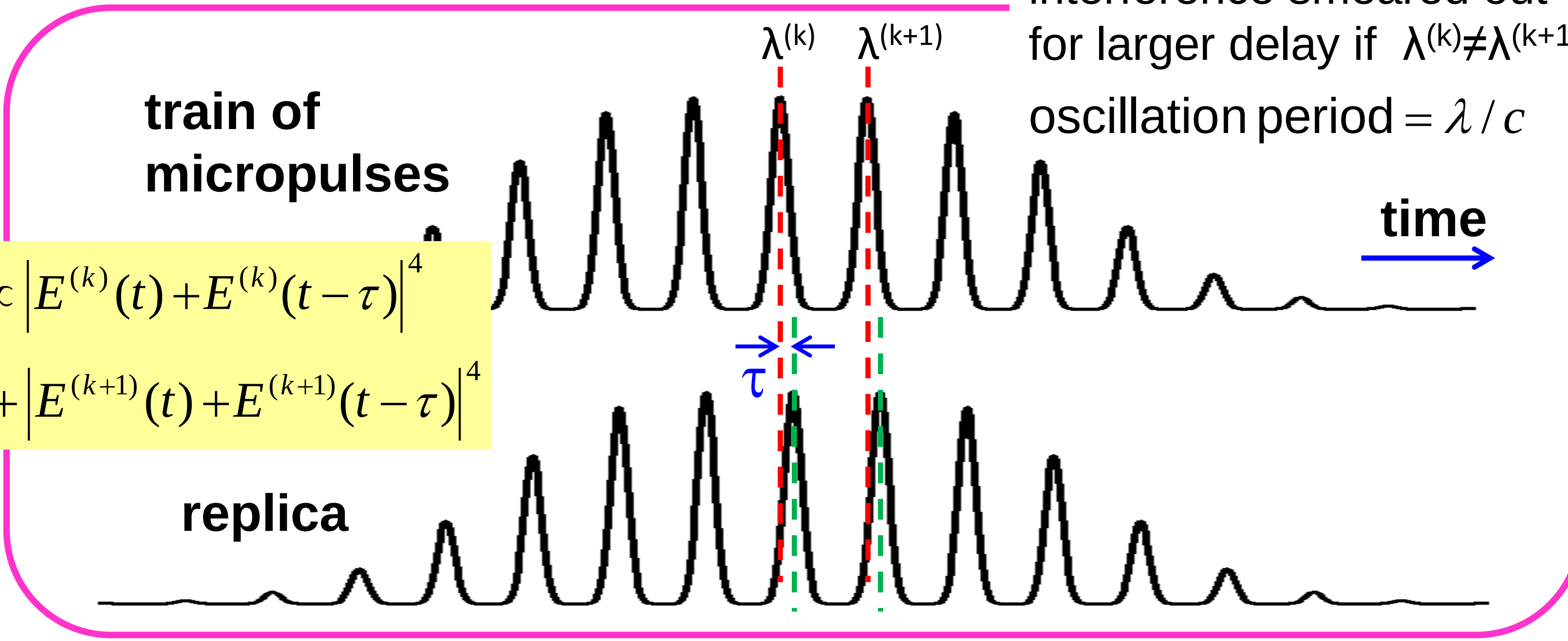


Idea to estimate the shot-to-shot change of laser wavelength

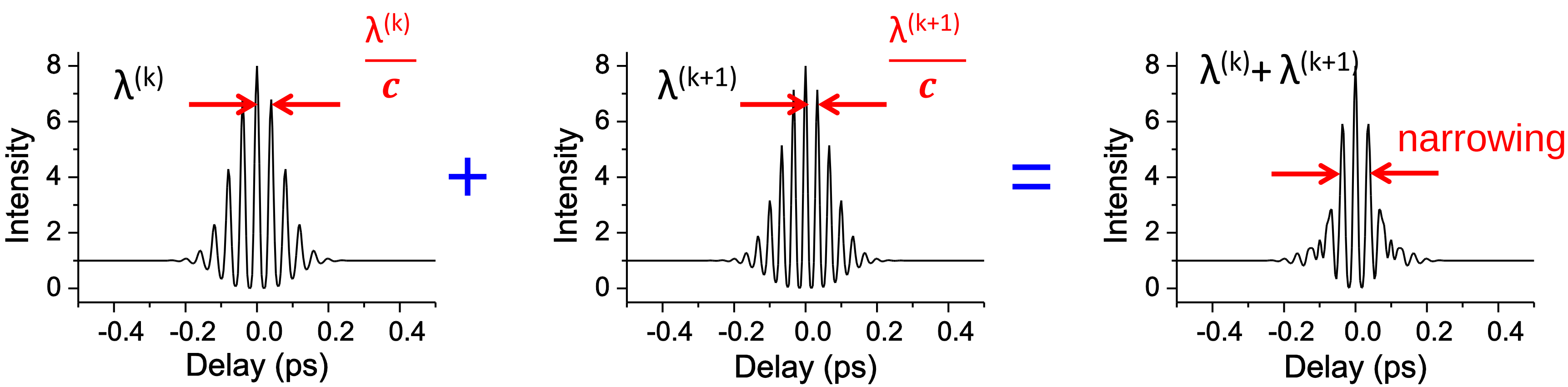
How does it work?

interference smeared out for larger delay if $\lambda^{(k)} \neq \lambda^{(k+1)}$

oscillation period $= \lambda / c$



$$I_{FRAC}(\tau) \propto \left| E^{(k)}(t) + E^{(k)}(t-\tau) \right|^4 + \left| E^{(k+1)}(t) + E^{(k+1)}(t-\tau) \right|^4$$



IAC and FRAC signals with various fluctuations

Intensity of the macropulse

$$I(t) = \sum_{k=1}^{M} \left| E^{(k)}(t) \right|^2$$

Field amplitude of the *k*th micropulse

$$E^{(k)}(t) = \sqrt{a_1^{(k)} I_0^{(k)}} \exp\left\{ -2\ln 2 \left[\frac{t-(k-1)\Delta t}{a_2^{(k)} \tau_0} \right]^2 \frac{1}{1-i\alpha} \right\} \exp\left[i a_3^{(k)} \omega_0^{(k)} t + \phi^{(k)}(t) \right]$$

τ_p : micropulse duration $\tau_p = \sqrt{1+\alpha^2}\,\tau_0$

$\omega_0^{(k)}$: central frequency of the kth micropulse

$a_1^{(k)}, a_2^{(k)}, a_3^{(k)}$: fluctuation of intensity, duration, and central frequency of the k[th] micropulse

autocorrelation signals

$$\begin{cases} I_{IAC}(\tau) \propto \int_{-\infty}^{\infty} I(t) I(t-\tau)\, dt \\ I_{FRAC}(\tau) \propto \sum_{k=1}^{N} \int_{-\infty}^{\infty} \left| E^{(k)}(t) + E^{(k)}(t-\tau) \right|^4 dt \end{cases}$$

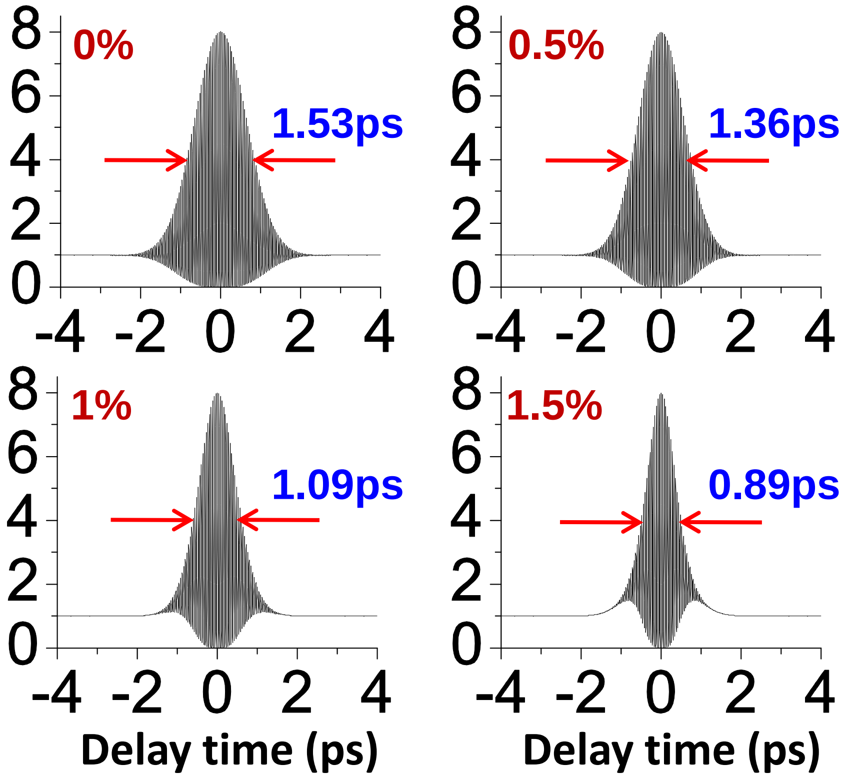
Narrowing of FRAC signals by wavelength fluctuation

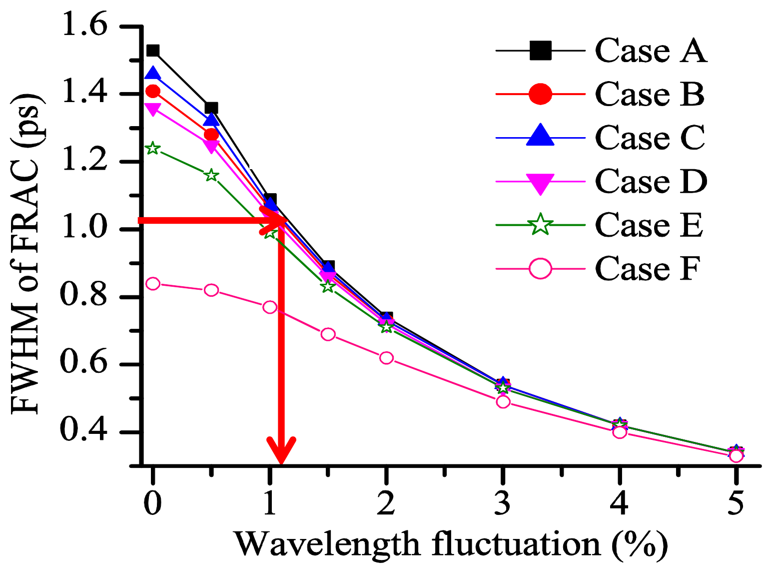
After averaging over thousands of shots,

IAC signals : no change

FRAC signals: narrowing by shot-to-shot wavelength change

For 1 ps pulse,





FRAC signal narrowing ⬍ Wavelength fluctuation

Qin *et al*., Jpn.J.Appl.Phys. (in press)

Retrieval of pulse duration from FRAC signals

If we can retrieve the pulse duration from the FRAC signals, we may only perform the FRAC measurement !

Expectation values of $I_{FRAC}(\tau)-1$

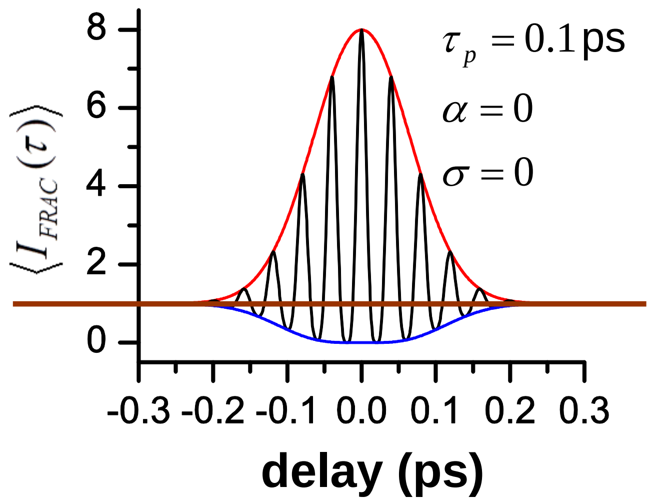
$$\int_{-\infty}^{\infty} d\tau \left[\left\langle I_{FRAC}(\tau)\right\rangle -1\right] = \int_{-\infty}^{\infty} d\tau \left[\left\langle \int_{-\infty}^{\infty} \left[E(t)+E(t-\tau)\right]^4 dt \right\rangle -1\right]$$

$$= \int_{-\infty}^{\infty} d\tau \left[4\exp\left[\frac{-\ln 2(3+\alpha^2)\tau^2}{2\tau_p^2} - \frac{\sigma^2\omega_0^2\tau^2}{2}\right] \cos\left(\frac{\ln 2\alpha^2\tau^2}{2\tau_p^2}\right) \cos(\omega_0\tau) \right.$$

$$+ \exp\left[\frac{-2\ln 2(1+\alpha^2)\tau^2}{\tau_p^2} - 2\sigma^2\omega_0^2\tau^2\right] \cos(2\omega_0\tau)$$

$$\left. + 2\exp\left(\frac{-2\ln 2\tau^2}{\tau_p^2}\right)\right]$$

$$\therefore \int_{-\infty}^{\infty} d\tau \left[\left\langle I_{FRAC}(\tau)\right\rangle -1\right] = \sqrt{\frac{2\pi}{\ln 2}}\,\tau_p$$

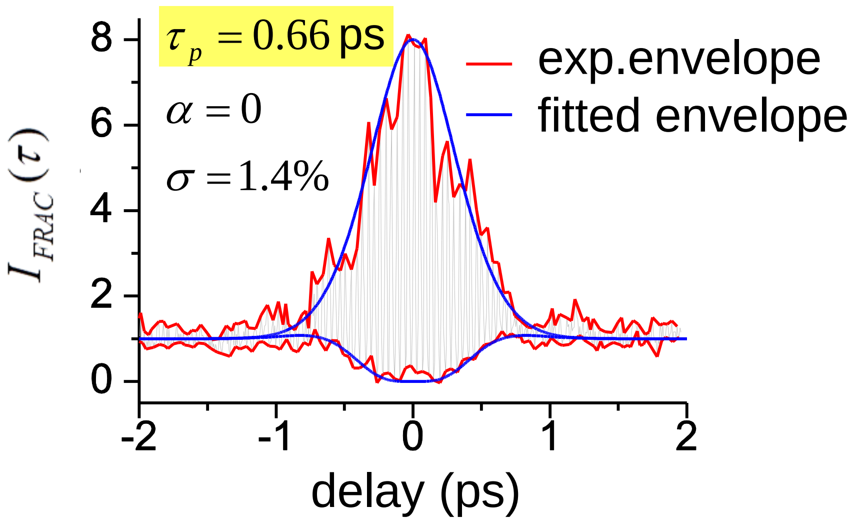


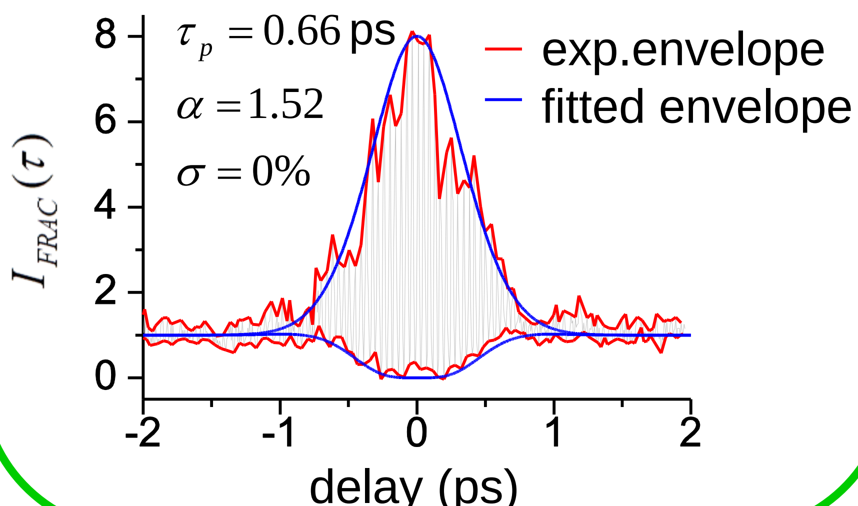
Pulse duration τ_p is retrieved by the *time-integration* of FRAC signals

Experimental results

FRAC measurement

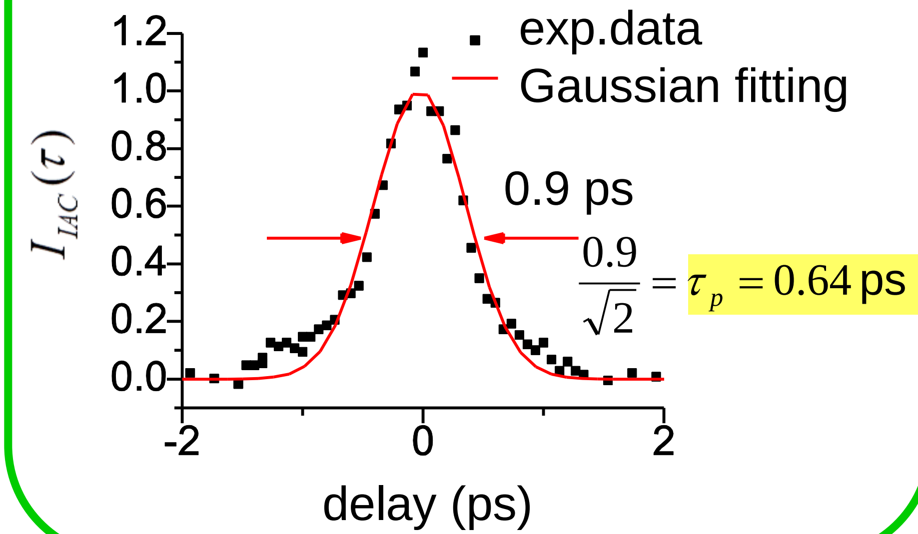
step size = 2 μm (= 1/150 ps)





IAC measurement

step size = 10 μm (= 1/30 ps)



- pulse duration **0.64~0.66 ps** by both IAC and FRAC methods
- wavelength stability is **< 1.4 %**

Qin *et al.* (in preparation)

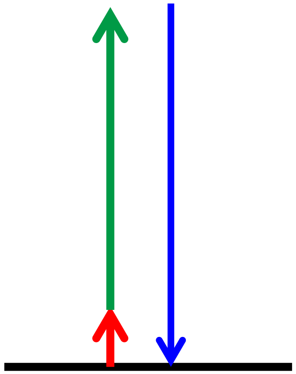
Toward single-shot measurement of Mid-IR FEL pulse spectra

Mid-IR : MCT-based array photodetector (very expensive)
Near–IR: Si-based array photodetetor (cheap!)

Convert the MIR laser pulse into the NIR pulse by sum-frequency mixing !

ω_1 **(11 μm) +** ω_2 **(1064 nm)** $\rightarrow$ ω_3 **(970 nm)**

KU-FEL	Nd:YAG or microchip lasers	SFM signal (near-IR)
< 1 ps	20 ns or 0.8 ns	< 1 ps

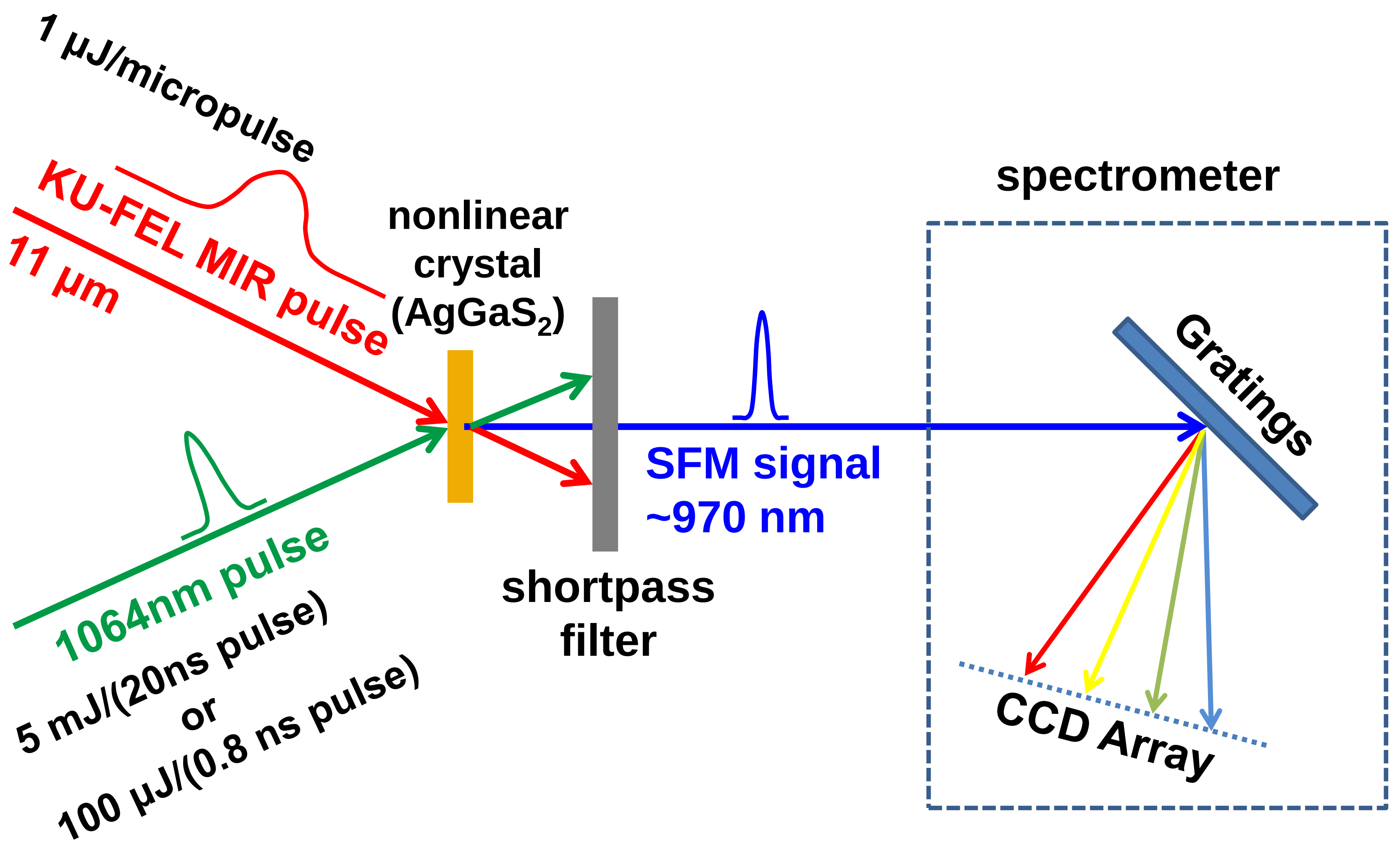


Signal intensity

$I_{SFM} \propto I_{MIR} \times I_{1064nm}$

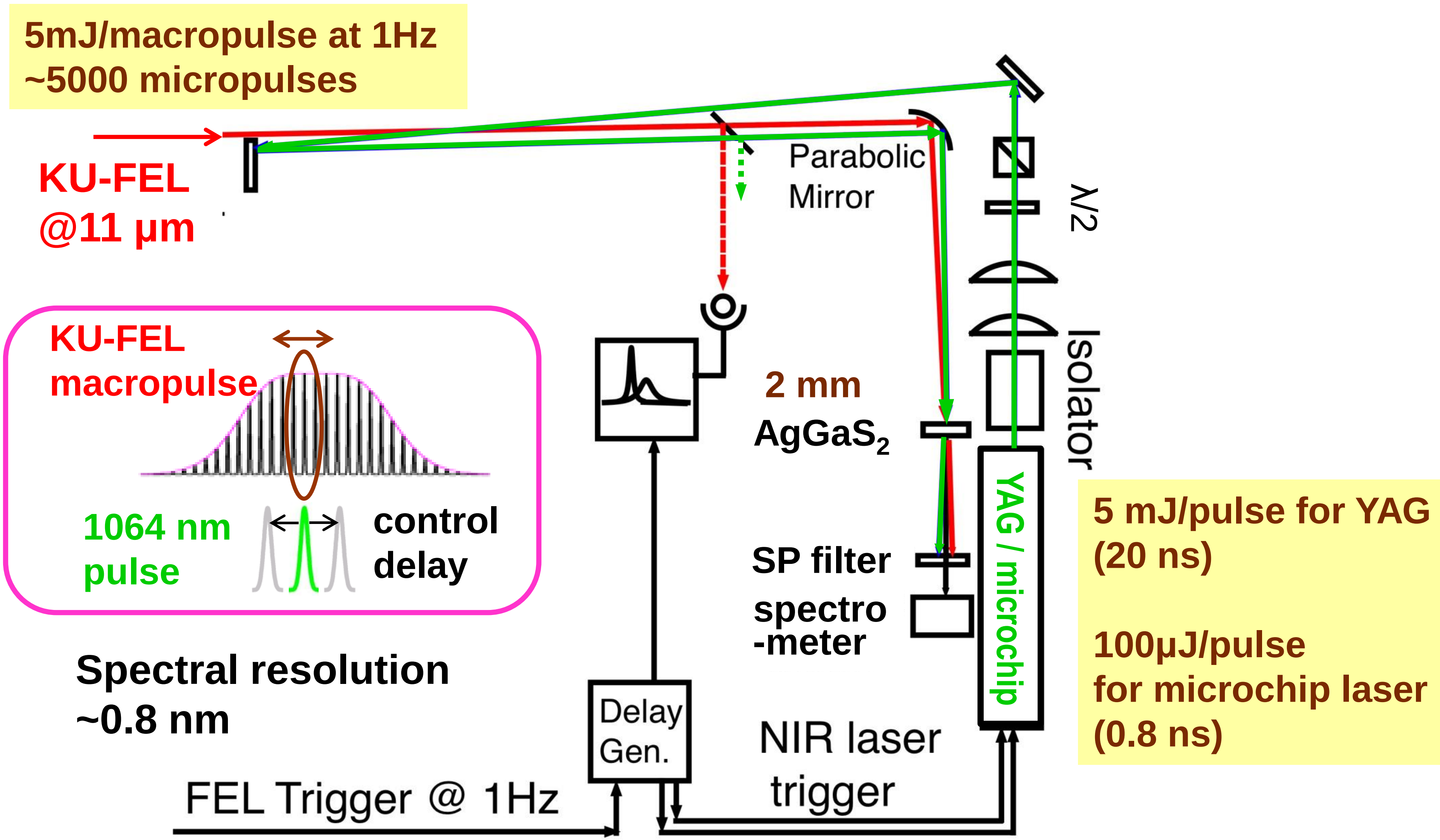
Wang *et al.* (in preparation)

Schematics of sum-frequency mixing



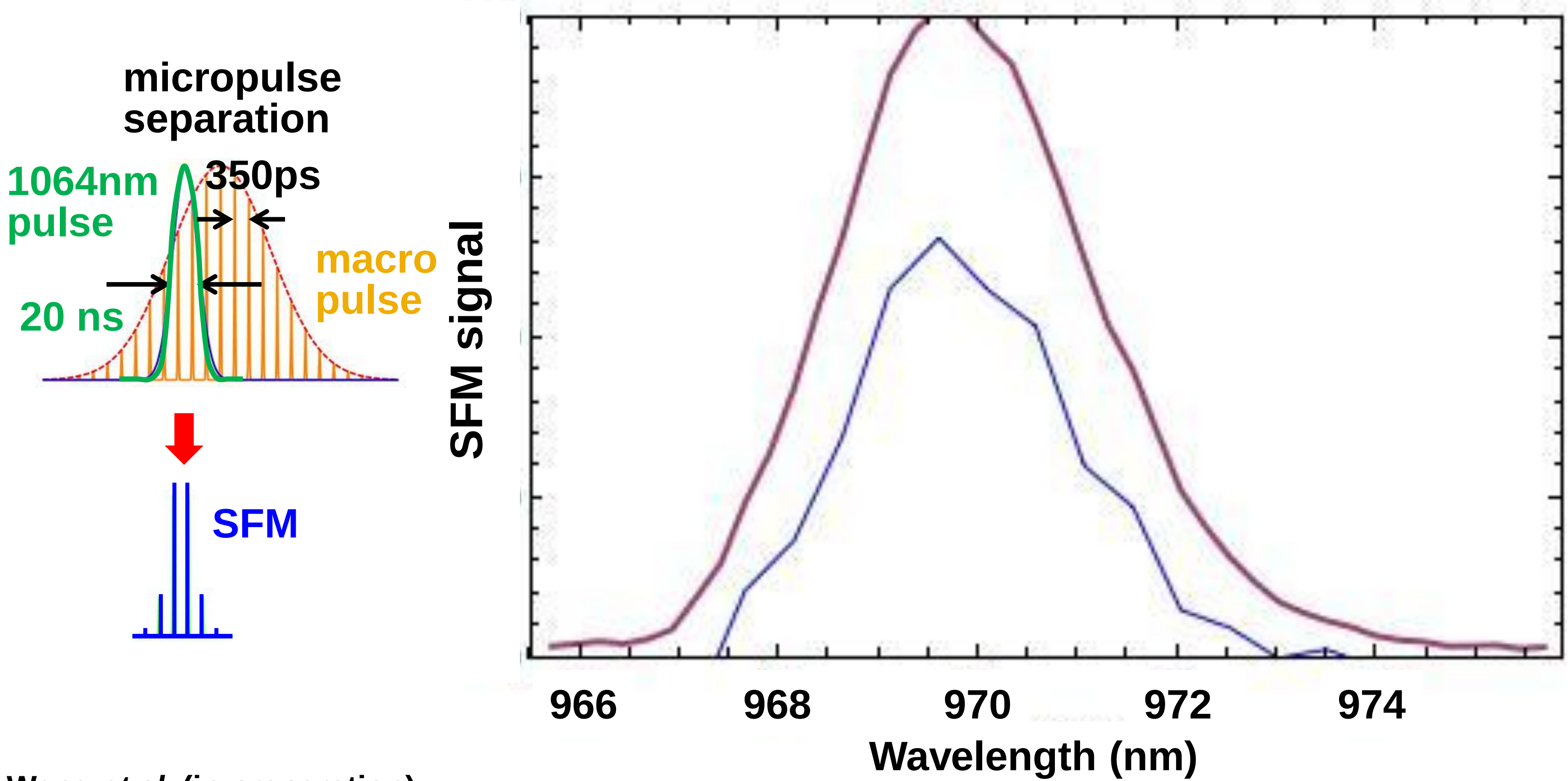
SFM signal detectable?

Experimental setup for sum-frequency mixing



Shot-to-shot change of the SFM spectra by 20 ns Nd:YAG laser

Sum of the $\frac{20\,ns}{350\,ps} = 57$ micropulse spectra in the same macropulse



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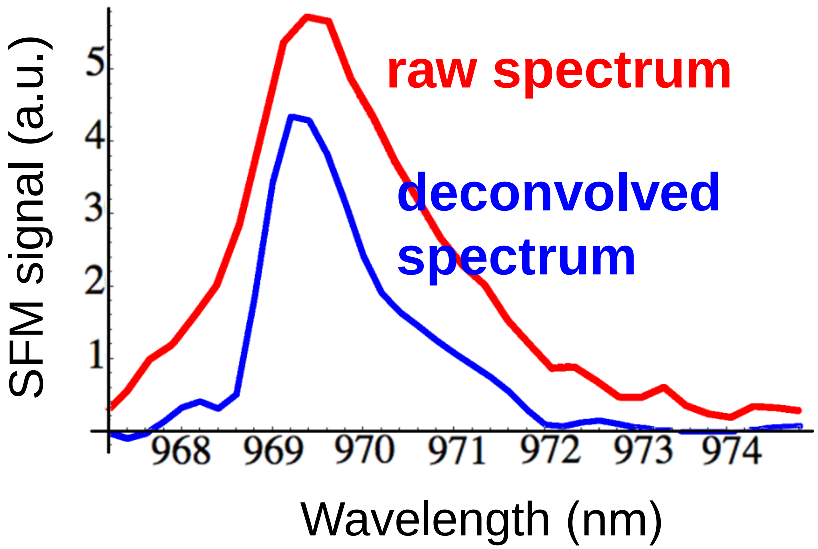
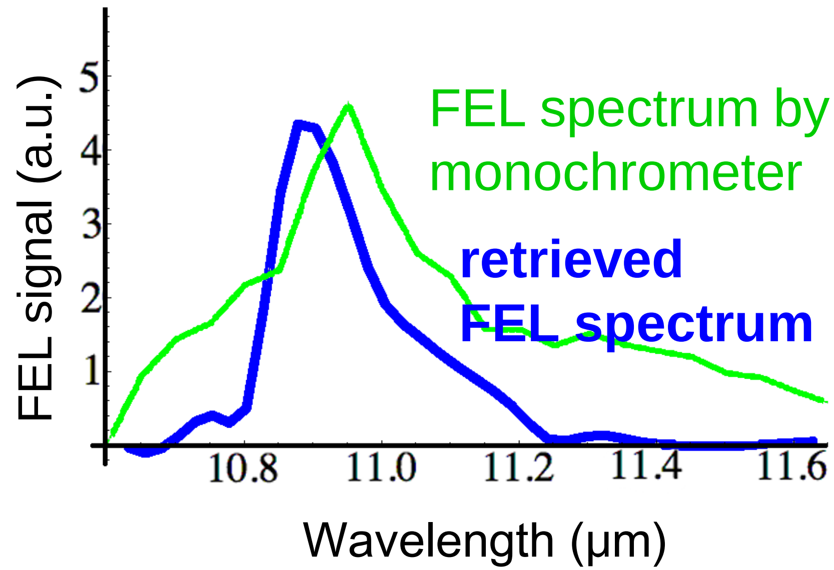
Retrieval of the FEL spectra

$$\lambda_{FEL} = \left(\frac{1}{\lambda_{SFM}} - \frac{1}{\lambda_{1064nm}}\right)^{-1}$$





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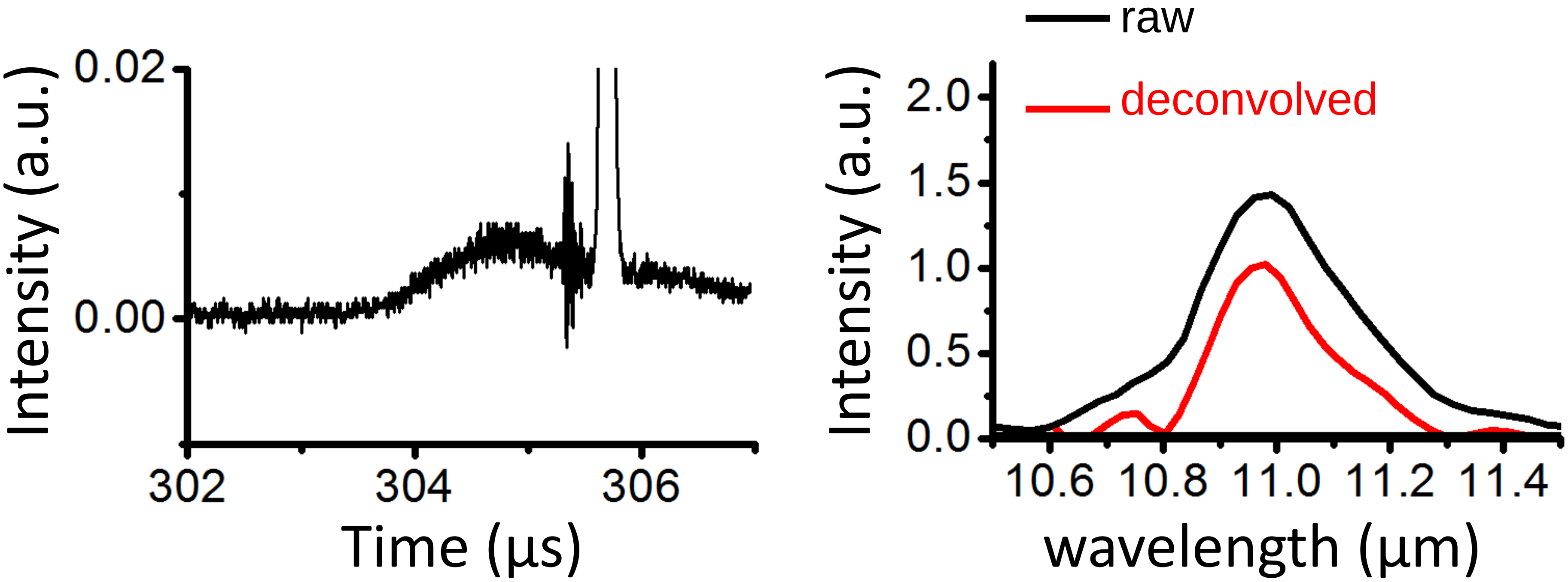
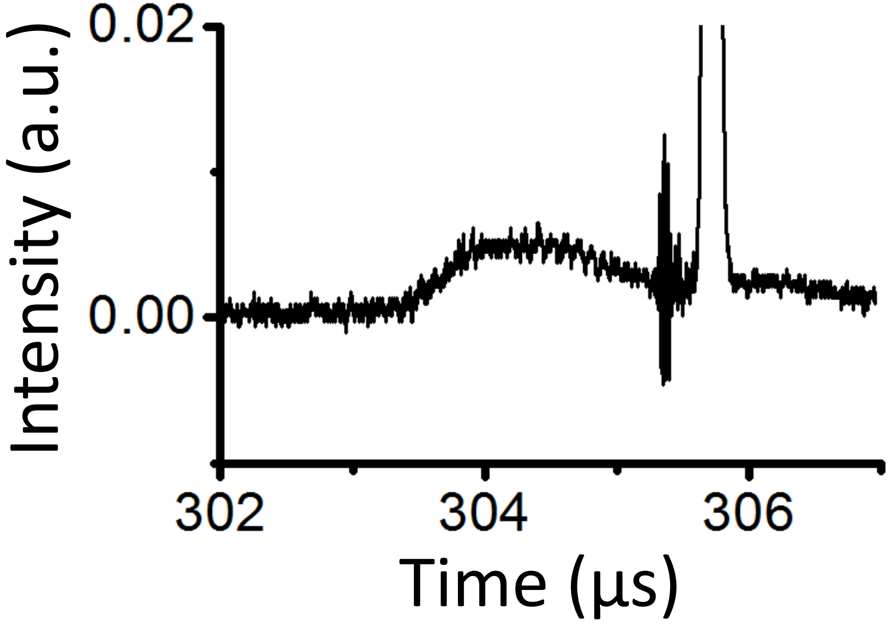
Macropulse shape

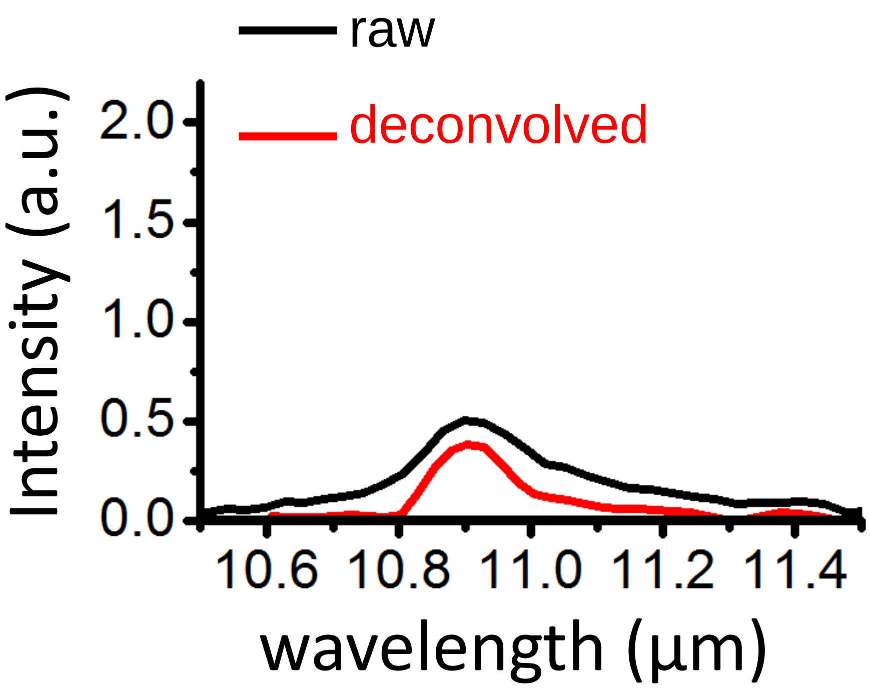
FEL spectrum



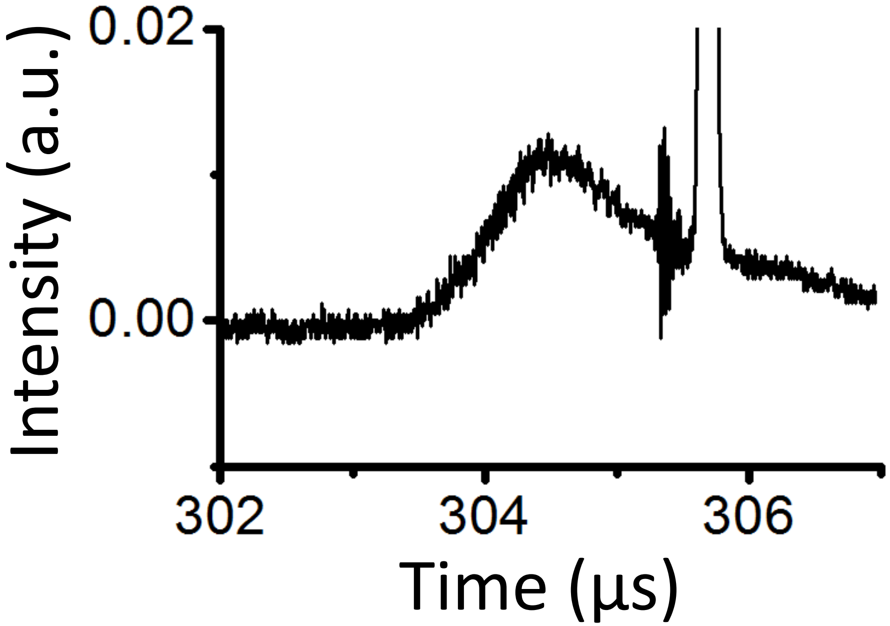
Macropulse shape



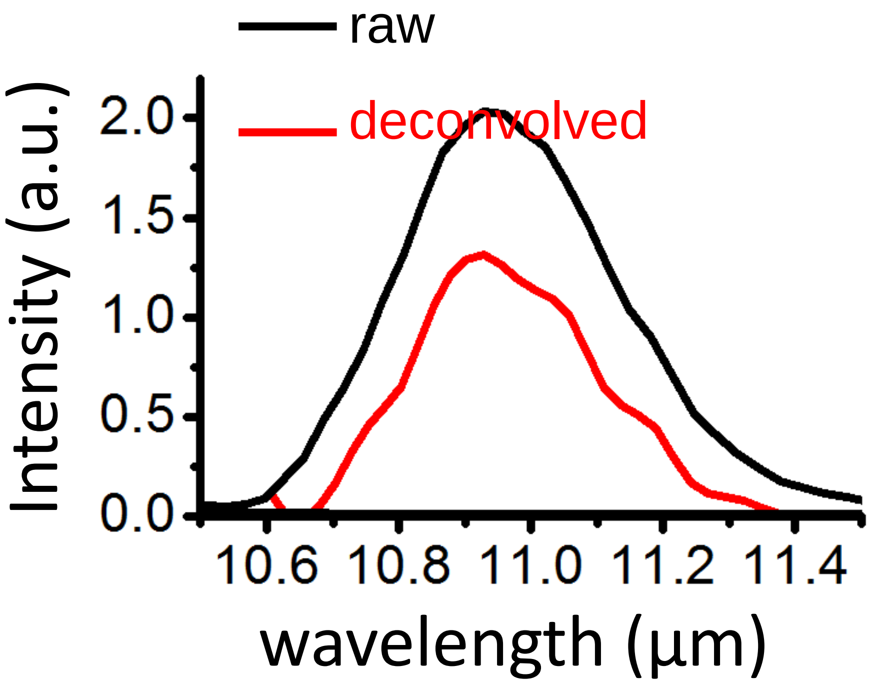
FEL spectrum



Macropulse shape



FEL spectrum



Summary

Measurement of the pulse duration and wavelength stability of KU-FEL using fringe-resolved autocorrelation

Spectrally unresolved detection !

Periodicity of the fringe ⟷ wavelength information

micropulse duration = 0.64~0.66 ps

wavelength instability <1.4%

Single-shot measurement of the laser spectra of KU-FEL for *temporally selected* micropulse(s)

Sum-frequency mixing to generate near-IR signals