Ultrafast optics for X-ray free-electron lasers

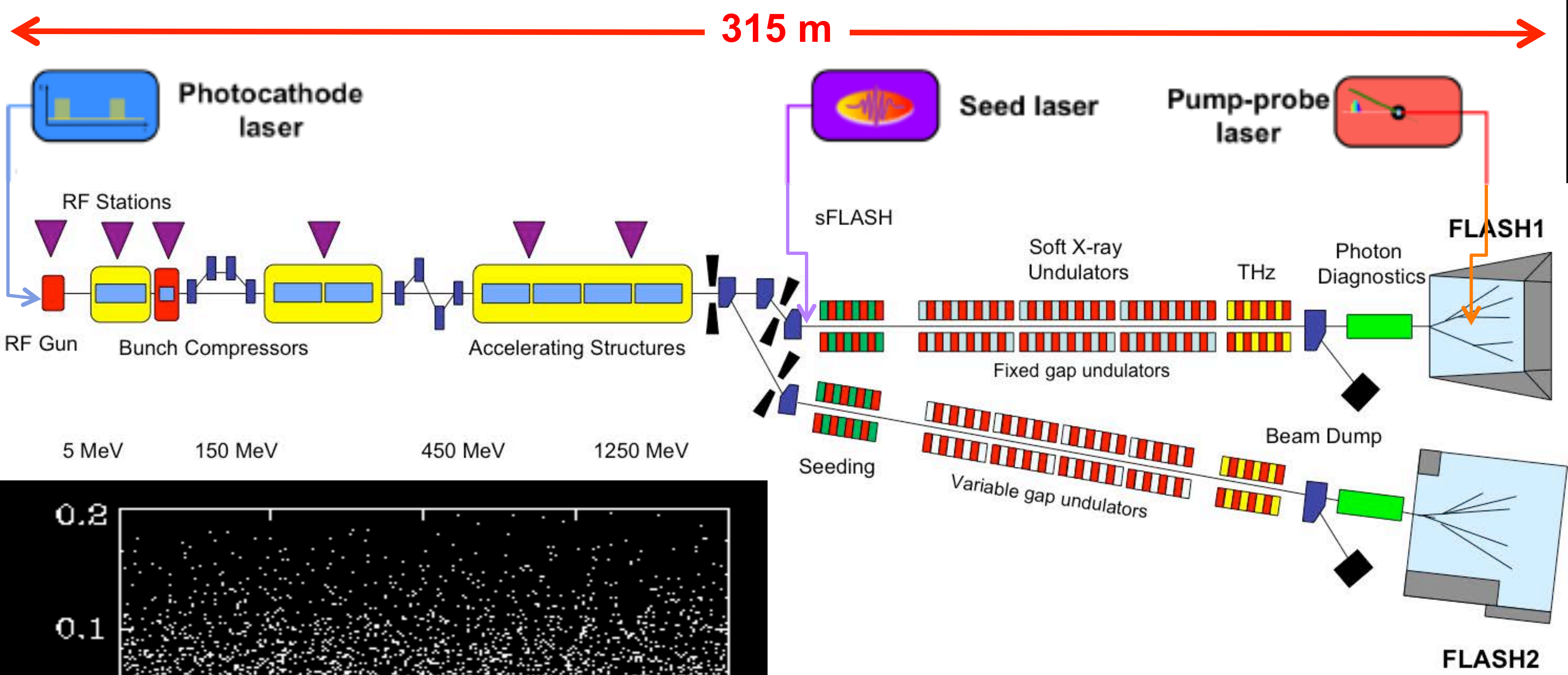
Franz X. Kärtner
Center for Free-Electron Laser Science (CFEL), DESY, Hamburg, Germany
Ultrafast Optics and X-Rays Division

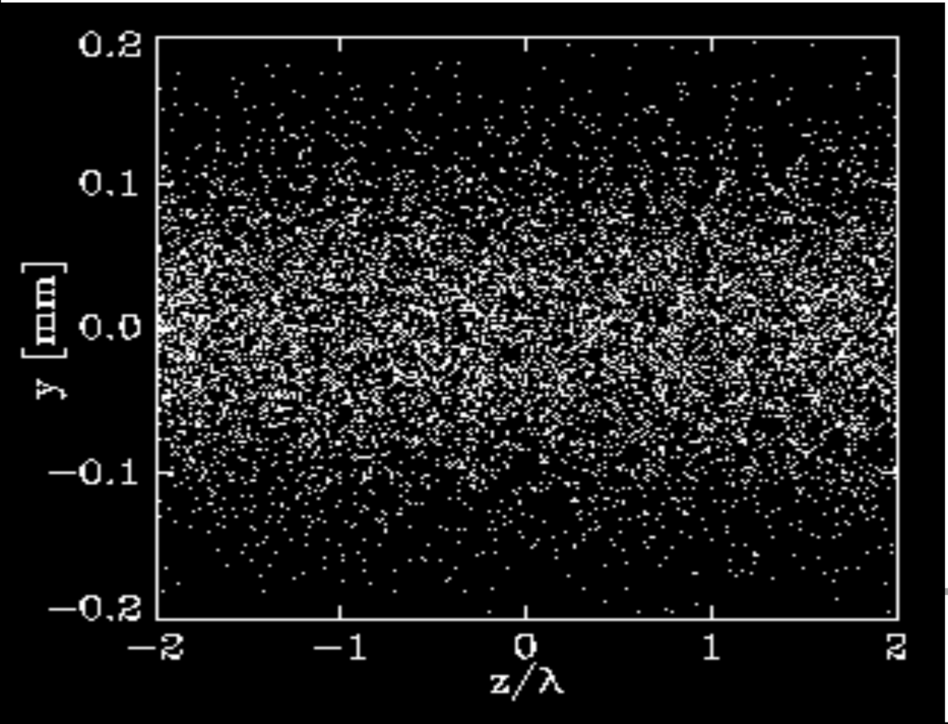
Department of Physics and The Hamburg Center for Ultrafast Imaging,
University of Hamburg, Germany
and
Department of Electrical Engineering and Computer Science and
Research Laboratory of Electronics, MIT, USA

Physics of and Science with X-ray Free-Electron Lasers
Varenna Summer School 2017

X-Ray FELs operating and under construction

Example: XUV FEL FLASH

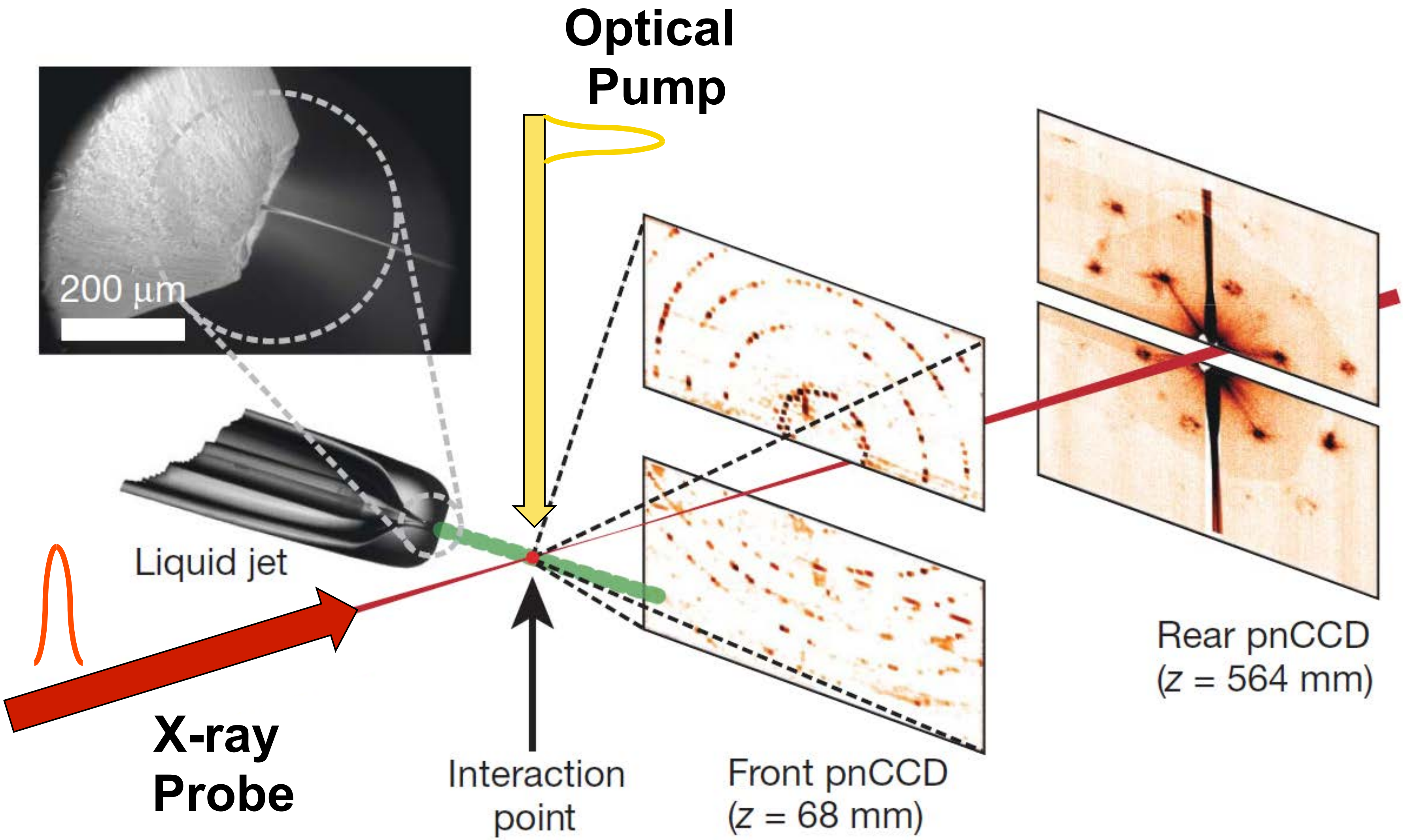




Micro-bunching enables coherent emission

Courtesy FLASH Facility

Serial X-ray crystallography (time resolved)

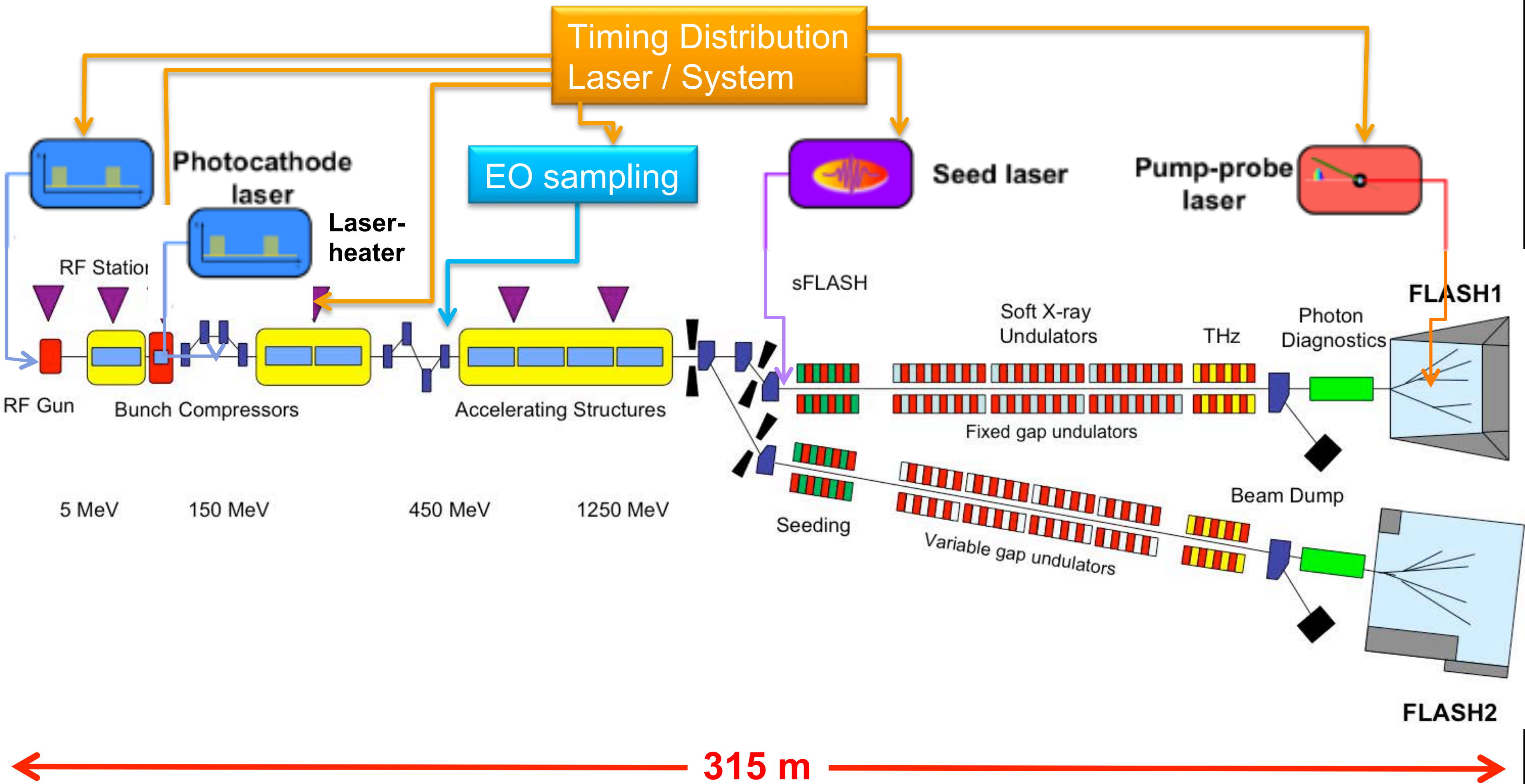


Imaging before destruction w. fs-x-rays **Molecular movie**

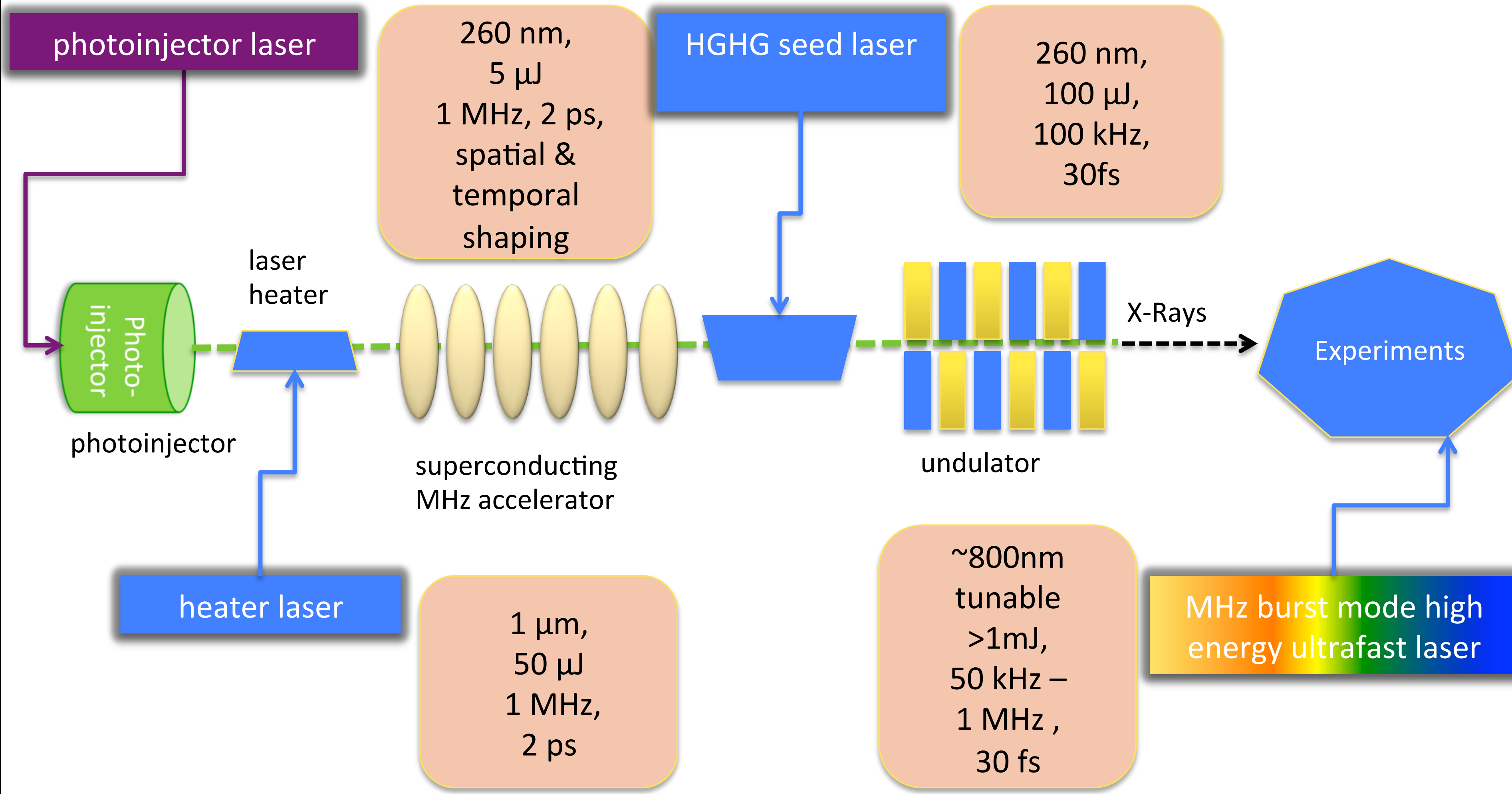
Outline

- X-ray FELs: Super - Microscopes in Space and Time
  - Structure, Dynamics and Function of Atoms, Molecules and Materials
- What Ultrafast Lasers Can Do for X-Ray FELs?
  - Femtosecond and Attosecond Timing Distribution
  - Pump-Probe Laser Technology
  - Fully Coherent Output by Seeding (HHG, HGHG, EEHG, ...)
  - Photo Injector, Laser heater, Diagnostics, …..
- Compact Coherent X-ray Sources
  - Controlled Electron Bunch Generation
  - THz Generation
  - THz Guns, Acceleration, Manipulation, Diagnostics, …

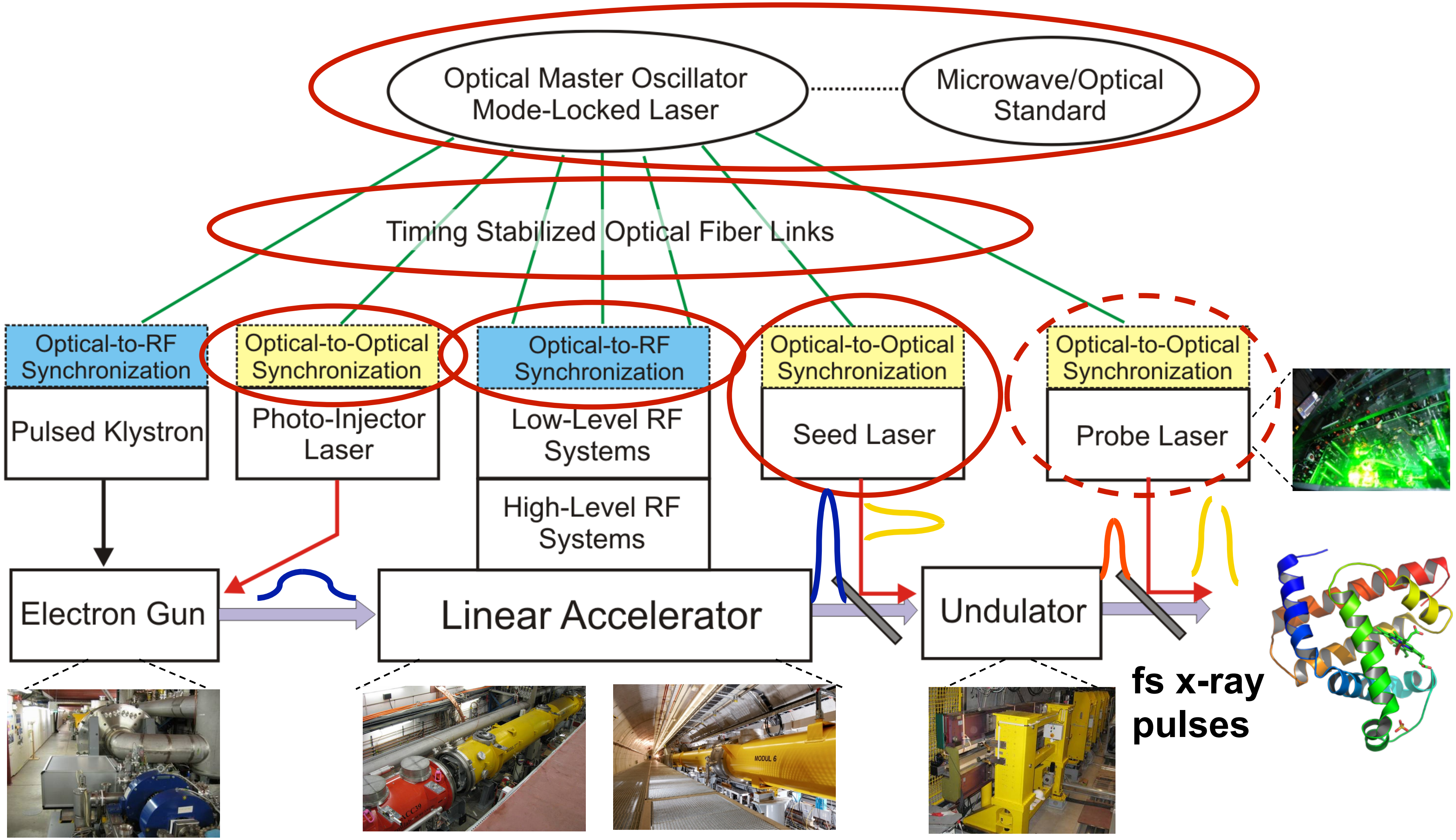
Lasers in FLASH



FLASH Laser Requirements



Pulsed femtosecond timing distribution



J. Kim et al, FEL 2004.

Other approaches: R. Wilcox, LBNL, cw-distribution, or post stamping

Pulsed timing and synchronization

Femtosecond lasers are very low jitter:

- High intracavity pulse energy
- High Q Cavity
- 10 - 100 fs pulses, good time markers

→ sub-femtosecond jitter for f > 1kHz

Balanced optical cross correlation:

- High timing sensitivity (zeptoseconds)
- low drift (only dielectrics involved)
- attosecond laser to laser locks

→ attosecond laser-to-laser locks and fiber links

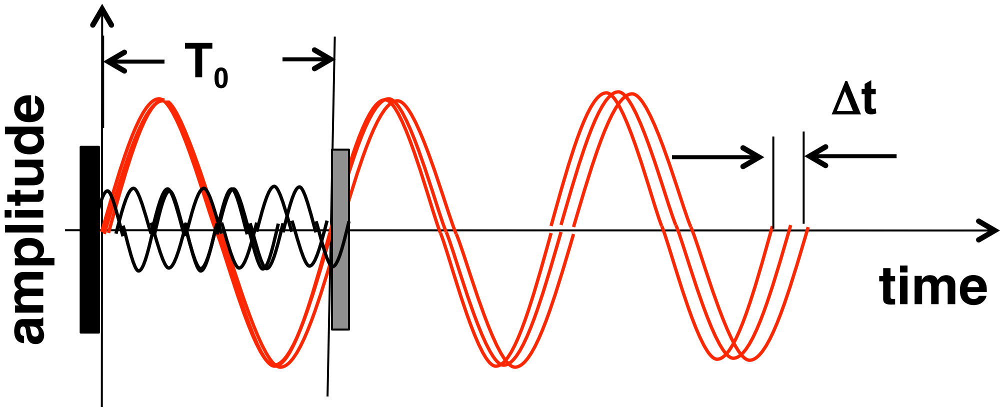
Balanced optical microwave phase detection:

- sub-femtosecond jitter microwaves

J. Kim, et al. Nat. Photonics 2, 733 (2008).

Timing Jitter of Femtosecond Lasers

Electronic Oscillator



Dissipation-Fluctuation Theorem

$$\frac{d}{dt} < \Delta t_{RF}^2 > \approx T_0^2 \cdot \frac{1}{W_{mode}} \cdot \frac{kT}{\tau_{cav}}$$

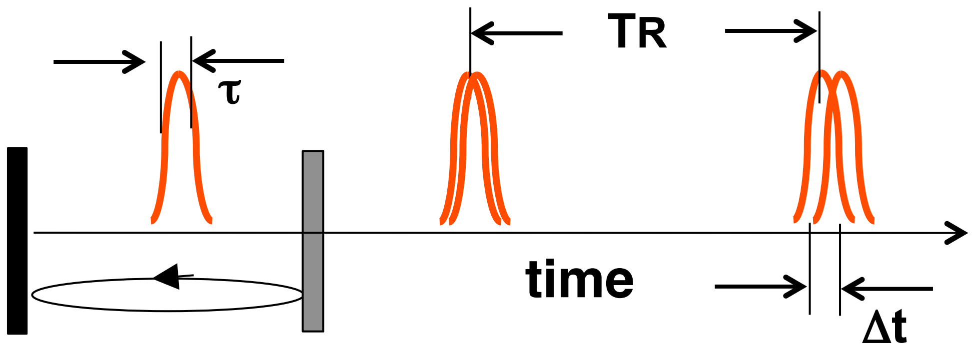
period ~100ps

cavity lifetime

10^{-6}

Femtosecond Laser

pulse width ~100fs



$$\frac{d}{dt} < \Delta t_{ML}^2 > \approx \tau^2 \cdot \frac{1}{W_{pulse}} \cdot \frac{h\omega_c}{\tau_{cav}}$$

Optical Cavity

$$\hbar\omega_c \sim 50kT$$

kT = thermal energy

$\hbar\omega_c$ = photon energy

10^{-4}

H. A. Haus and A. Mecozzi, IEEE JQE *29, 983* (1993).

J. Kim and F. X. Kärtner, Laser & Phot. Rev., 1–25 (2009).

How Do We Measure Low Jitter?

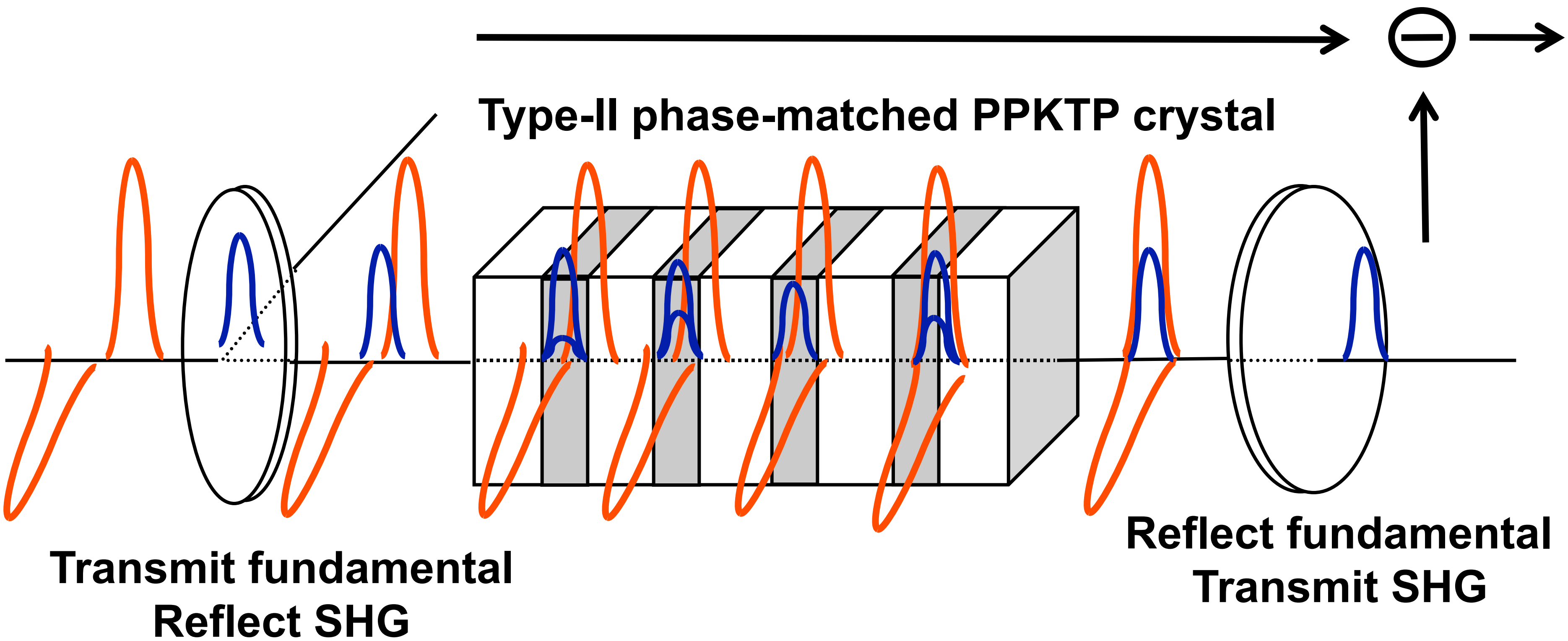
Sensitive Time Delay Measurements

by

Balanced Optical Cross Correlation

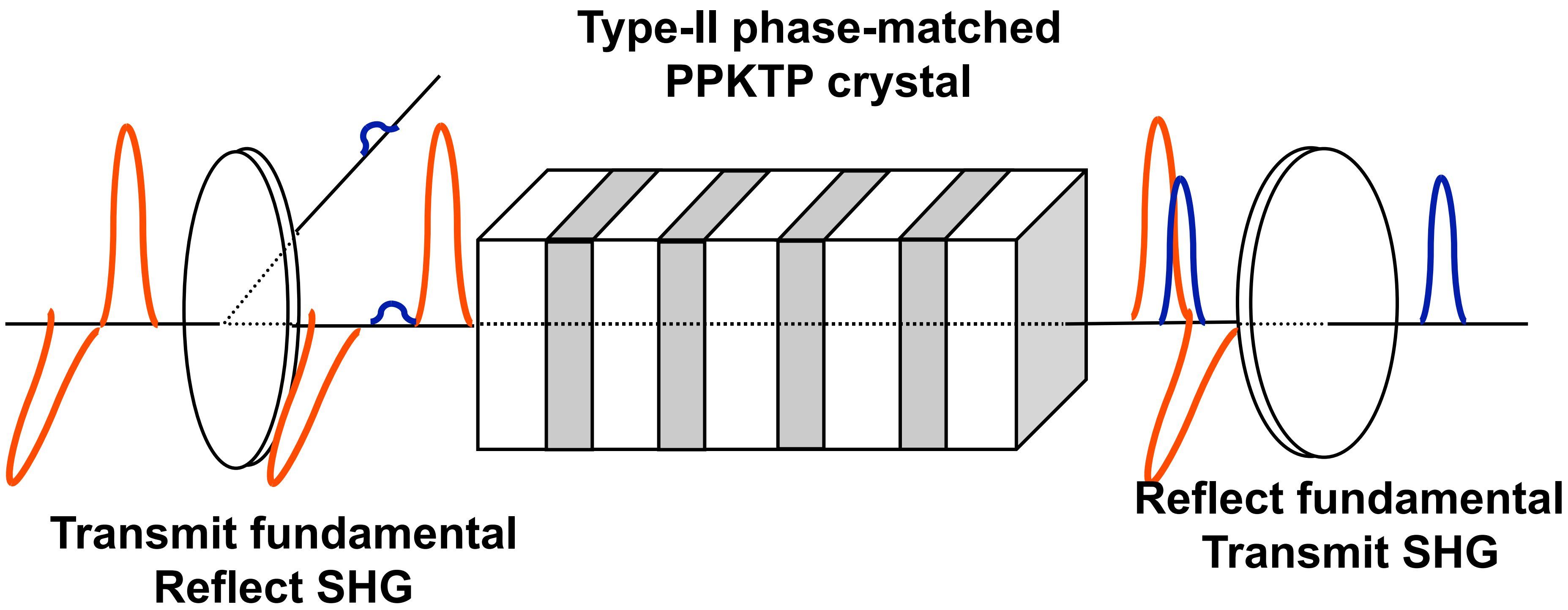
Single-crystal balanced cross-correlator

T. Schibli et al, OL 28, 947 (2003)



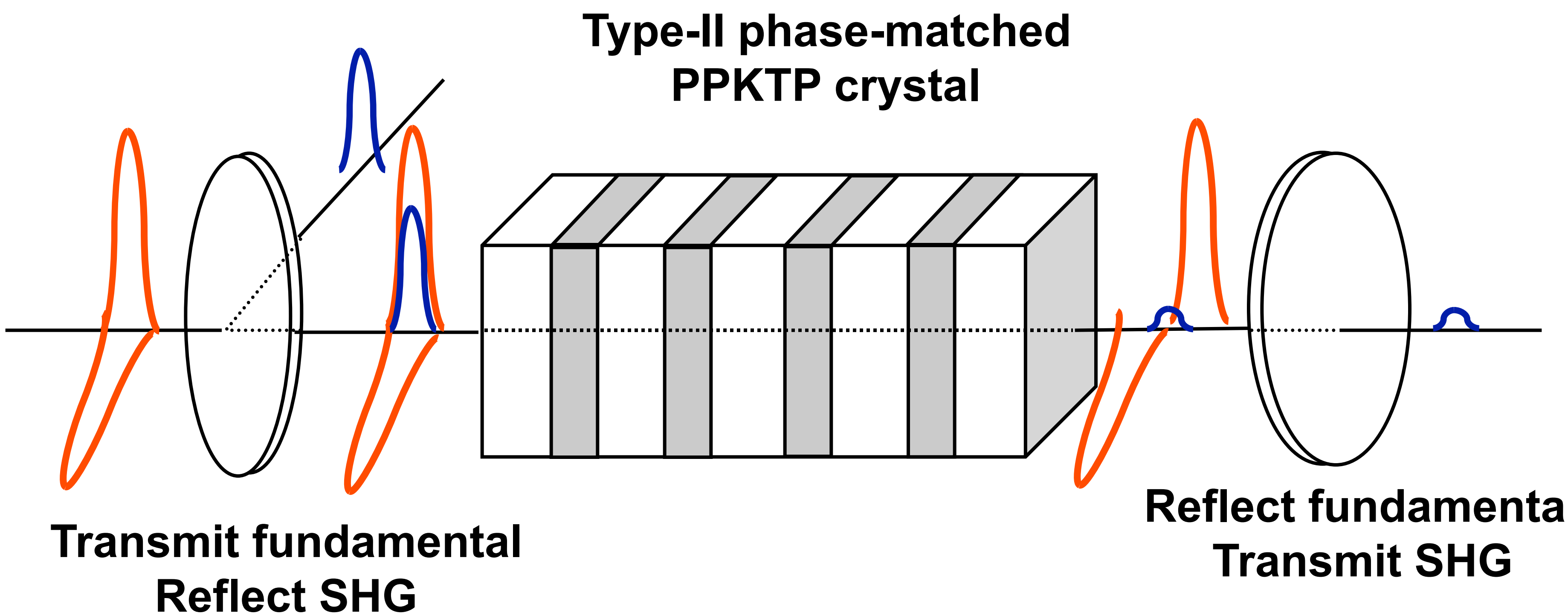
J. Kim et al., Opt. Lett. 32, 1044 (2007)

Single-crystal balanced cross-correlator



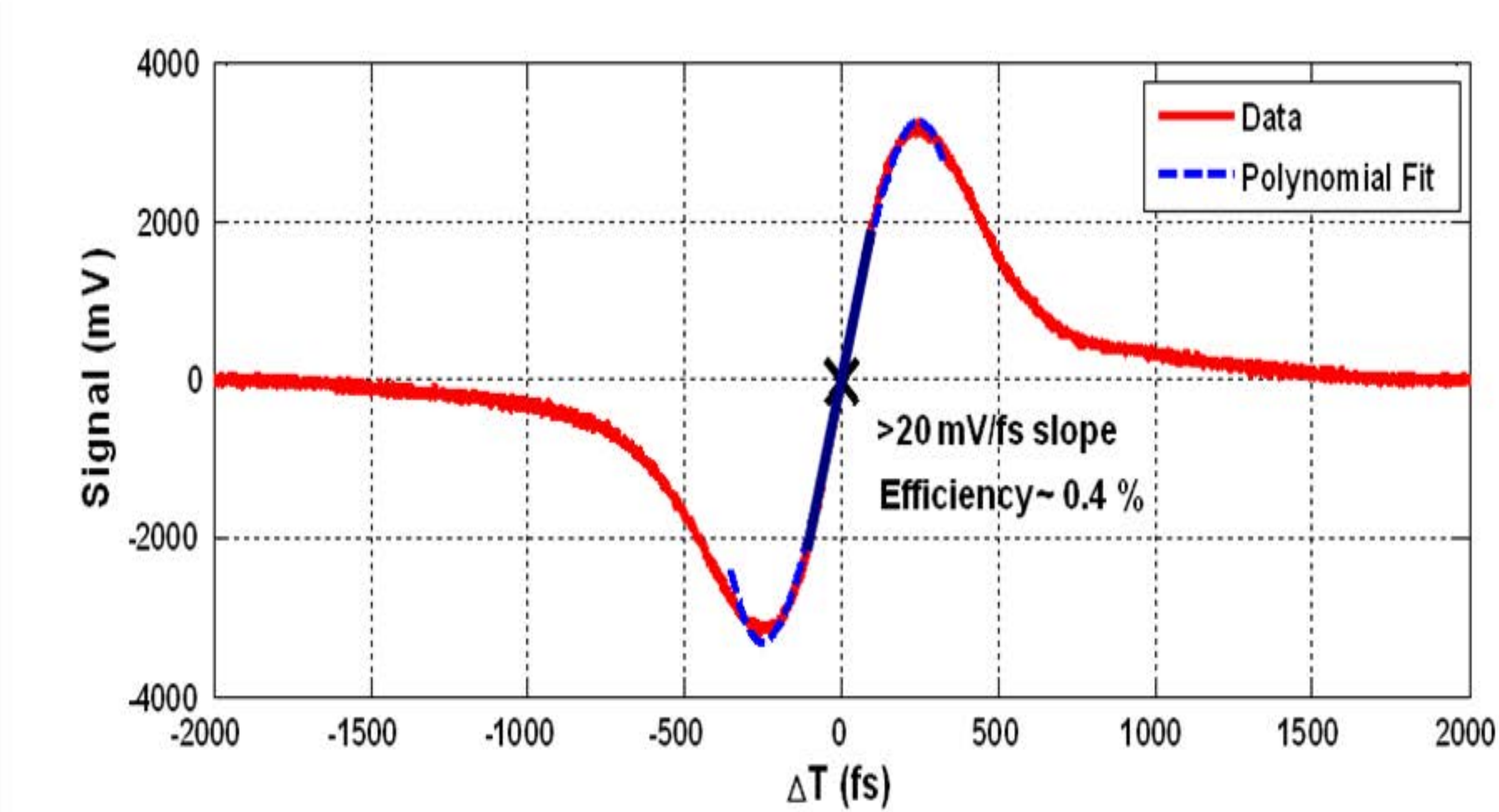
J. Kim et al., Opt. Lett. 32, 1044 (2007)

Single-crystal balanced cross-correlator



J. Kim et al., Opt. Lett. 32, 1044 (2007)

Single-crystal balanced cross-correlator

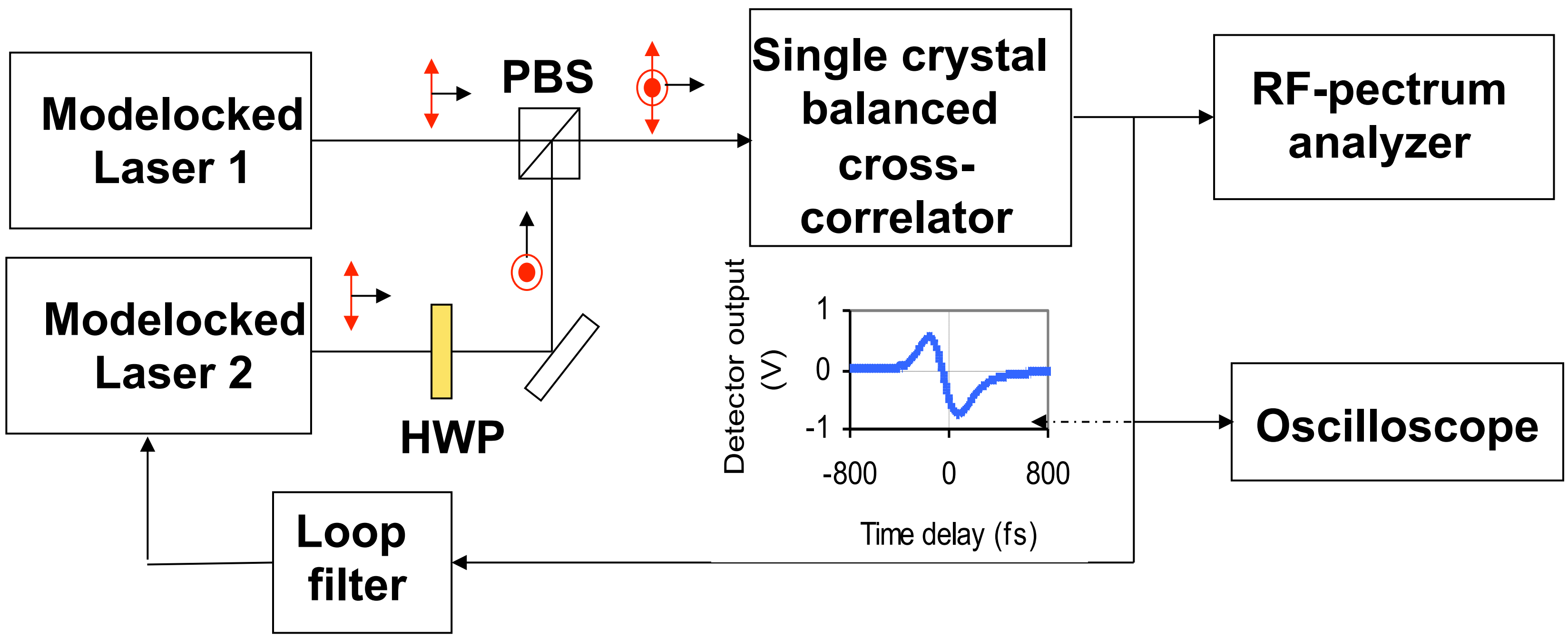


80 pJ, 200 fs
1550nm input pulses
at 200 MHz rep. rate

In comparison:
Typical microwave mixer
Slope ~1 μV/fs @ 10 GHz
Greatly reduced thermal drifts!

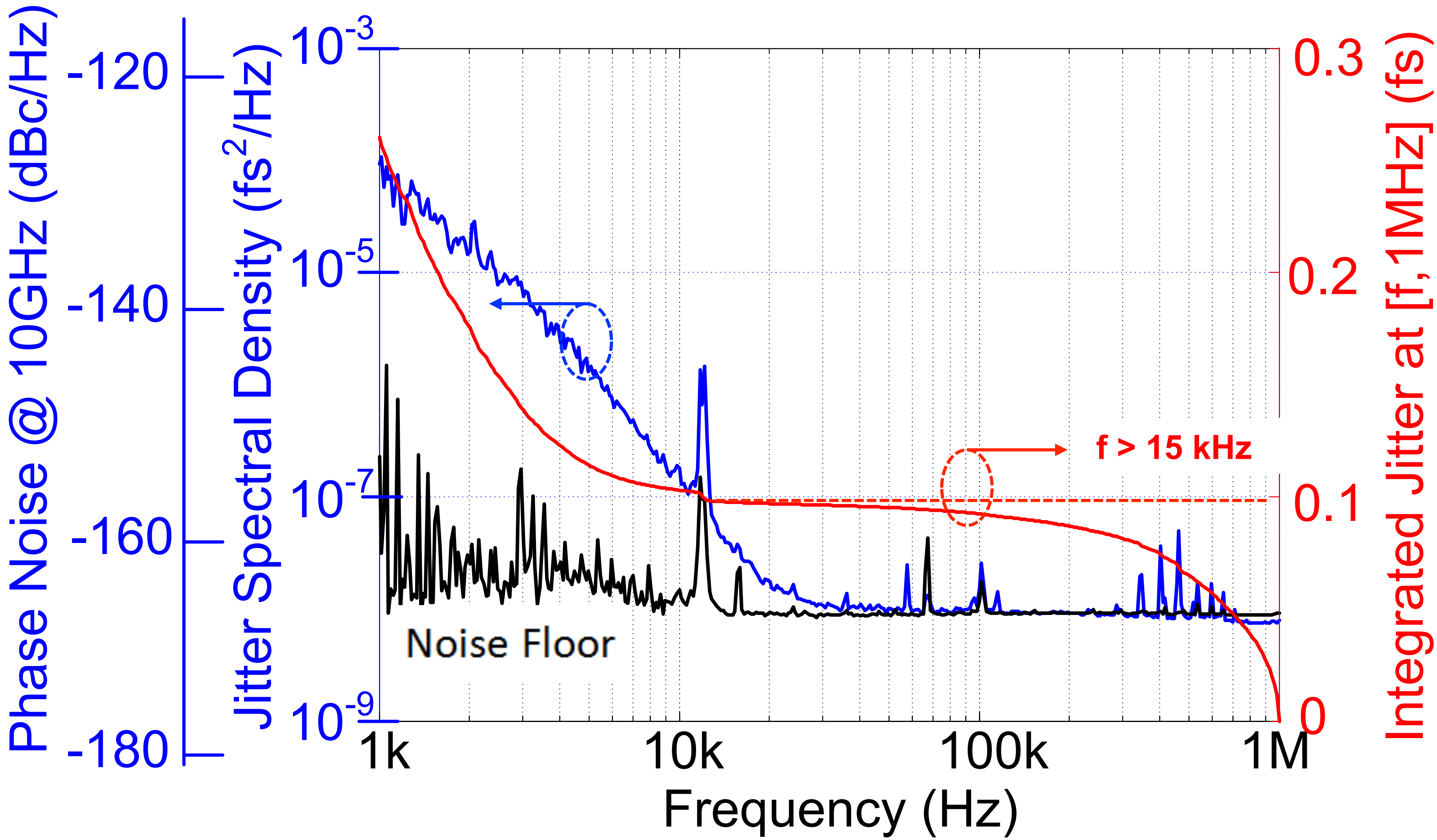
Timing jitter of lasers

Phase detector method → Timing Detector method



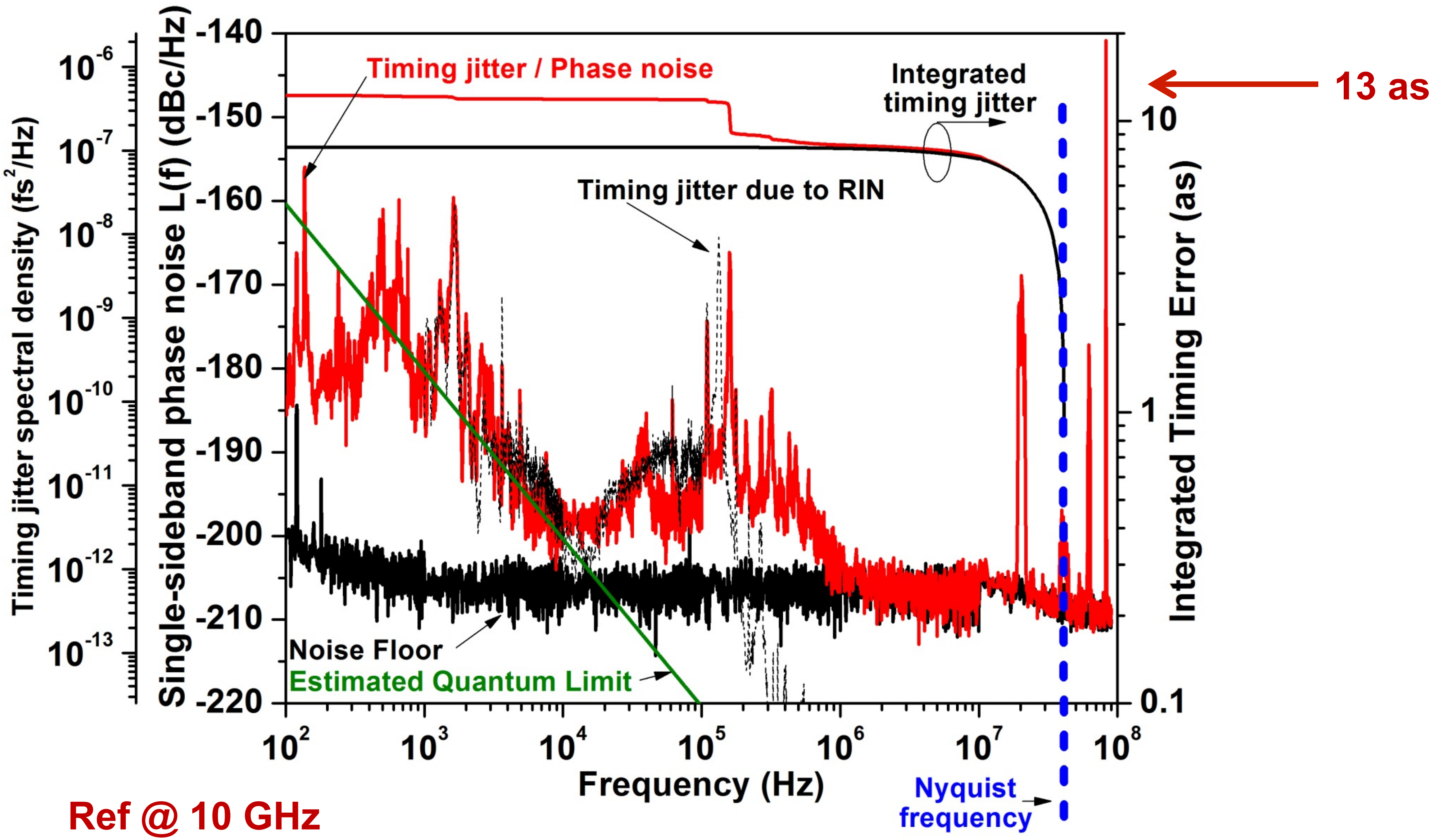
J. Kim, et al. , Opt. Lett. 32, 3519 (2007).

Timing jitter of OneFive:Origami Laser



K. Safak et al., Int. J. Structural Dynamics 2:(4) 041715 (2015).

Two 10-fs Ti:Sapphire Lasers Synchronized within 13 as

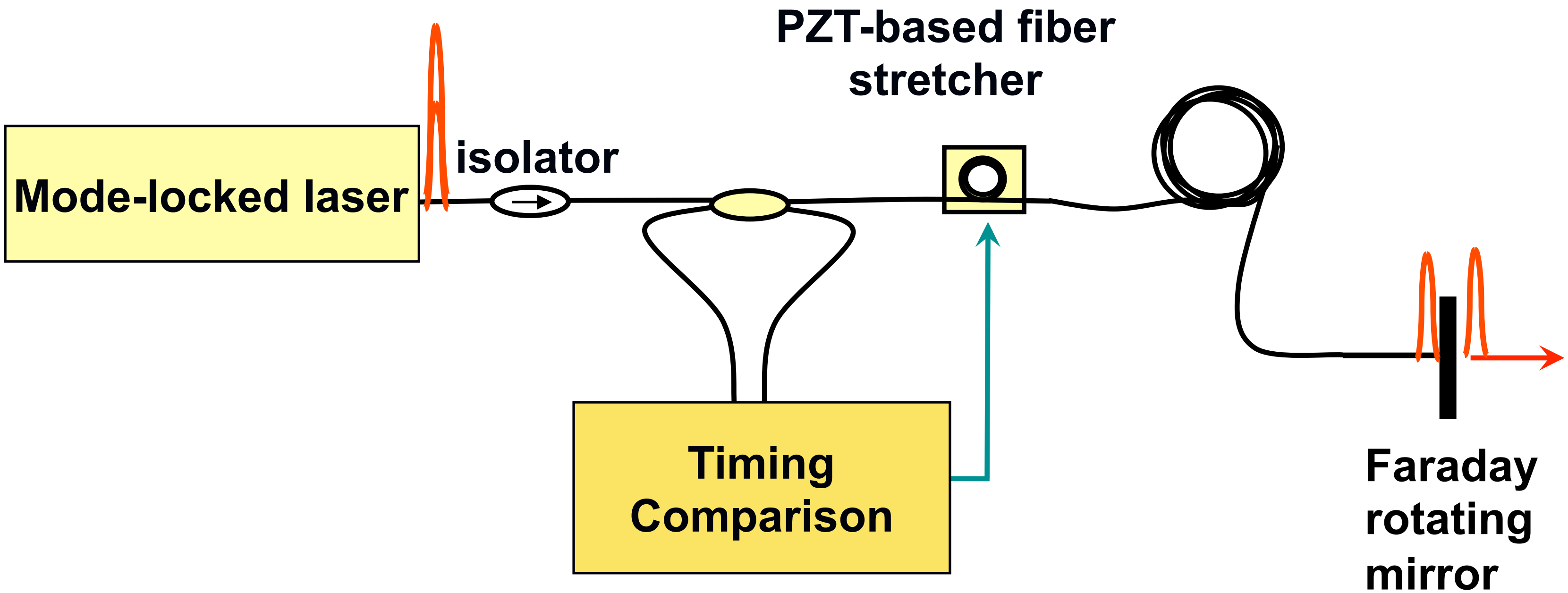


Ref @ 10 GHz

A. Benedick, et al. Nat. Phot. 6, 97-100, 2012

Timing-stabilized fiber links

Fiber link ~ 100m - 5km
SMF/DCF or PM/PMDCF

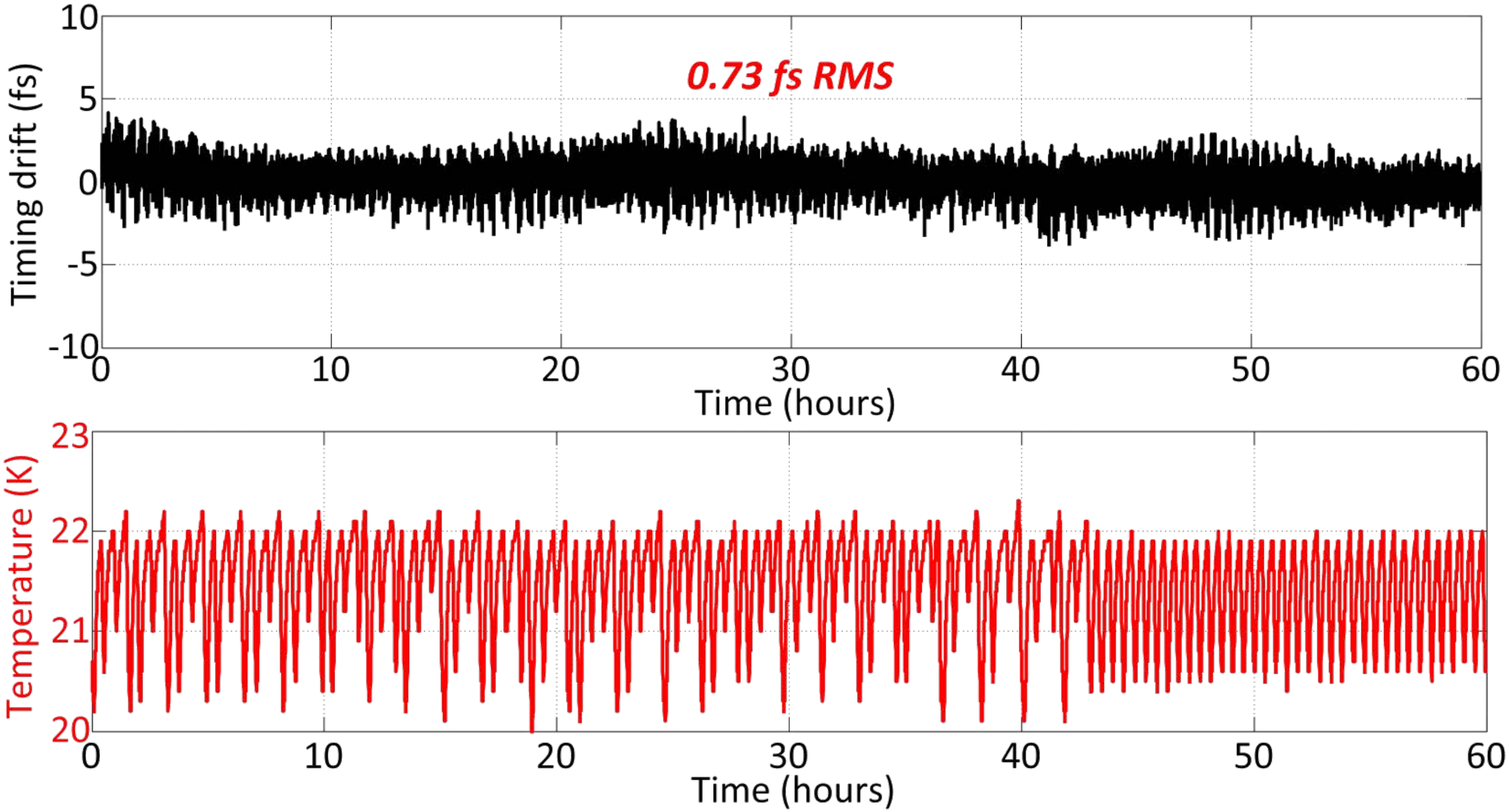


Cancel fiber length fluctuations slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 μs → ~100 kHz BW

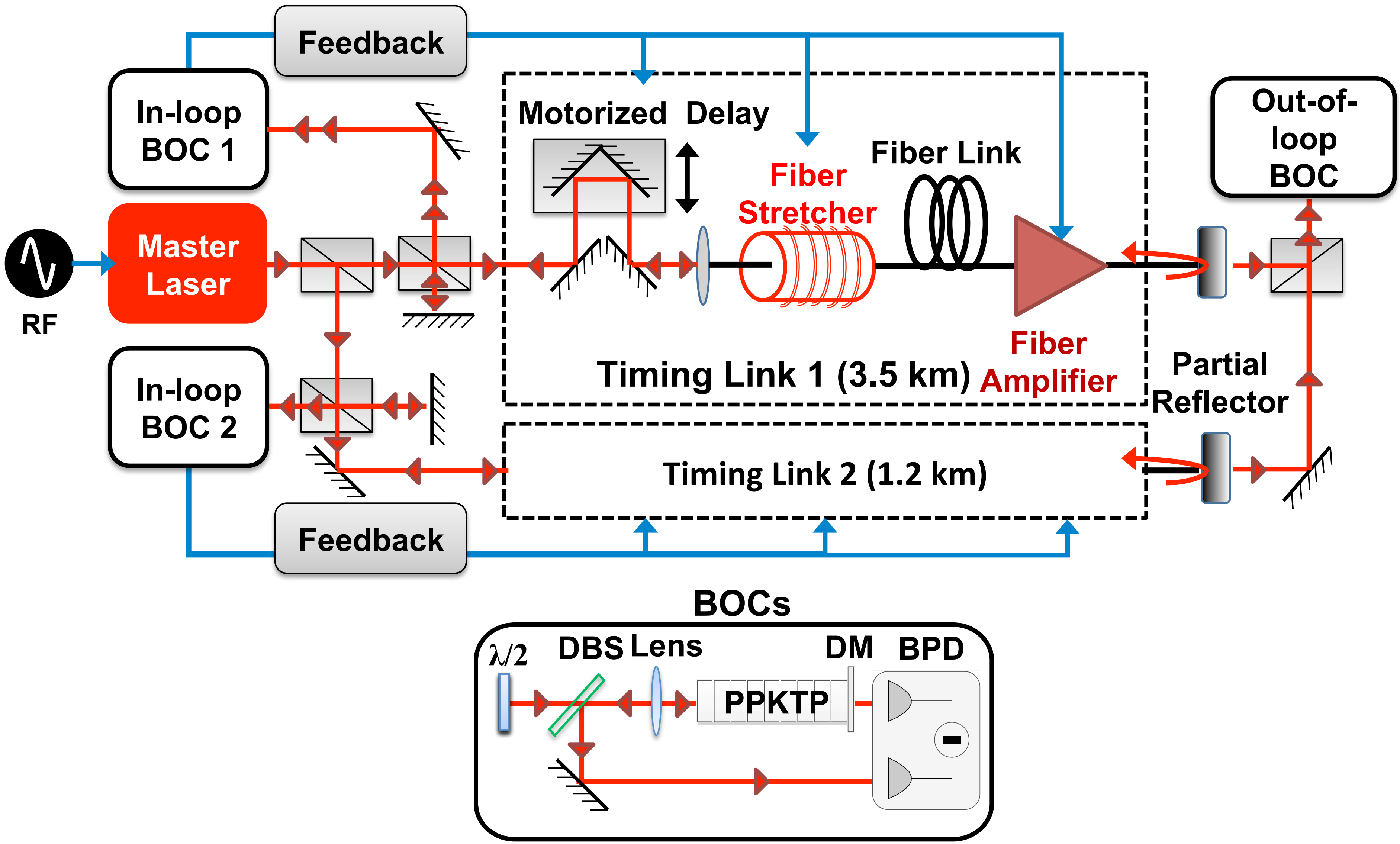
60 hours operation in commercial system

Out-off loop timing titter between two 150 m PM-links in a 16-link system



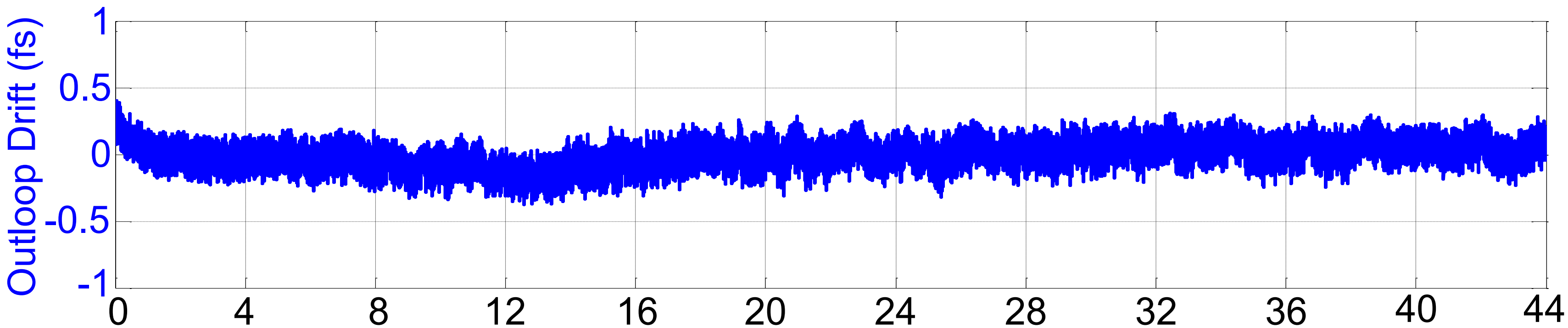
Courtesy Cycle GmbH

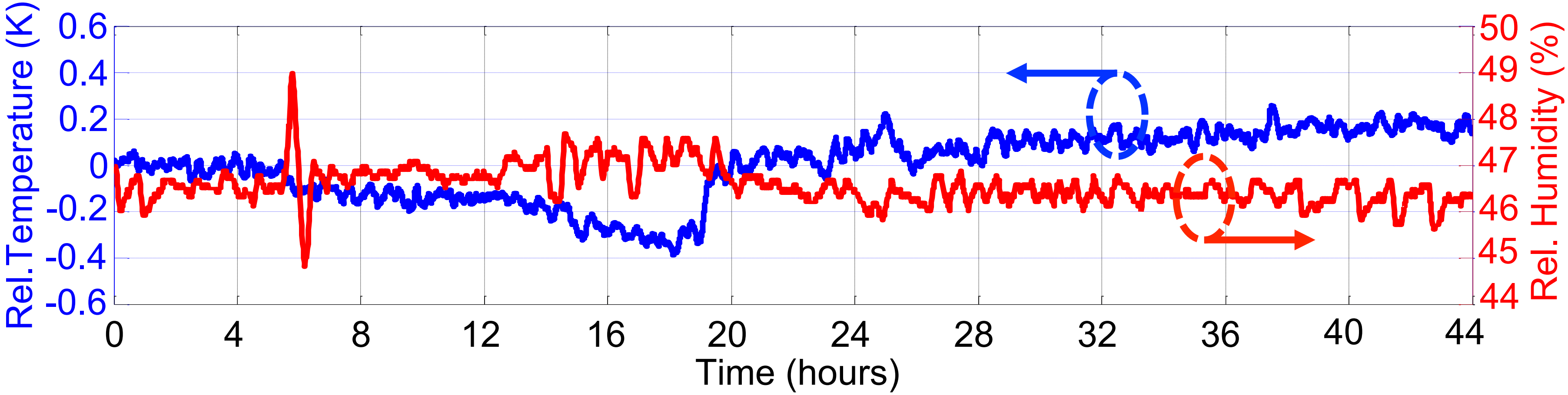
Fiber network stabilization with sub-fs precision



High precision PM-link results (OFS)

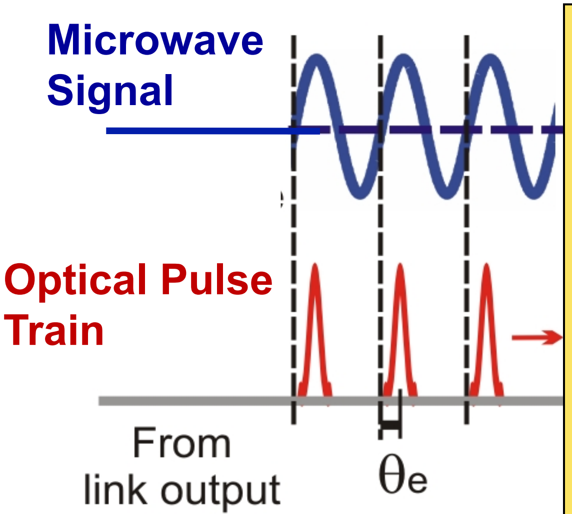
Laser-to-Laser Remote Synch.: 100 as RMS & 0.6 fs Pk-Pk drift (< 1Hz) over 44 h

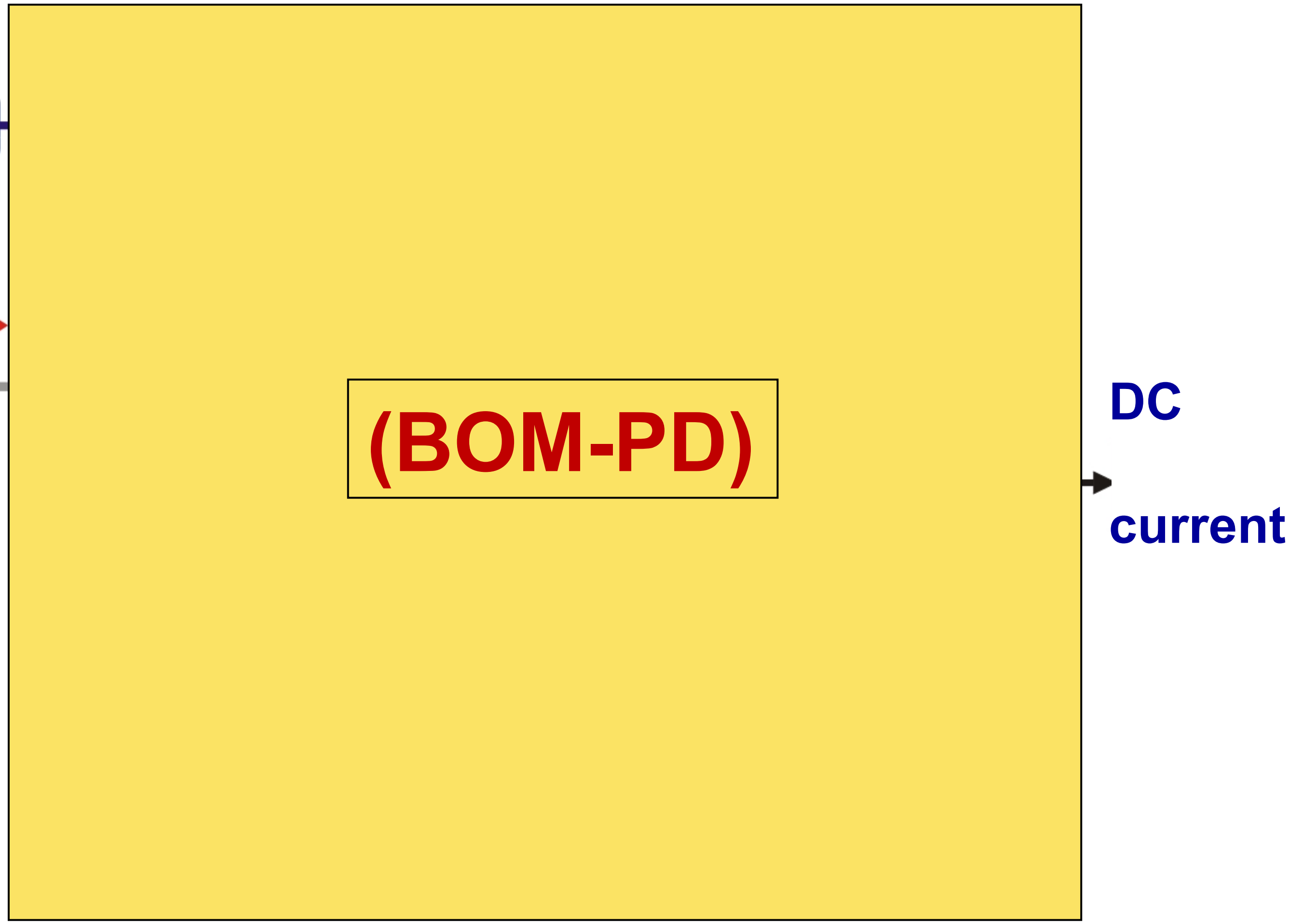




M. Xin et al., Light: Science & Applications July 2016; doi: 10.1038/lsa.2016.187.

Balanced Optical-Microwave Phase Detector





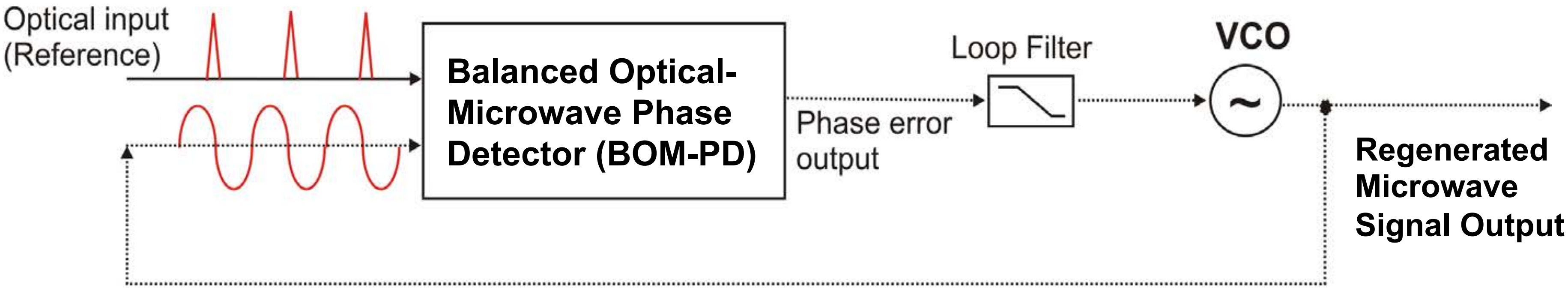
Convert Phase /Timing information in optical domain into intensity modulation

Electro-optic sampling of microwave signal with optical pulse train

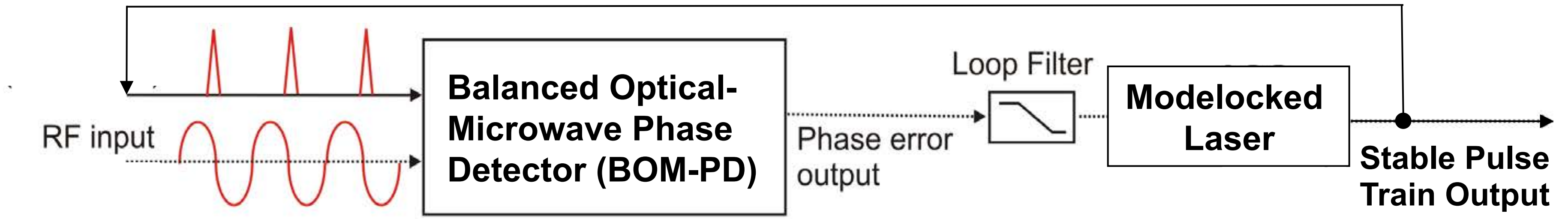
J. Kim et al., Opt. Lett. **29**, 2076 (2004), **31**, 3659 (2006).

Optoelectronic Phase-Locked Loop (PLL)

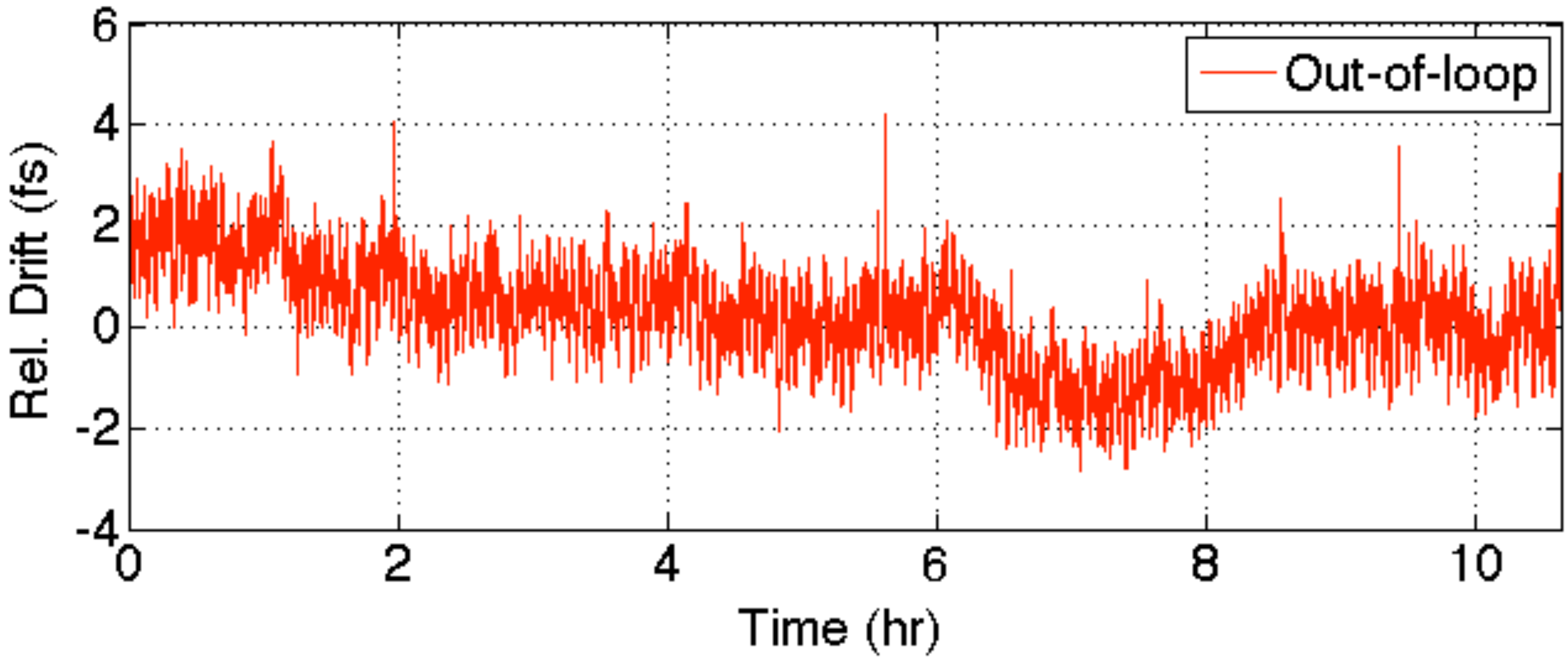
Regeneration of a high-power, low-jitter and drift-free microwave signal whose phase is locked to the optical pulse train.



Tight locking of modelocked laser to microwave reference



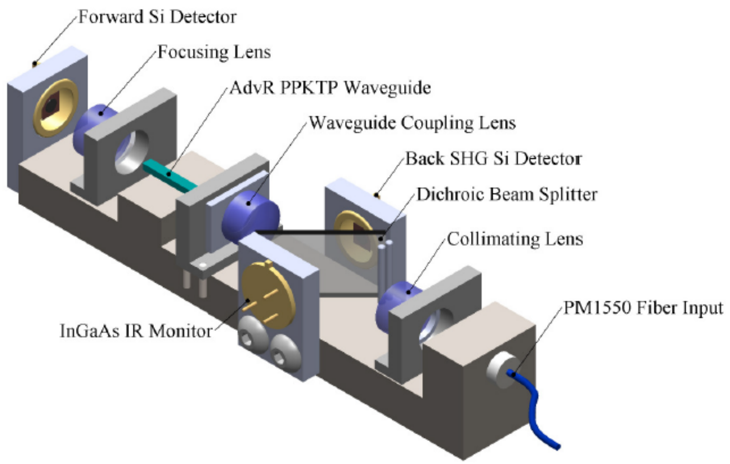
Long-term stability: < 1 fs rms drift over 10 hours

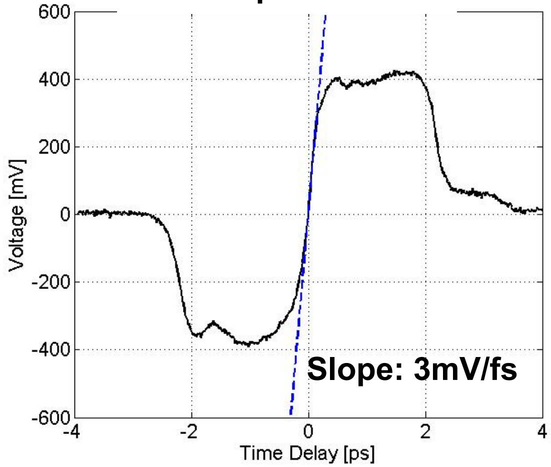


M. Y. Peng, A. Kalaydzhyan, F. X. Kärtner, Opt. Express, 22:(22) pp.27102 (2014).

Integrated Waveguide BOCs

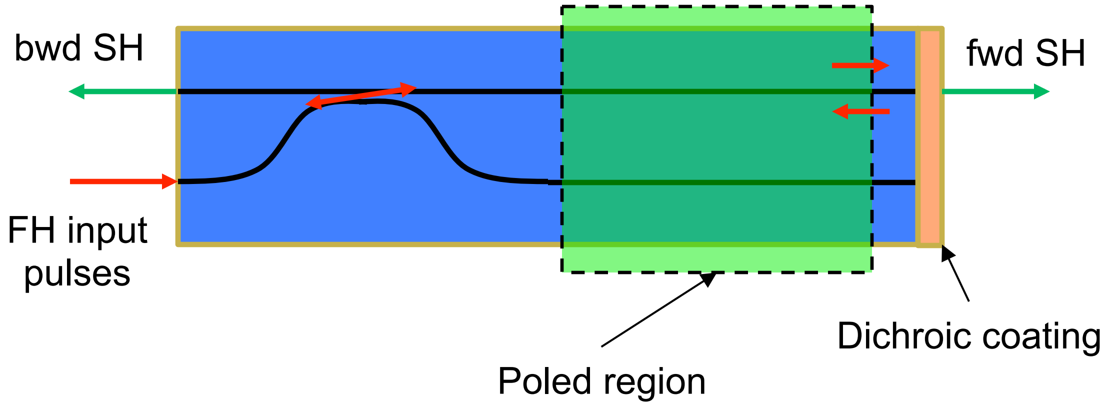
- **Packaged waveguide BOC module with miniaturized coupling optics:**

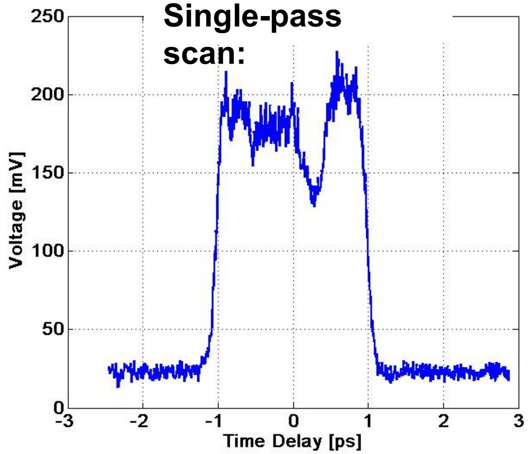




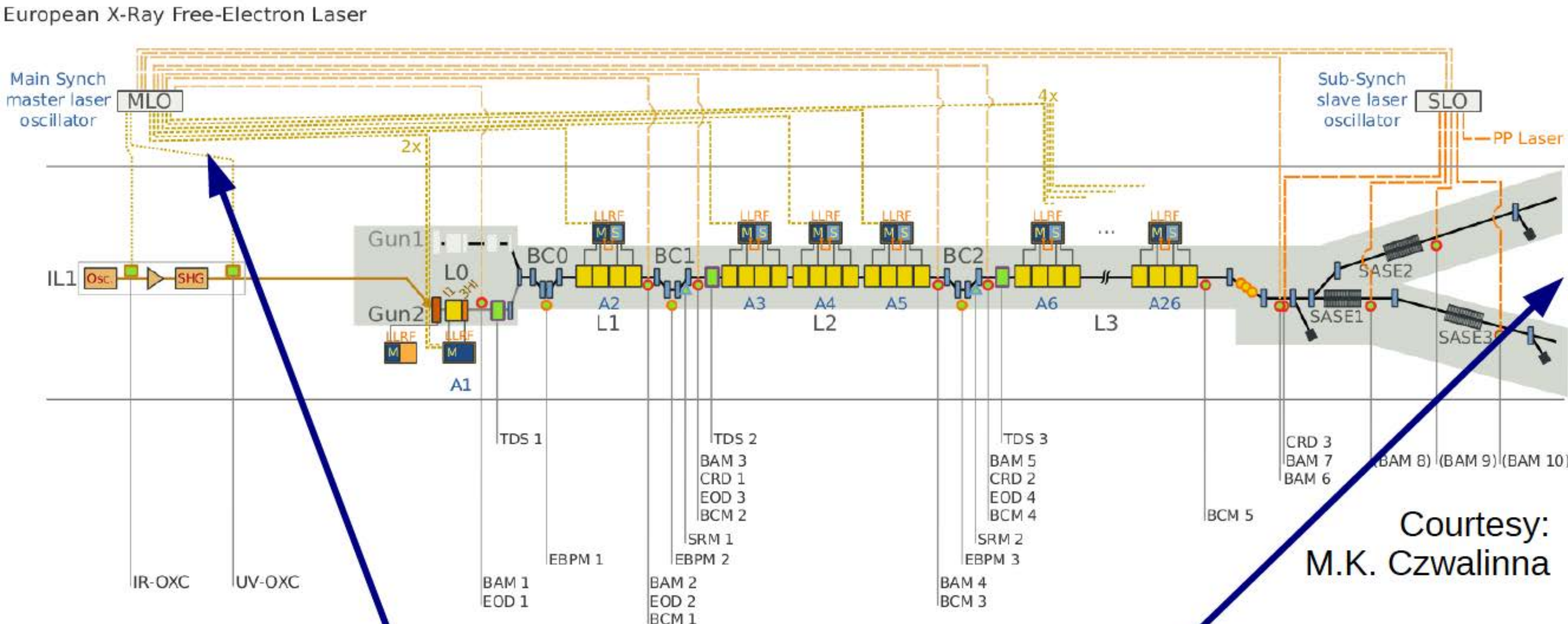
Input:
P_{avg} = 10mW
f_{rep} = 80MHz
τ = 200fs

- **Next generation devices: KTP waveguides with integrated WDM couplers**





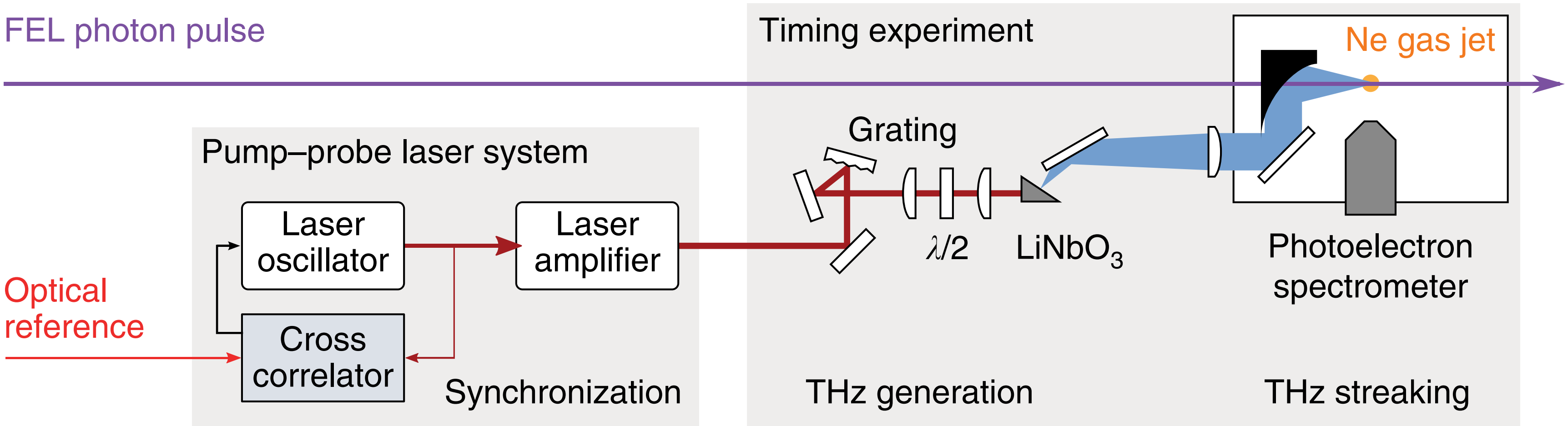
European XFEL Timing Distribution System

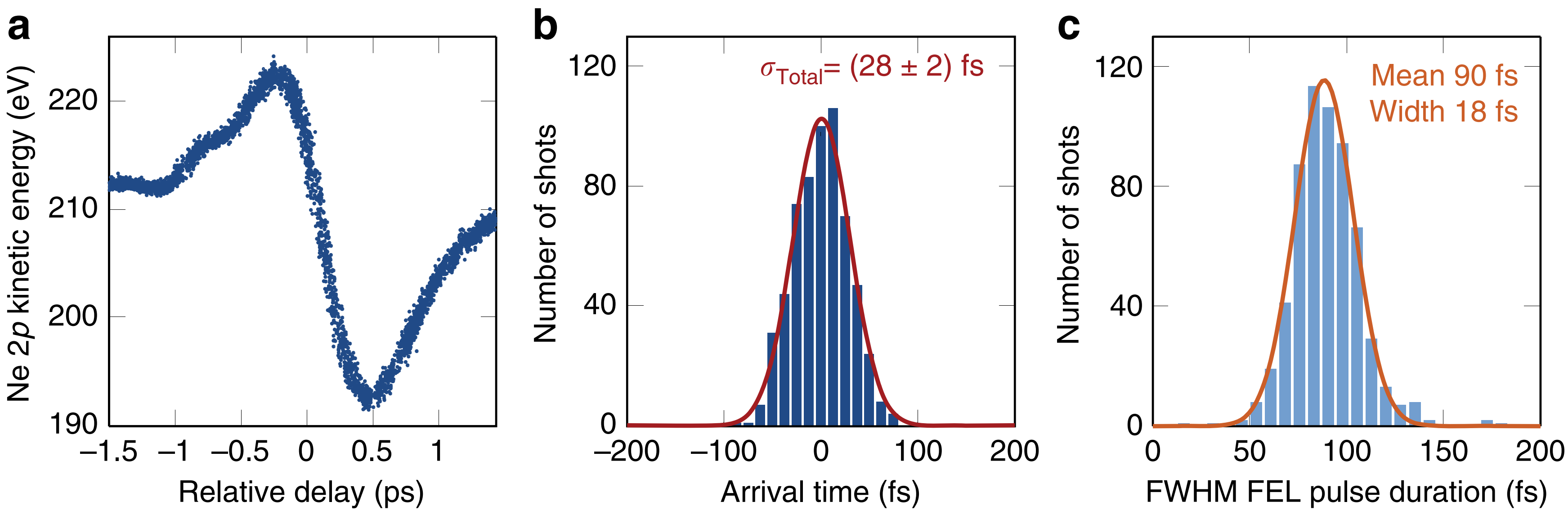


Courtesy:
M.K. Czwalinna

- XTIN: 24 link stabilization units at injector site
- XHEXP1: 2nd synchronization room in the experimental hall
  - Slave laser oscillator
  - 8 link stabilization units (space for up to 20)

THz streaking of FEL - pulses



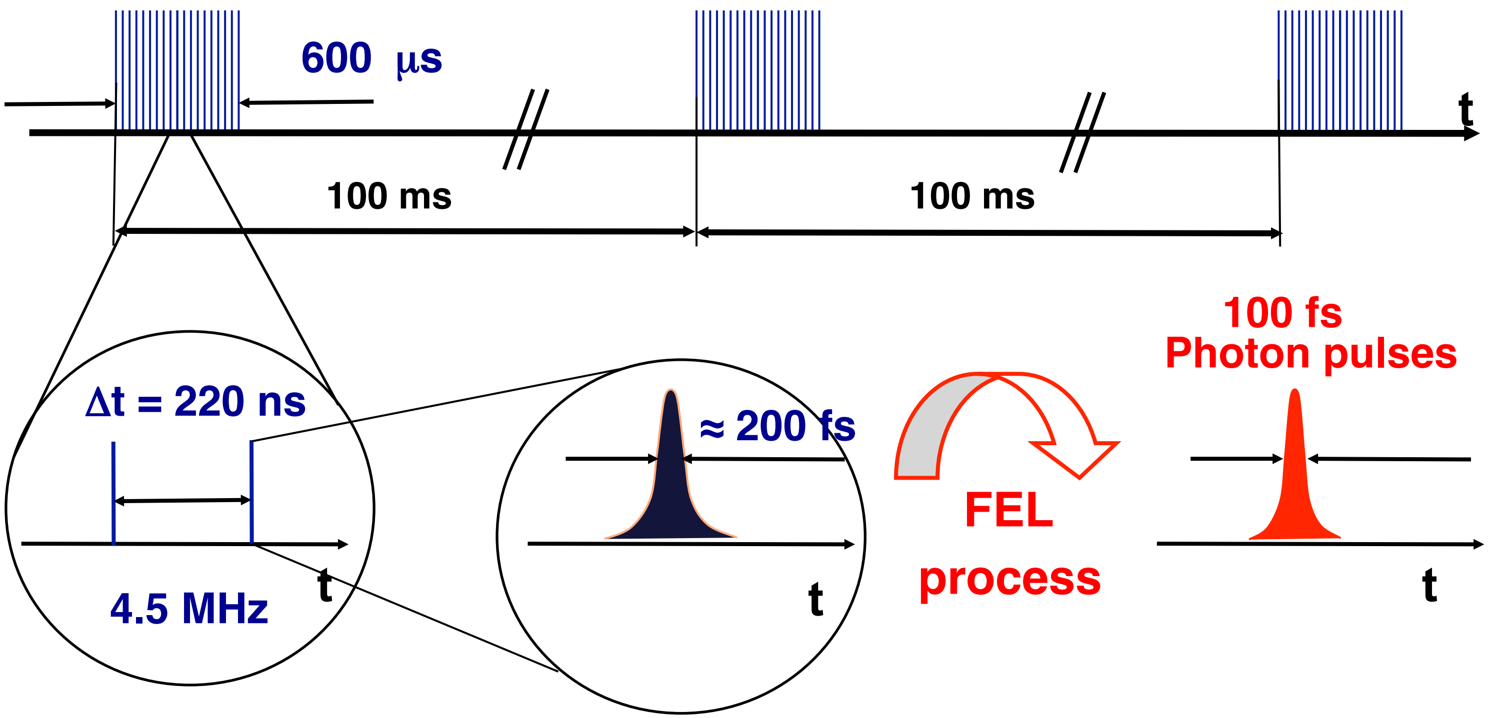


Schulz et al. Nat. Com. 6, 9538 (2015)

The Laser Challenge – High Repetition Rate FELs

Pulse Formats at FLASH / European XFEL

10Hz electron bunch trains (with 800 / 2700 bunches à 0.1…1 nC)



Burst mode: Thermal Transients

LCLS II: continuous 100kHz / 1 MHz

→ Large Average Power Lasers

OPCPA Pump Laser Technology

Burst-mode power amplifier

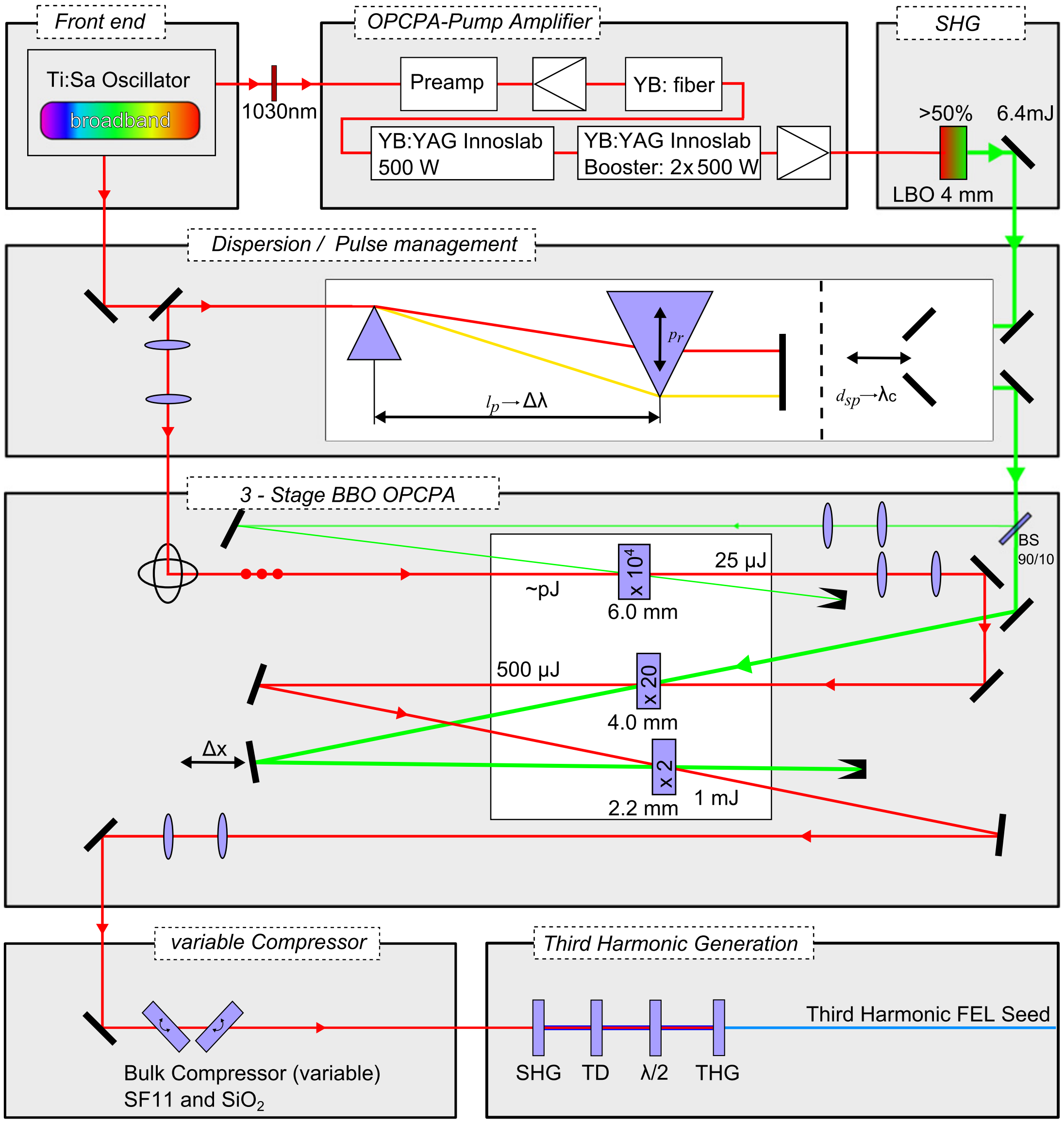
Amp. Technology / Property	Yb-Fibre	Yb-Fibre + coherent combining	Yb:YAG InnoSlab	Yb:YAG Thin-Disk		Cryo-Yb:XXX
				Regen	Multi-pass	
TEM_{00} av. power	++	++	+	+	+	+
CPA pulse energy	– –	??	+	+	+	+
Sub-ps capable	+	+	+	+	+	+
MHz rep-rate	++	++	++	– –	++	++
Gain / amp-length	++	++	++	– –	– –	++
Thermal transients	++	++	0	0	0	0
Complexity	+	– –	0	–	–	LN_2
Availability (near term)	+	– – +	+	+	+	–

Tavella Group: Development

Höppner et al.
New J. Phys. 17,053020 (2015)

In burst mode:
> 112 W
> 1.2 mJ
> 30 fs tunable
@ 100 kHz

Thin Disk amplifier
6 - 13 kW in burst mode

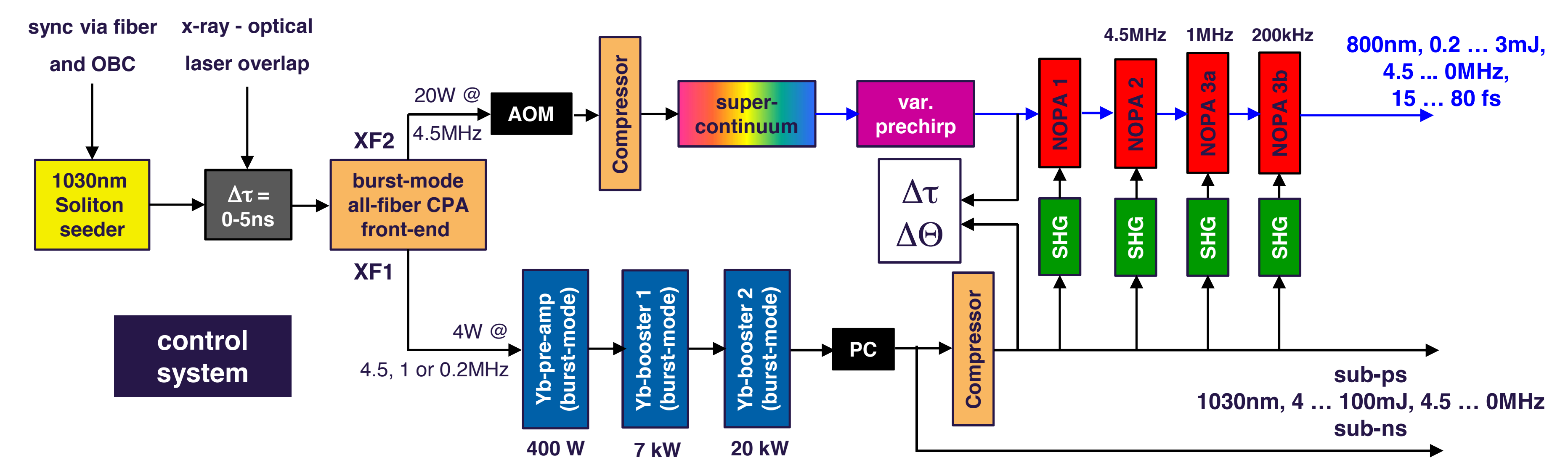


XFEL PP-Laser Development by M. Lederer

European XFEL

XFEL / DESY 5th LAC-meeting, 1st / 2nd June 2015

Pump-Probe laser concept and status:



- **Arbitrary pulse and burst selection for „pulse-on-demand“ (PoD)**

In burst mode: > 1 mJ @ 200 kHz (15 fs); > 200 W

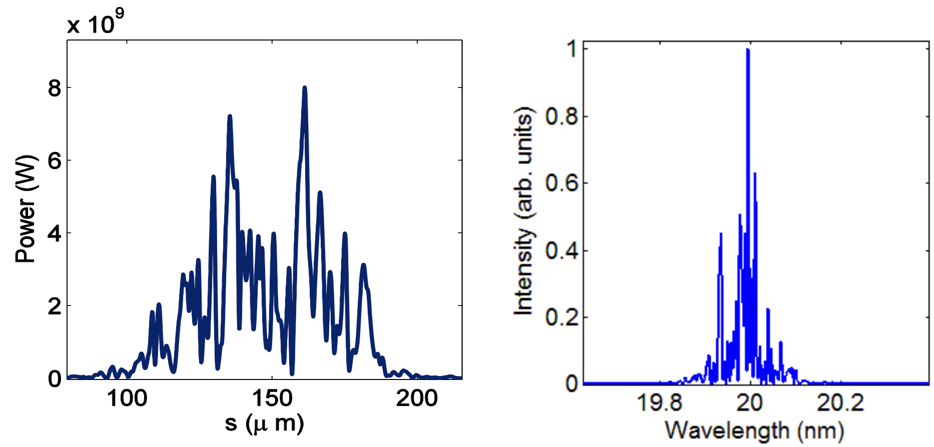
SASE versus Seeding

Self-Amplified-Spontaneous-Emission (SASE):

Start-up from spontaneous radiation is a statistical process

- → **Temporal and spectral coherence not adequate.**
- → **Precise pump-probe experiments difficult.**

Genesis Sim

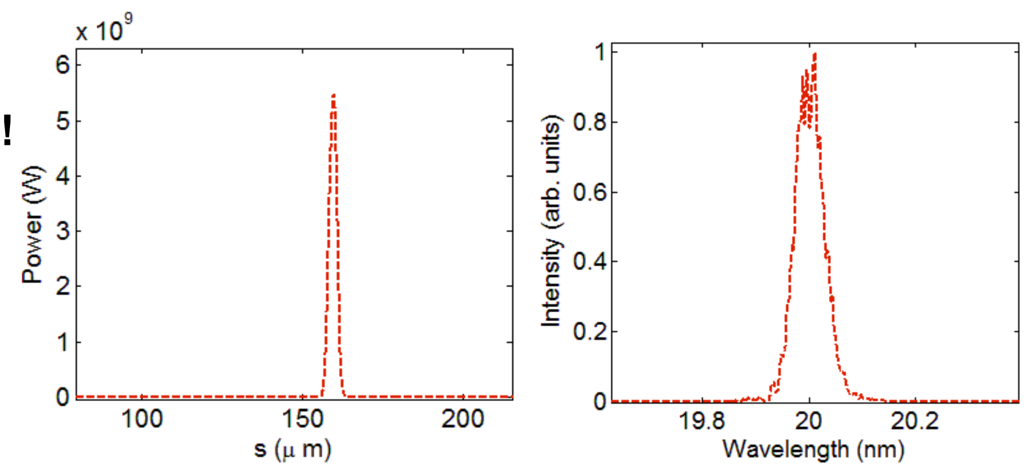


Seeding:

External XUV source starts the process!

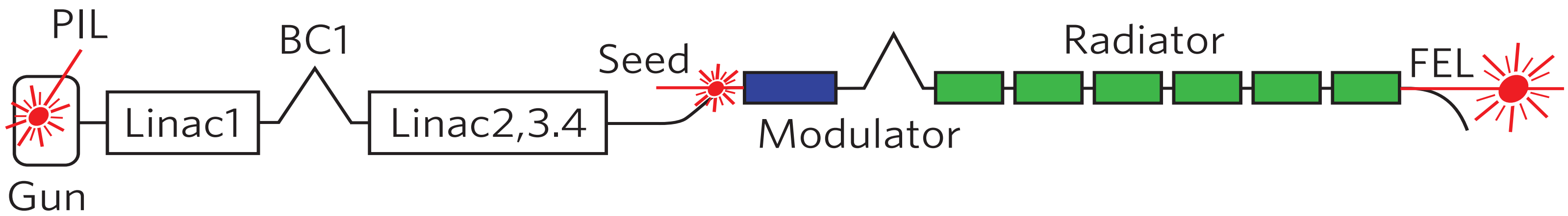
- → **External pulse imprints characteristics on e-bunch**

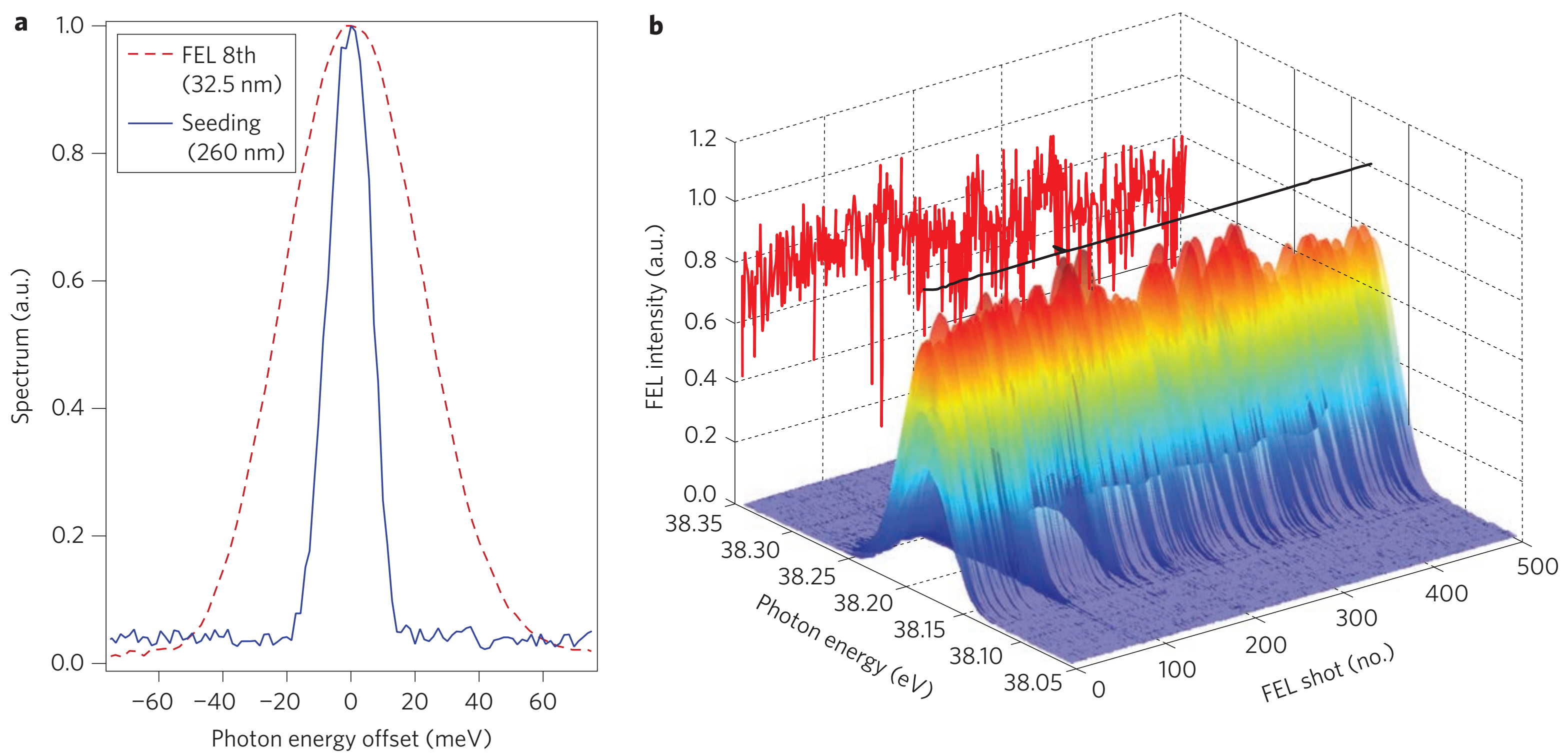
Driving laser tightly synchronized to pump-probe laser



Courtesy of Franz Tavella

Successful UV Seeding at FERMI and HGHG



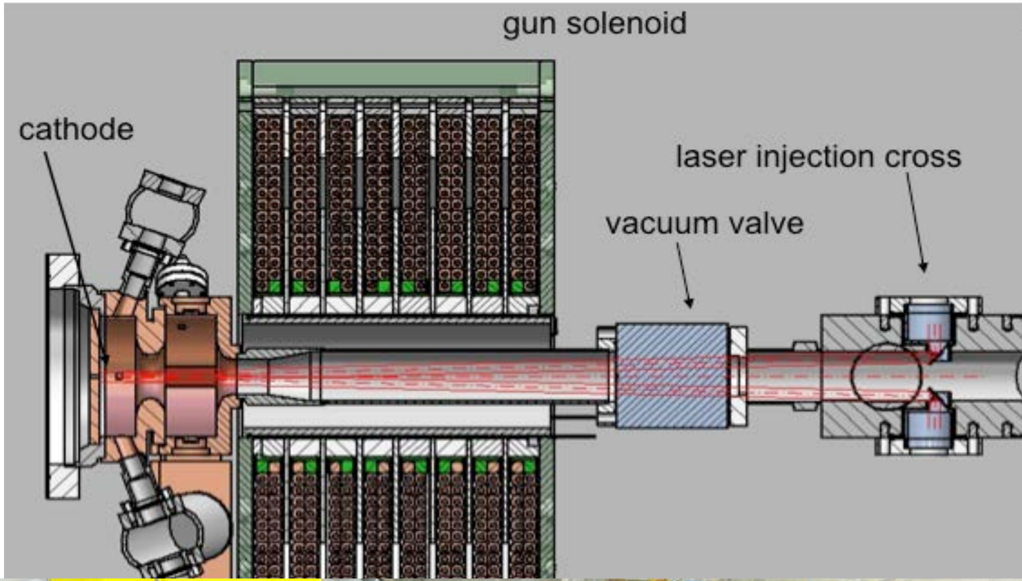


Single-shot and multi shot spectra at 32 nm.

E. Allaria et al., Nat. Photonics 6, 699 (2012)
& Nat. Photonics 7, 913 (2013)

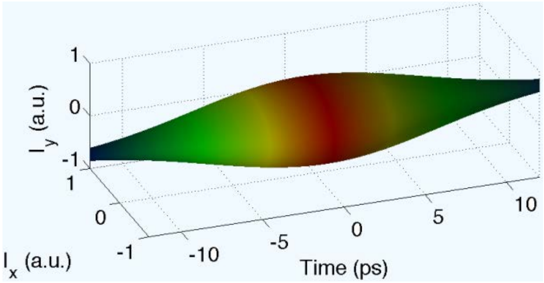
Photocathode Laser: UV ps laser system (Courtesy: I. Hartl)

- 10 to 120 Hz systems:
  Cu cathode,
  1mJ, 10ps, 260nm
- MHz burst mode:
  Cs:Te cathode
  3μJ, 10ps, 260nm
- Spatial and temporal shaping required for good emittance
- Instability directly translates to FEL instability
- Laser failure directly translates to FEL failure
- 24/7 operation,
  (4hr access every 2 weeks)
  radiation damage



Spatio-Temporal Pulse Shaping For Low Emittance

Standard

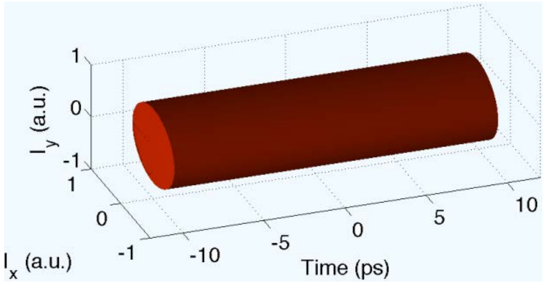


Temporal Gauss, spatial flat-top

Standard config. (non ideal)

Straight forward to obtain

Aim

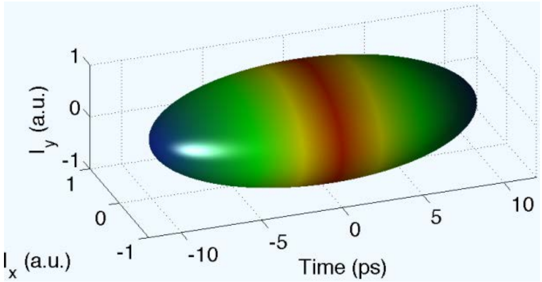


Temporal & spatial flat-top

Better emittance

Requires moderate efforts

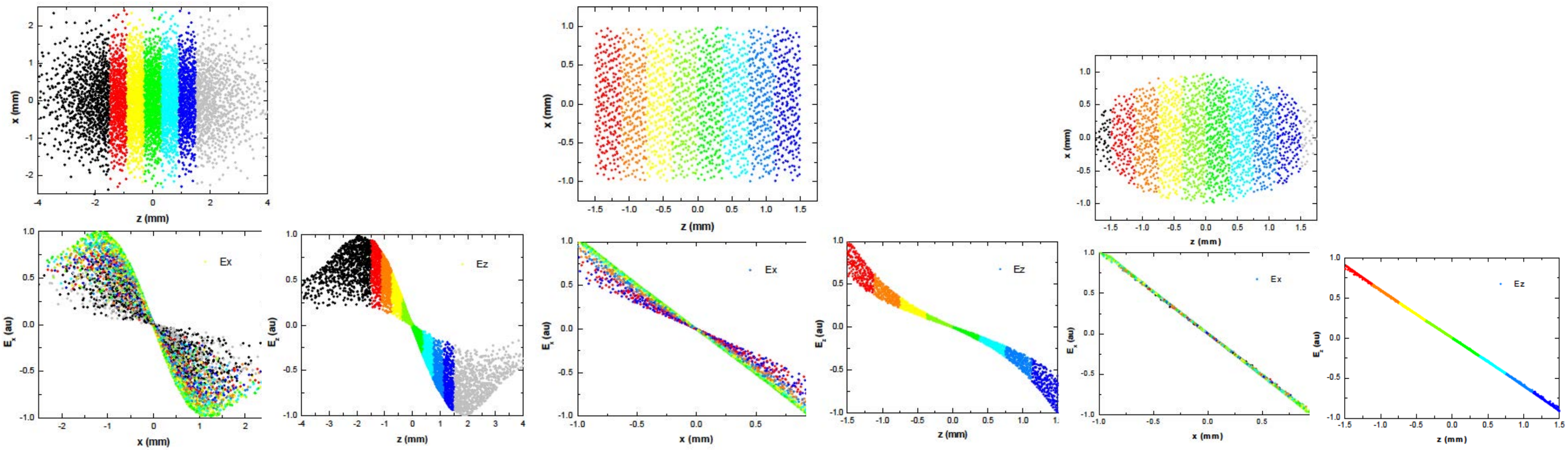
Future



Ellipsoidal / Egg

Lowest emittance

Very hard to obtain



Is a laser driven

compact <u>coherent</u> X-ray source

possible?

Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy *(AXSIS)*

Franz Kärtner
DESY, CFEL and University of Hamburg

Ralph Assmann
DESY, Hamburg

Henry Chapman
DESY, CFEL and University of Hamburg

Petra Fromme
Arizona State University, DESY

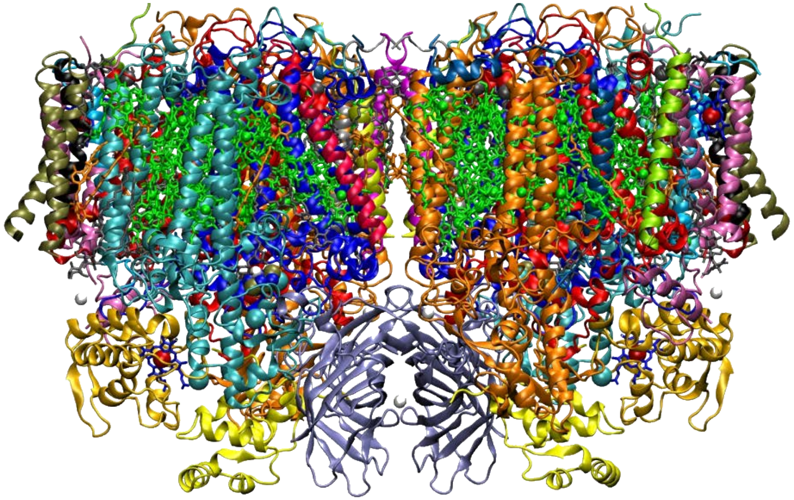
& Assoc. Scientists from Mid-Sweden University, DESY and MIT

MSU

ERC Synergy Project

Photosynthesis

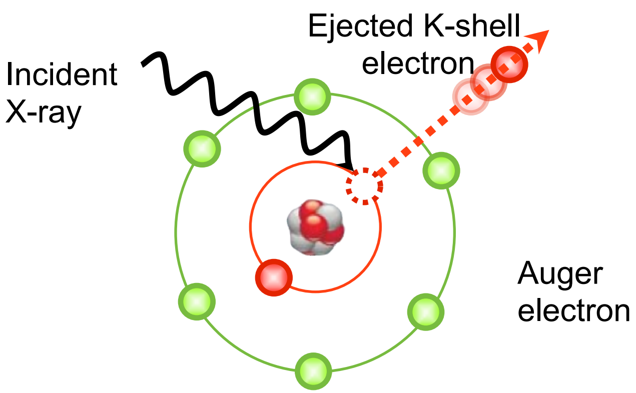
Photosynthesis transformed our planet 2.5B years ago producing oxygen, capturing solar energy and CO_2, that slowly converted to fossil fuels.



What is exactly happening?

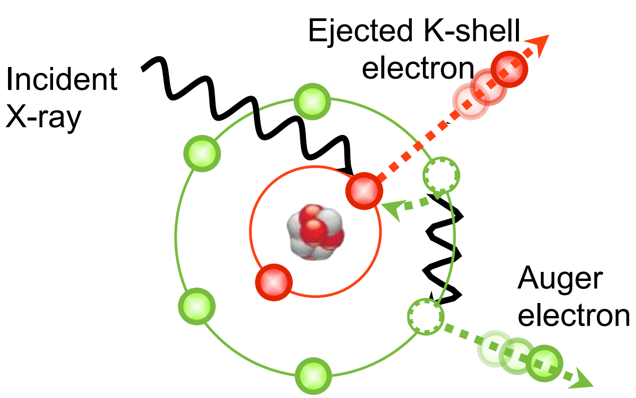
$$2H_2O + 4\ \text{photons} \longrightarrow O_2 + 4e^- + 4H^+$$

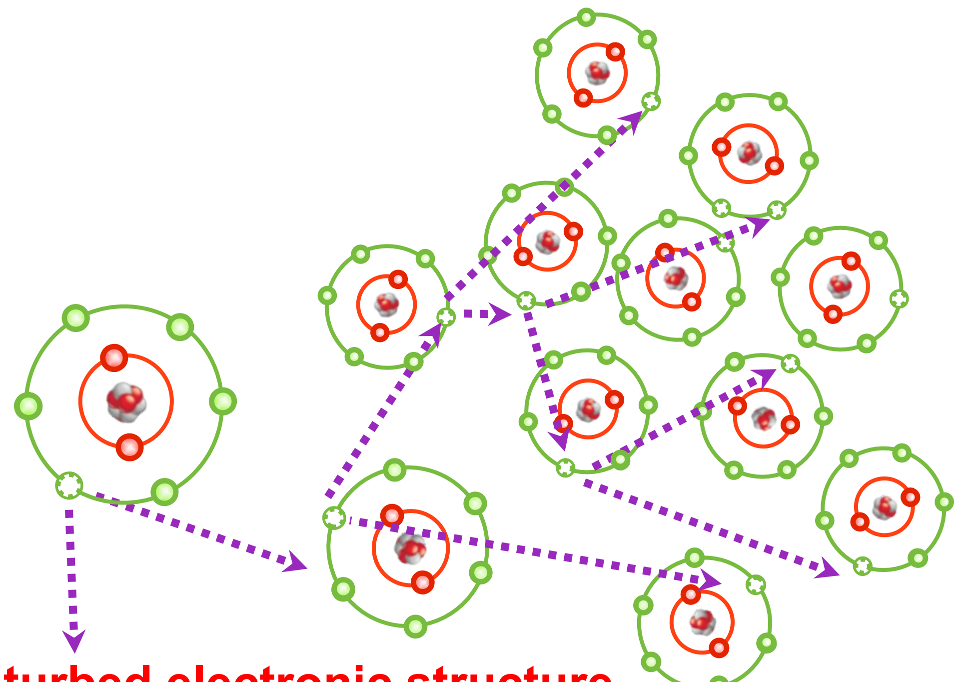
We must outrun electronic processes



We require sub-fs exposures to measure the chemical environment at atomic scale.

Time scale is **Auger decay rate**





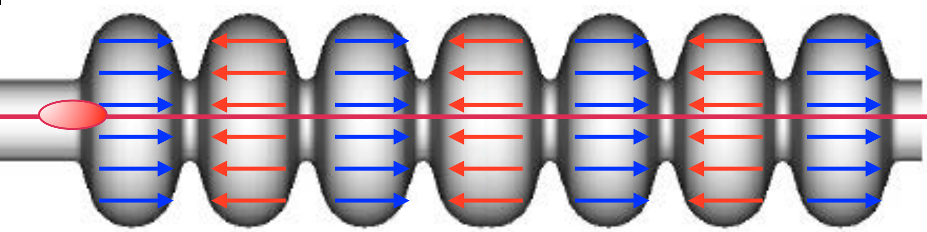
Auger decay rates
O: 3 fs
S: 1 fs
Mn: 0.2 fs

Attosecond X-rays → Undisturbed electronic structure

L. Young et al., Nature 466, 56–61 (2010)
S.-K. Son et al., Phys. Rev. Lett. 107, 218102 (2011) and Phys. Rev. A 83, 033402 (2011).

X-rays are produced from accelerated electrons

Traditional RF accelerator

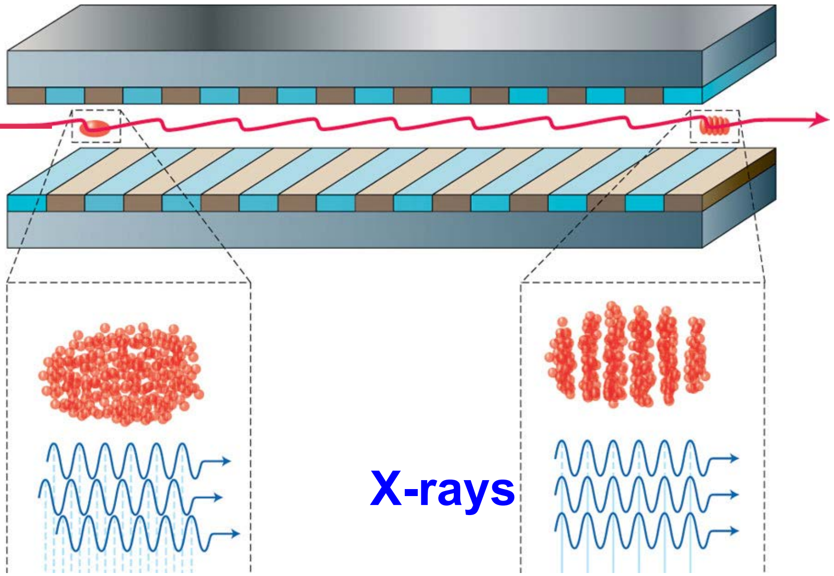


10 cm

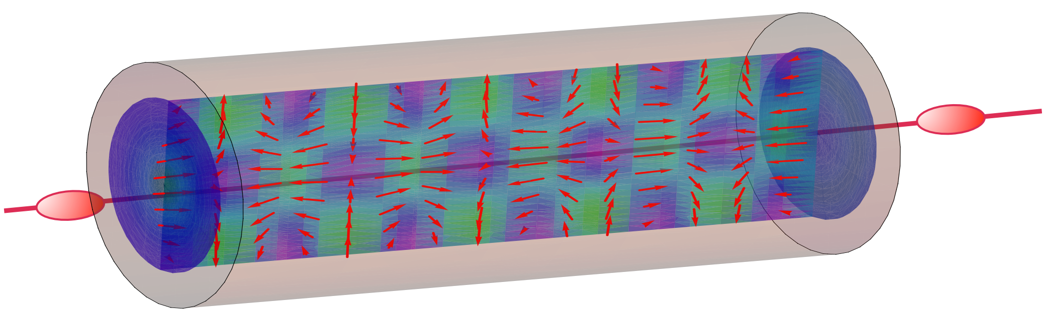
1 km

10 GeV

Magnetic undulator



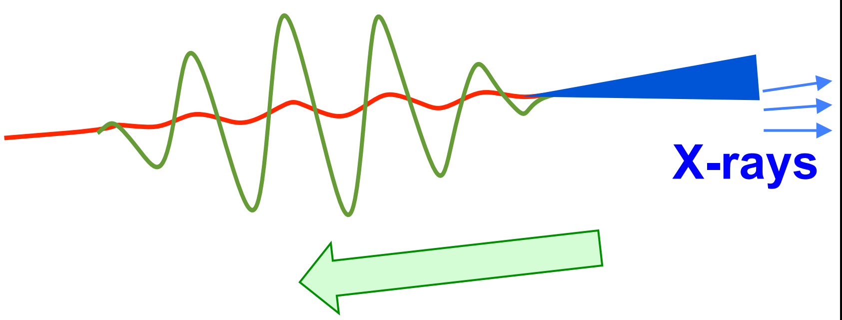
Terahertz cylindrical waveguide



100 μm

10 MeV

20 cm



Inverse Compton scattering

THz is interesting for acceleration and strong-field physics

- **Operation at higher frequencies**

higher breakdown fields

$$E_{break} \approx \frac{1}{\tau} \approx f$$

Historically:

[1] Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
[2] Loew, G.A., et al., 13th Int. Symp. on Discharges and Electr. Insulation in Vacuum, Paris, France. 1988.
[3] S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
[4] M. D. Forno, et al. PRAB. 19, 011301 and 111301 (2016).

- **Reduced pulse energy for same cavity electric field:**

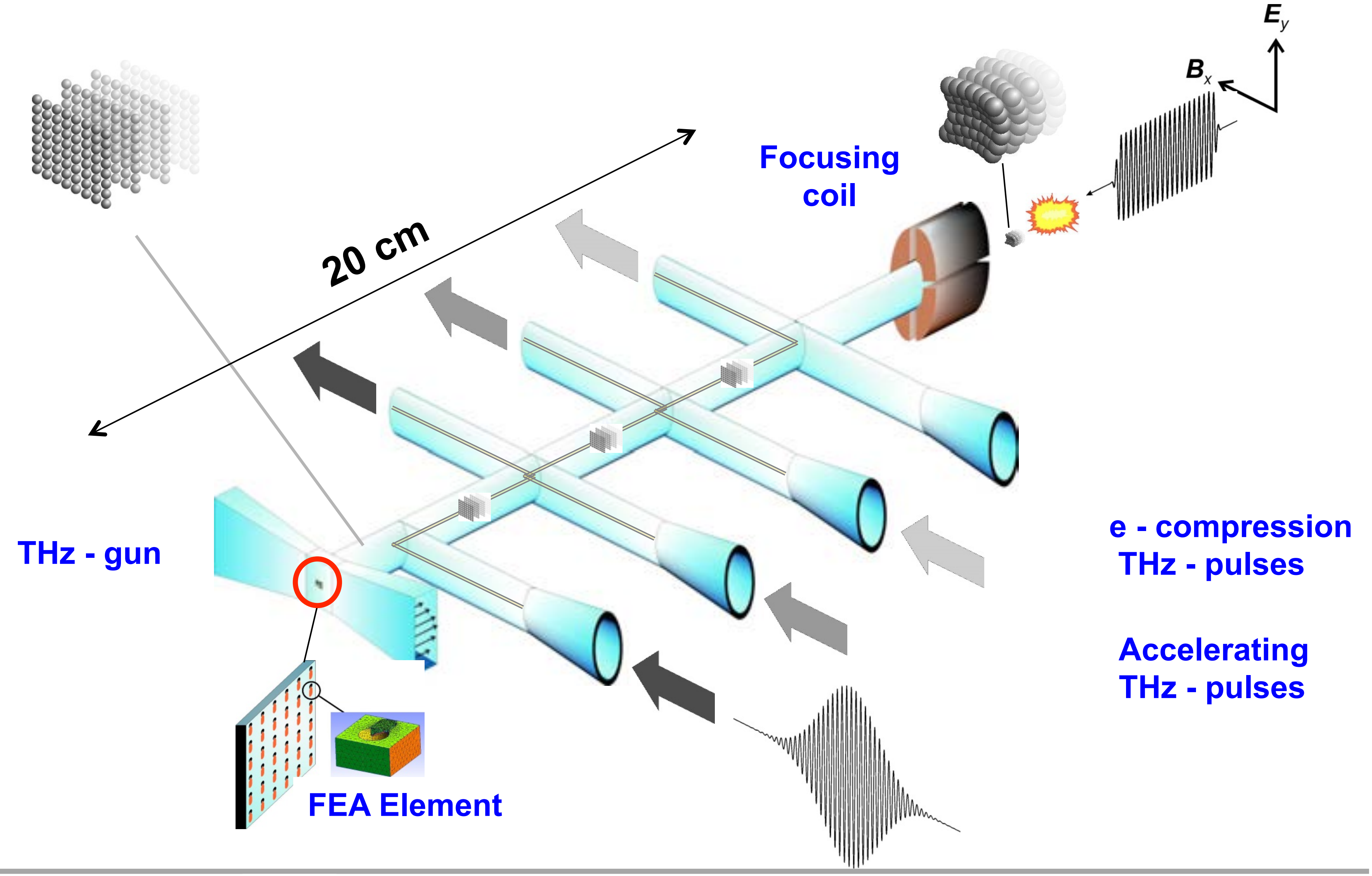
stored energy: $E_P \sim \lambda^{-3}$

reduced pulsed heating:
→ higher repetition rates possible!

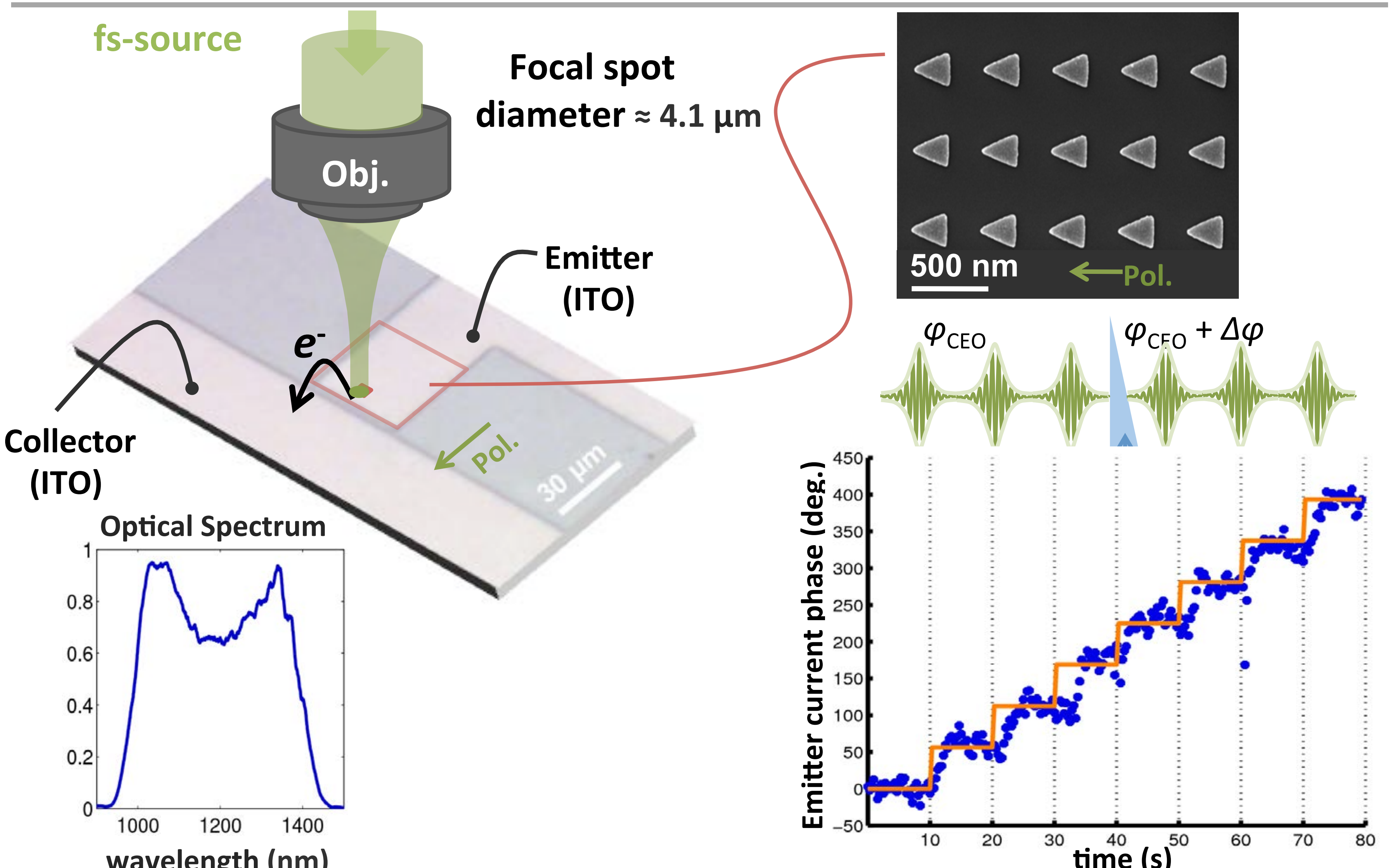
$$\Delta T \propto \frac{E_P}{A_{SURFACE}} \propto \frac{V_{CAVITY}}{A_{SURFACE}} \propto R \propto \lambda$$

- **High-gradient accelerators:** small size, short bunches and **low emittance!**

THz driven FEL like source

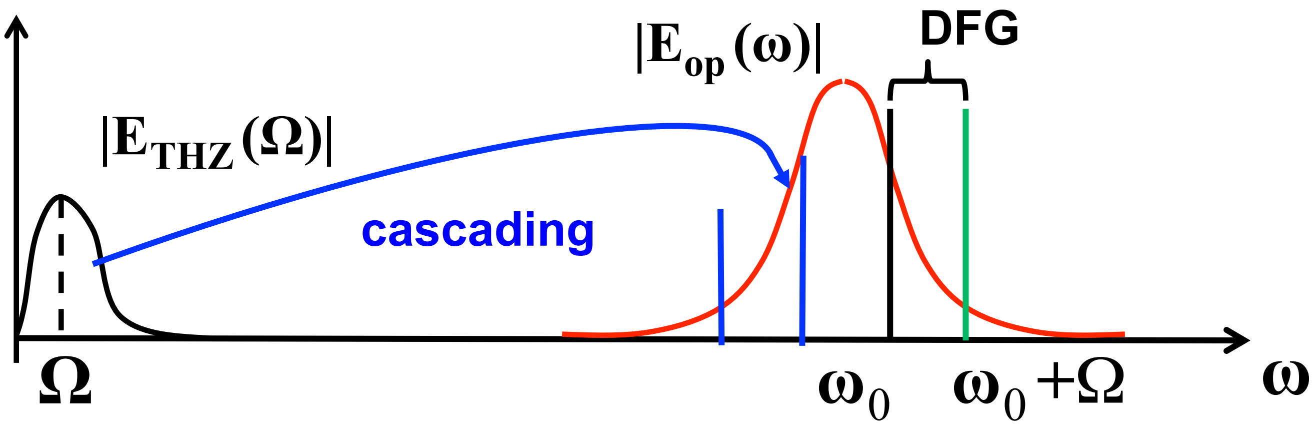


CEP sensitive field emitter array



Laser driven THz Sources

- **Optical rectification: ~ 1 % energy conversion efficiency[1], ~ mJ THz pulse energy[2,3]**



- **Intra-pulse difference frequency generation**
- **THz bandwidth can be as broad as optical pulse bandwidth**
- **Must satisfy phase-matching condition**

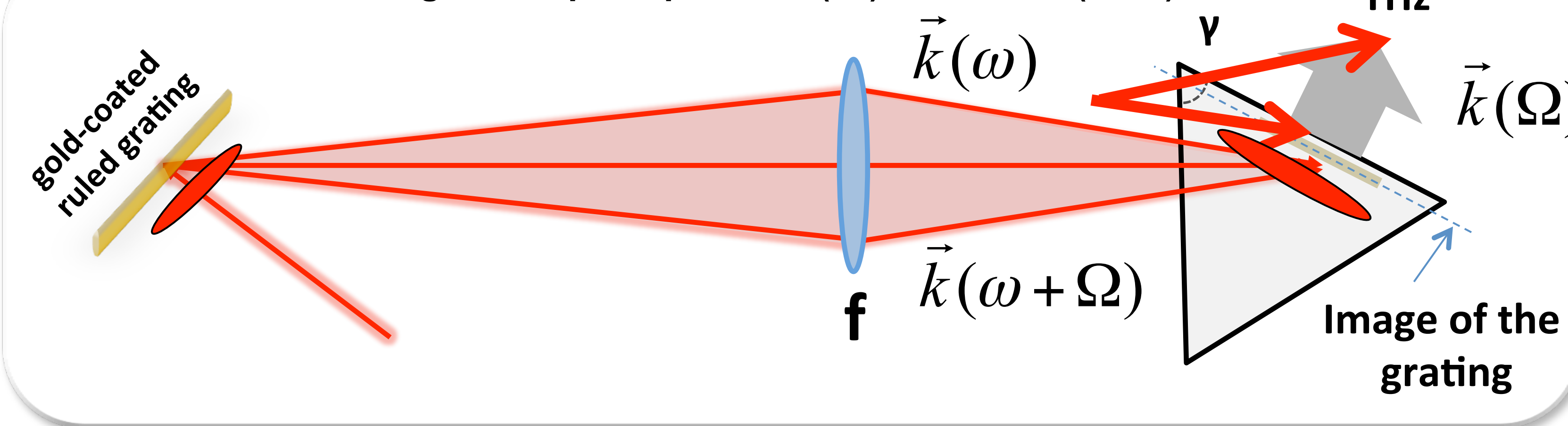
$$\vec{k}(\omega+\Omega)-\vec{k}(\omega)=\vec{k}(\Omega)$$

Lithium Niobate

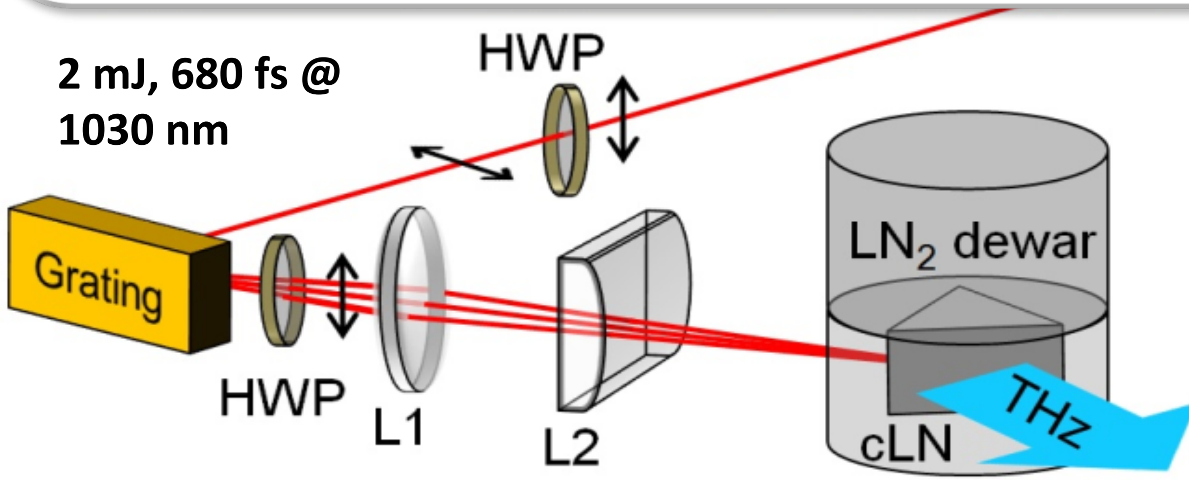
$$\boxed{n_g(\omega)=2, \quad n_p(\Omega)=5}$$

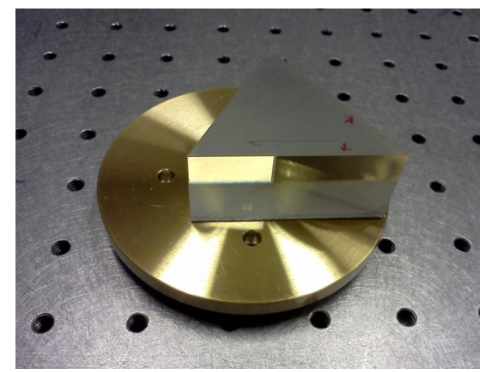
1. S. W. Huang et al Opt. Lett. 38(5), 796-798 (2013).
2. C. Vicario, Opt. Lett., 10.1364/OL.99.09999 (2014).
3. J. A. Fulop et al , Opt. Express 22(17), 20155-20163 (2014).

Optical rectification using Tilted Pulse Fronts



J. Hebling et al, Opt. Express 21:(10), 1161-1166 (2002).

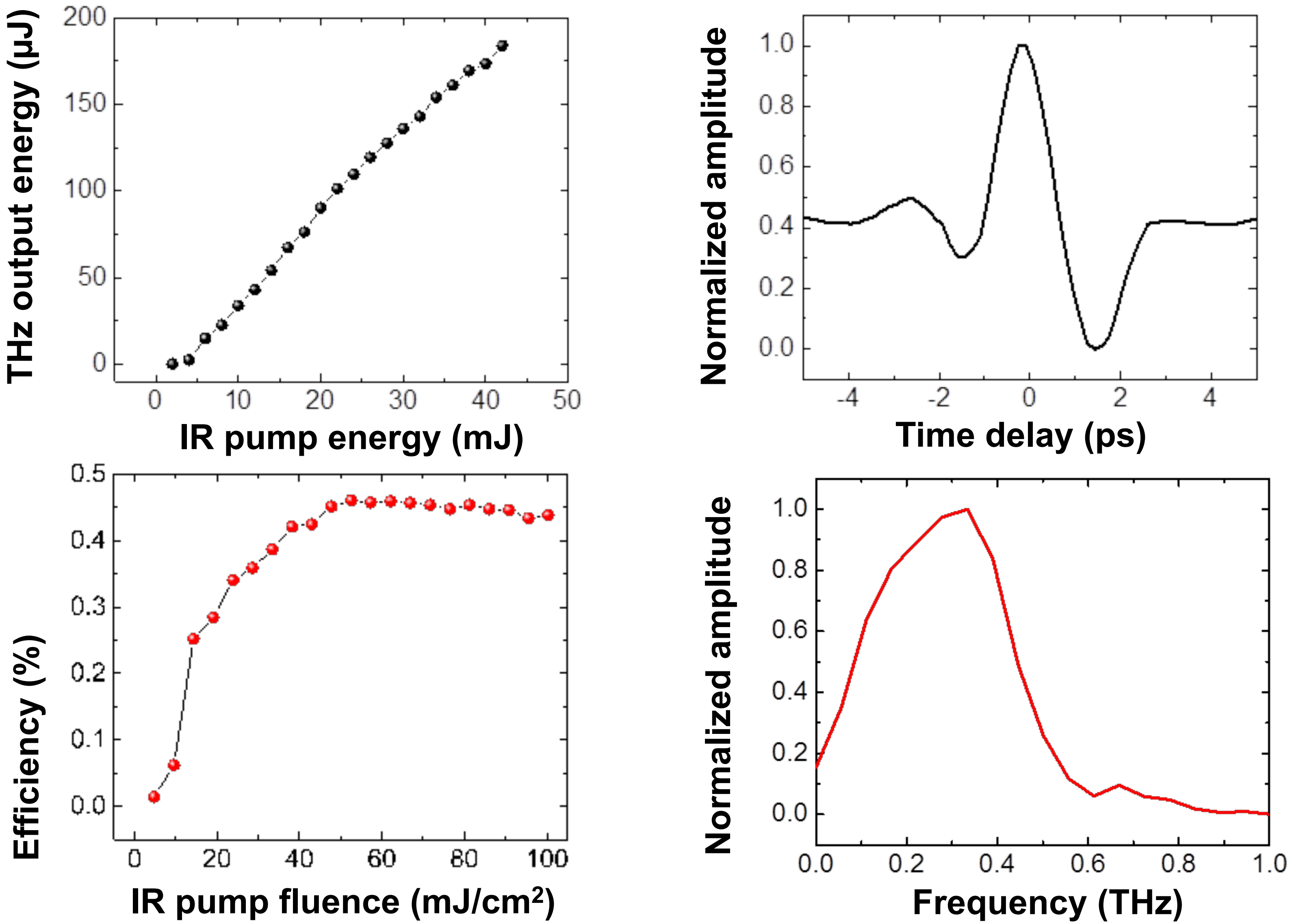




S. W. Huang et al Opt. Lett. 38(5), 796-798 (2013) → 1% optical to THz conv.

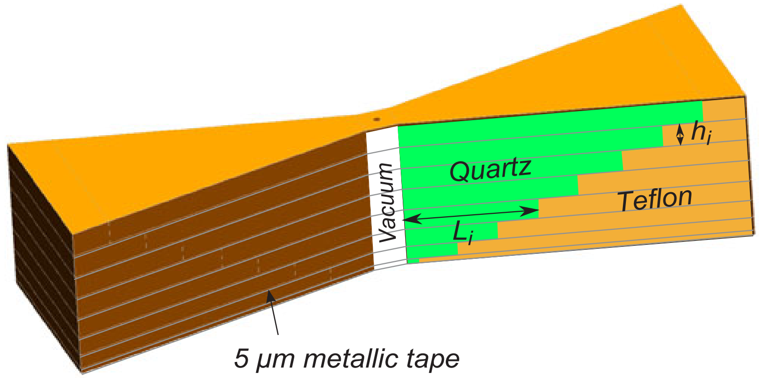
K. Ravi, et al., "Limitations to THz generation by optical rectification using tilted pulse fronts," Opt. Express 22, 20239 (2014).

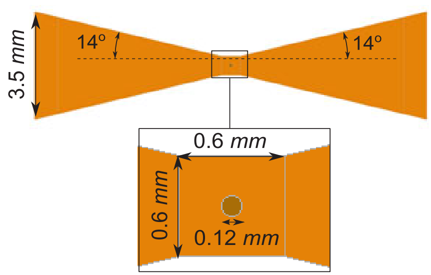
Cryogenic Yb:YLF laser 60 mJ, 1ps @ 90 K

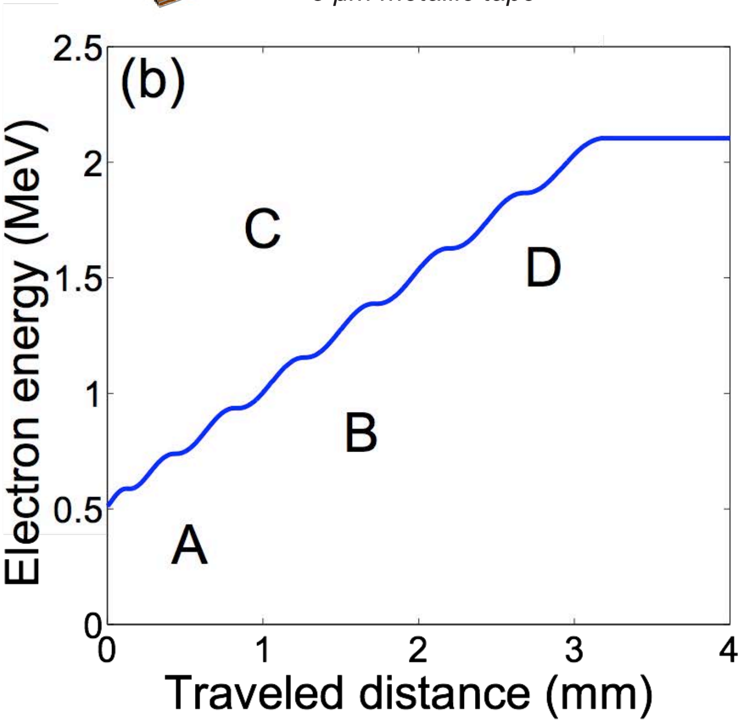


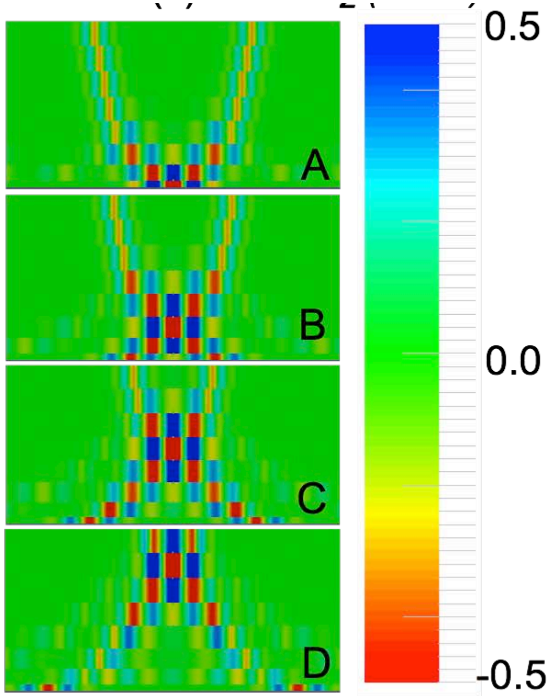
0.5% conversion, not yet fully optimized → 1% feasible

Single-cycle e-guns and accelerators







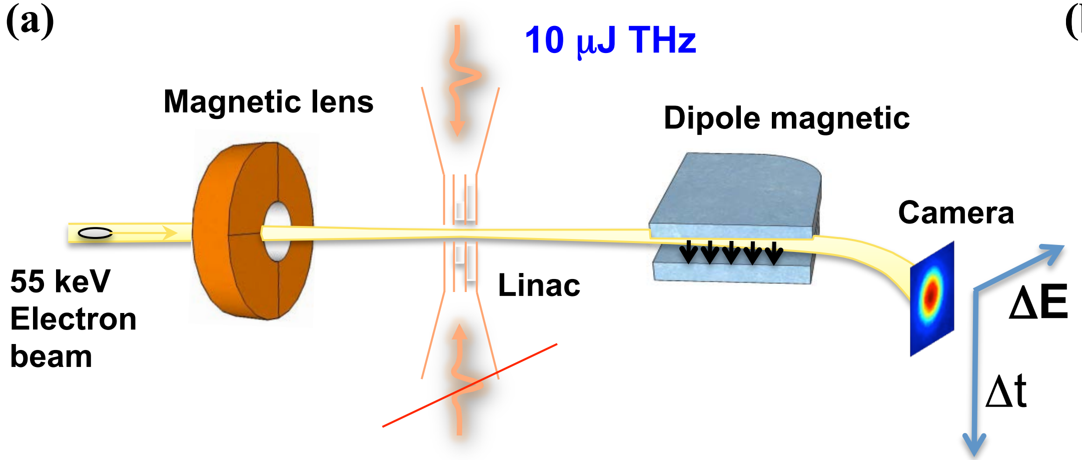


~ 2x1 mJ

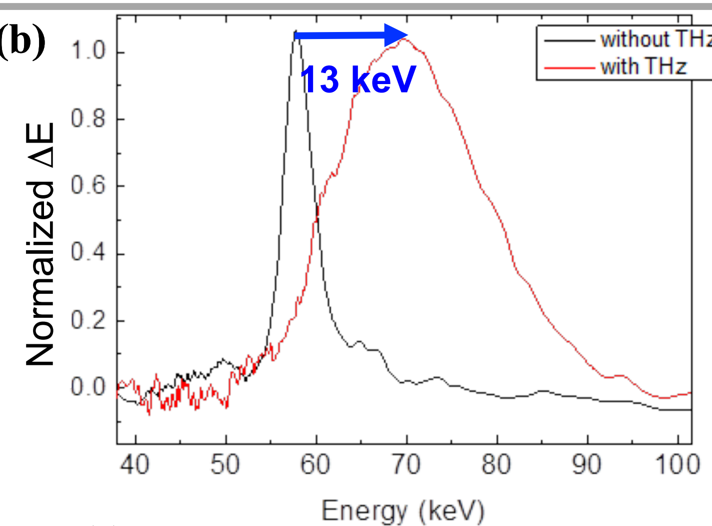
A. Fallahi, et al. PRSTAB 19, 081302 (2016)

THz Acceleration and Streaking

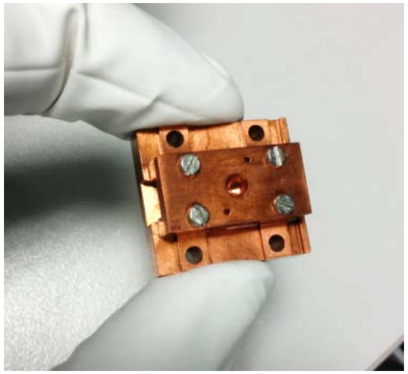
(a)



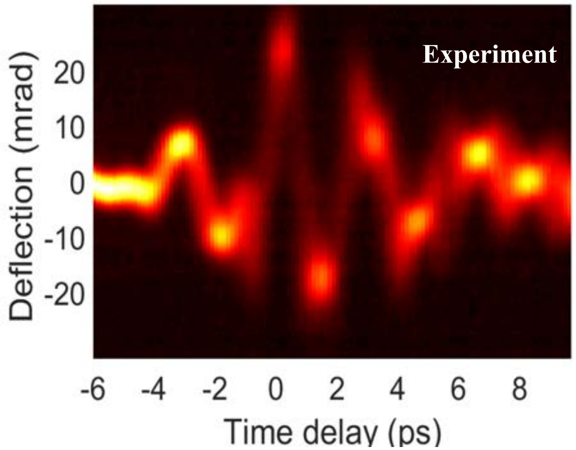
(b)



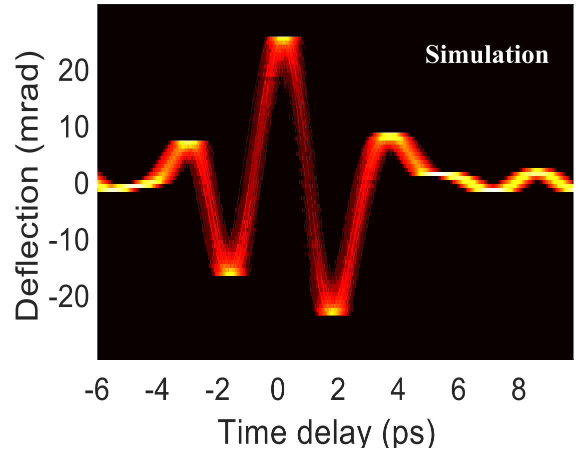
(c)

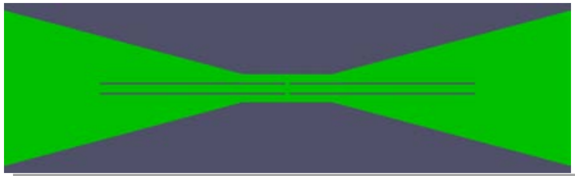


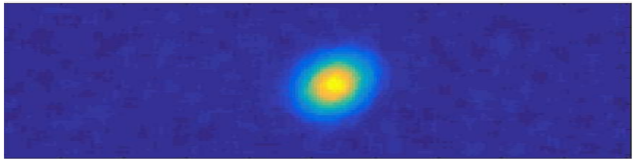
(d)



(e)







15 mrad/fs → supports fs resolution

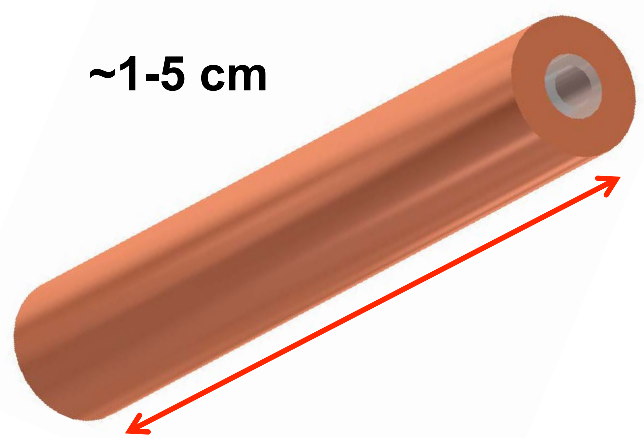
D. Zhang, to be published

THz Acceleration

• **Increasing operational frequency:** higher breakdown fields, reduced pulse energy ~ λ^{-3}, reduced pulsed heating and average power load

• **High-gradient accelerators:** reduced size, short bunches and improved electron beam quality

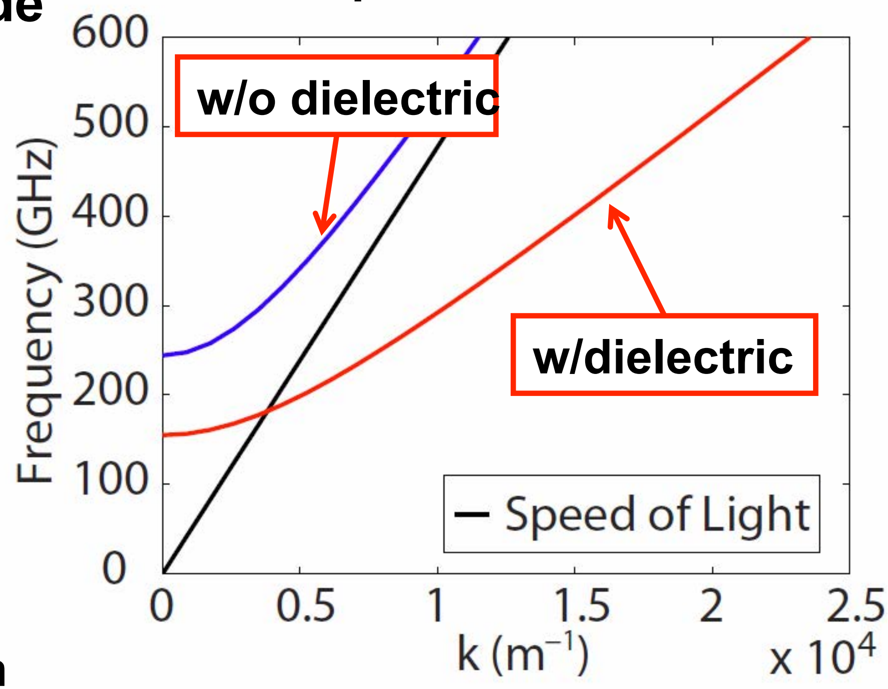
Dielectrically loaded metal waveguide



Copper Inner Diameter = 940 μm

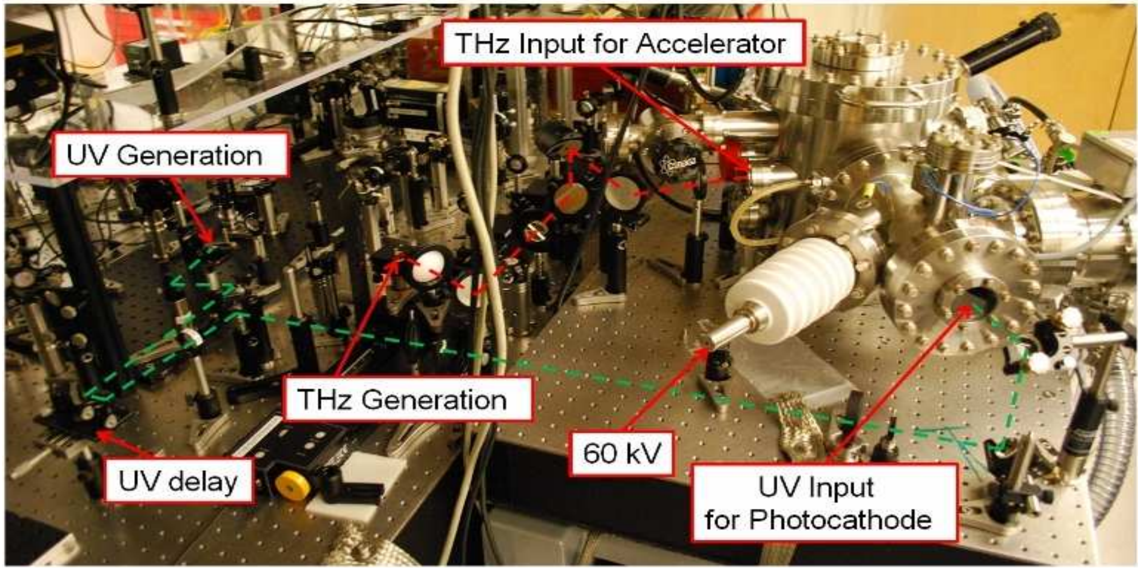
Fused Silica Inner Diameter = 400 μm

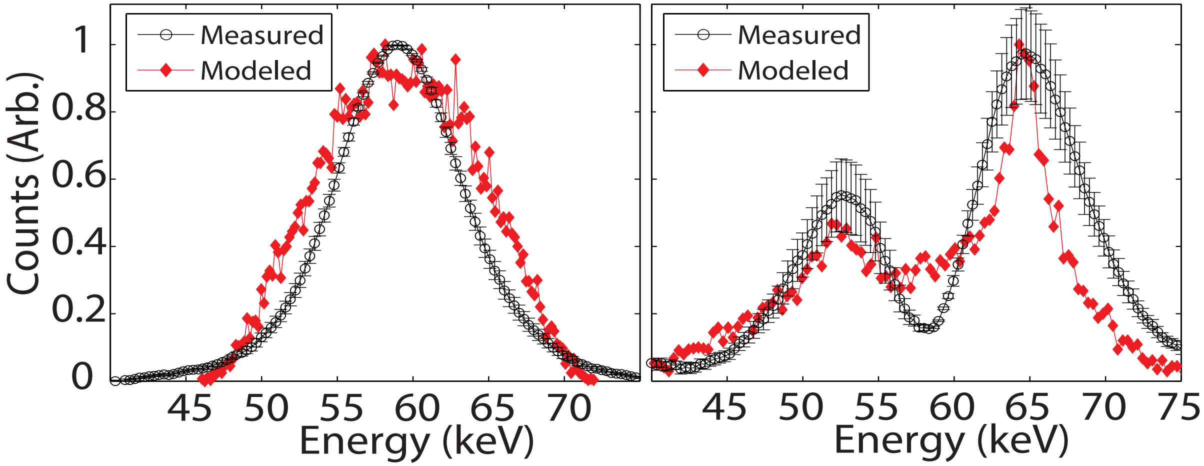
Dispersion Relation



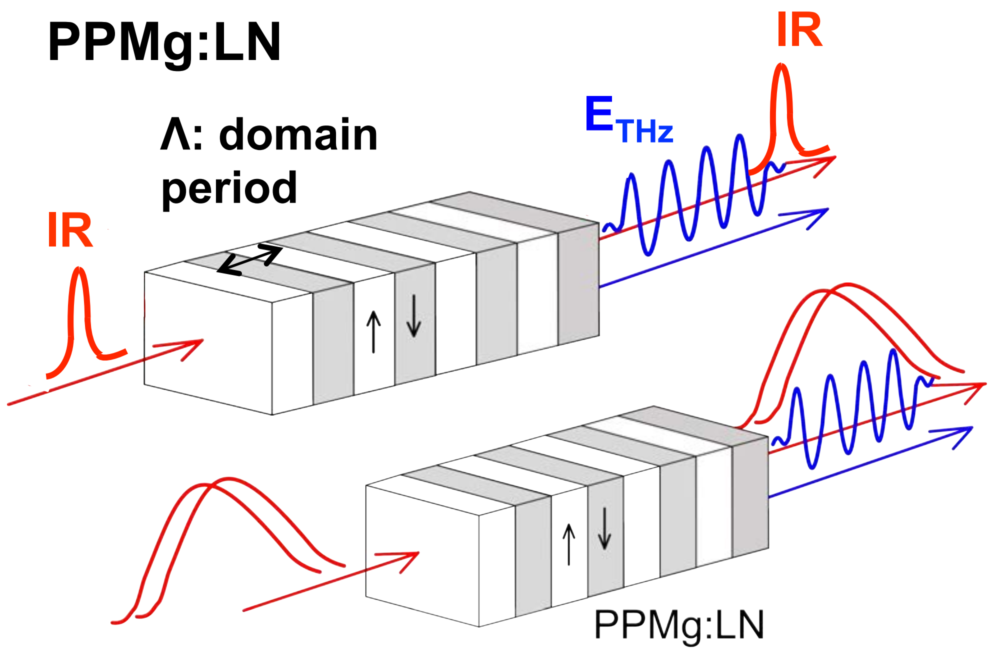
L.J. Wong et al., Opt. Exp. 21, 9792 (2013).

THz Acceleration





Quasi – phase matching for multi-cycle terahertz generation

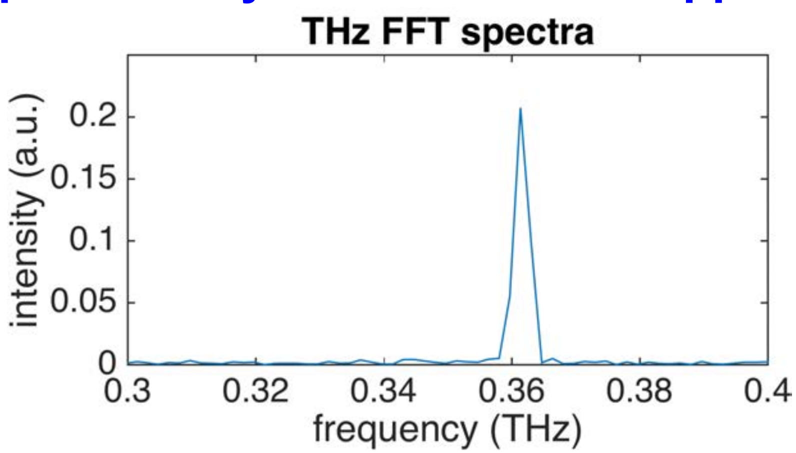


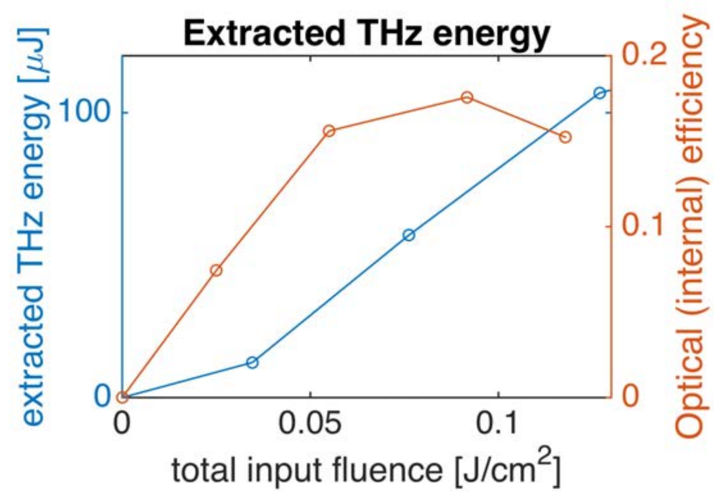
Lee, App. Phys. Lett. 77 (2000)
Lee, App. Phys. Lett. 78 (2001)
Yu, Opt. Comms. 284 (2011)

- μJ-level energies → 10^{-5} conversion efficiencies
- mJ - level energies → 10^{-3} conv. eff.

Carbajo, Opt. Lett. 40, 5762 (2015).

Chirp and Delay with 100 mJ Ti:Sapphire pulse



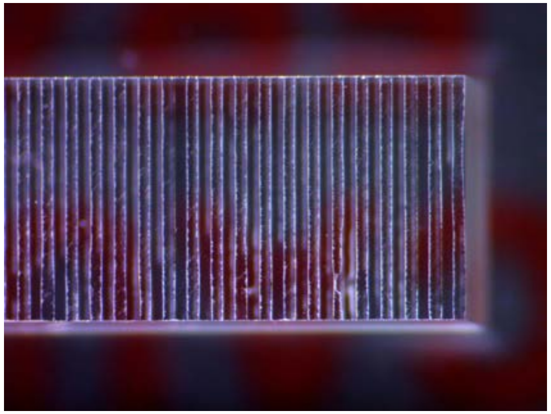


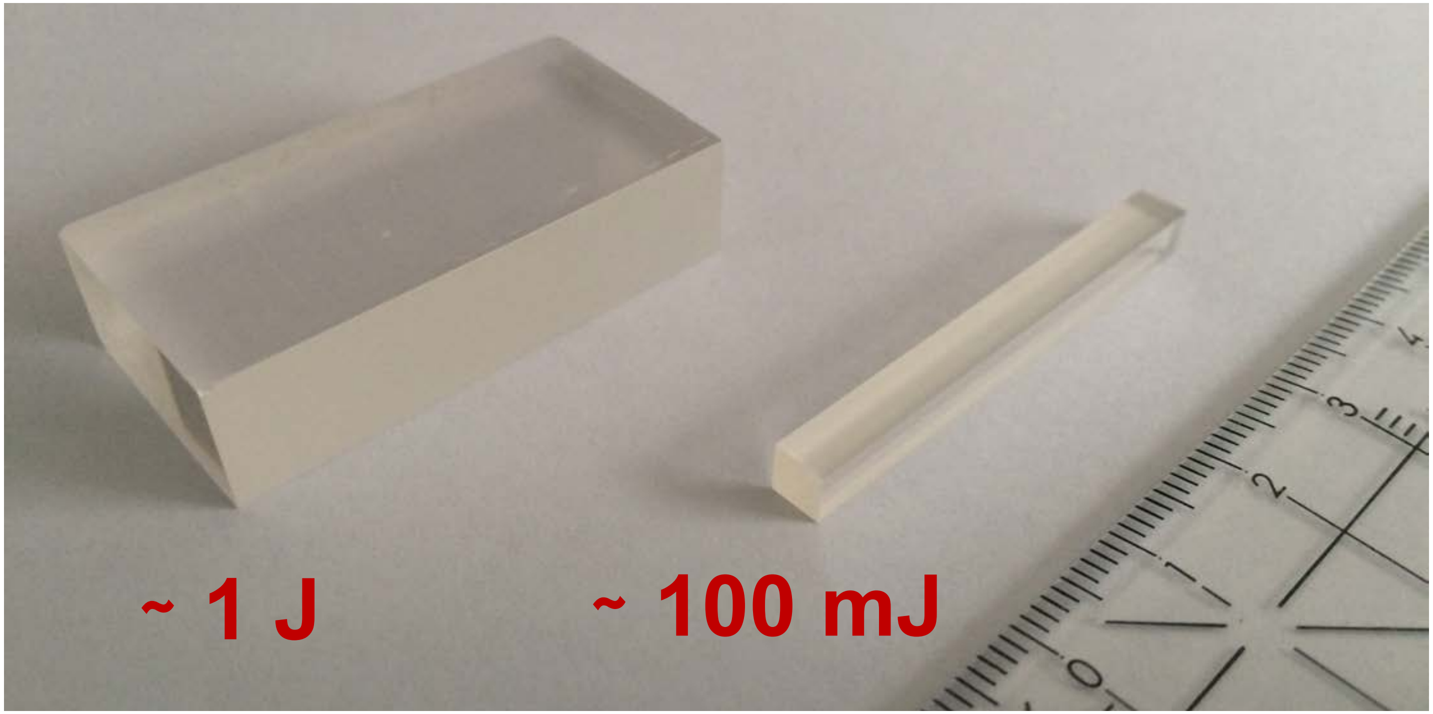
K. Ravi et al., Opt. Lett. 24, 25582 & Opt. Lett. 41, 3806 (2016).
R. Ahr et al., Opt. Lett. 42, 2118 (2017).

Quasi – phase matching for multi-cycle terahertz generation

PPMg:LN

- Poling period of 125µm – 1200µm feasible
- clear aperture of 10x15 mm^2, 40 mm long
- clear aperture of 4x4 mm^2, 40 mm long





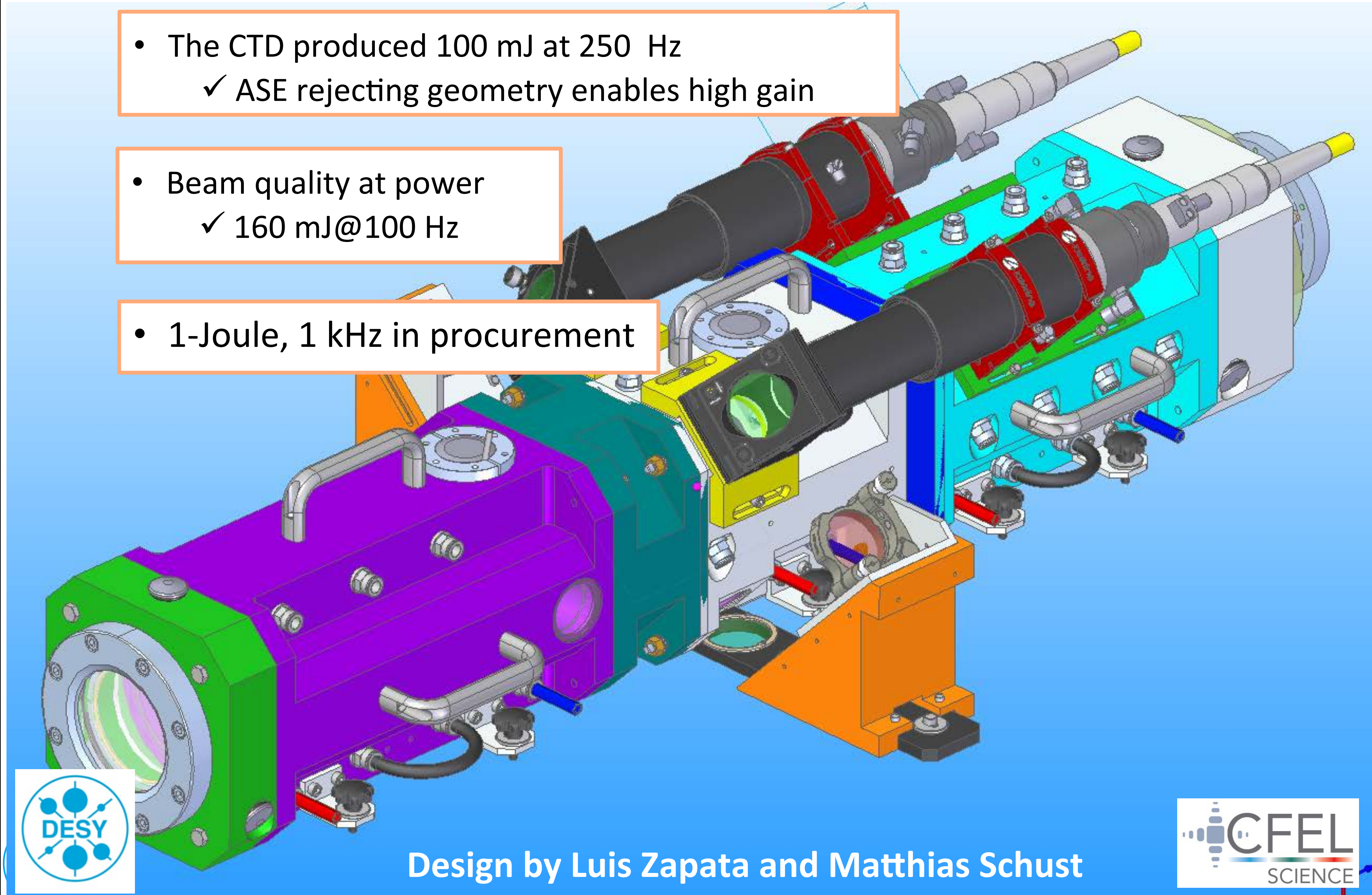
Thanks to Professor Taira, IMS Japan

1 Joule, 1 kHz Cryogenic Yb:YAG Laser

- The CTD produced 100 mJ at 250 Hz
  - ✓ ASE rejecting geometry enables high gain

- Beam quality at power
  - ✓ 160 mJ@100 Hz

- 1-Joule, 1 kHz in procurement



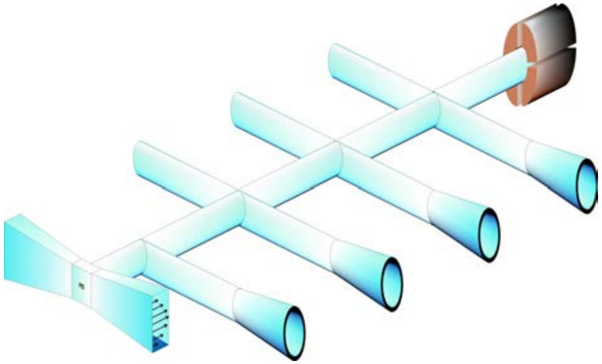
Design by Luis Zapata and Matthias Schust

Summary

- FELs are combined accelerator and laser facilities with unique challenges to Ultrafast Optics

  - Precision timing
  - High energy and power ultrafast sources

- Towards a laser driven compact coherent FEL source
  - Modulated electron beams source
  - THz generation & accelerators
  - Joule class picosecond lasers



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