Future Laser-based THz Light Sources at XFEL

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Lasers group (LAS), EuXFEL

Setting the stage…

European XFEL seeks to provide intense THz and mid-IR radiation in combination with X-ray pulses at all SASE beamlines & instruments

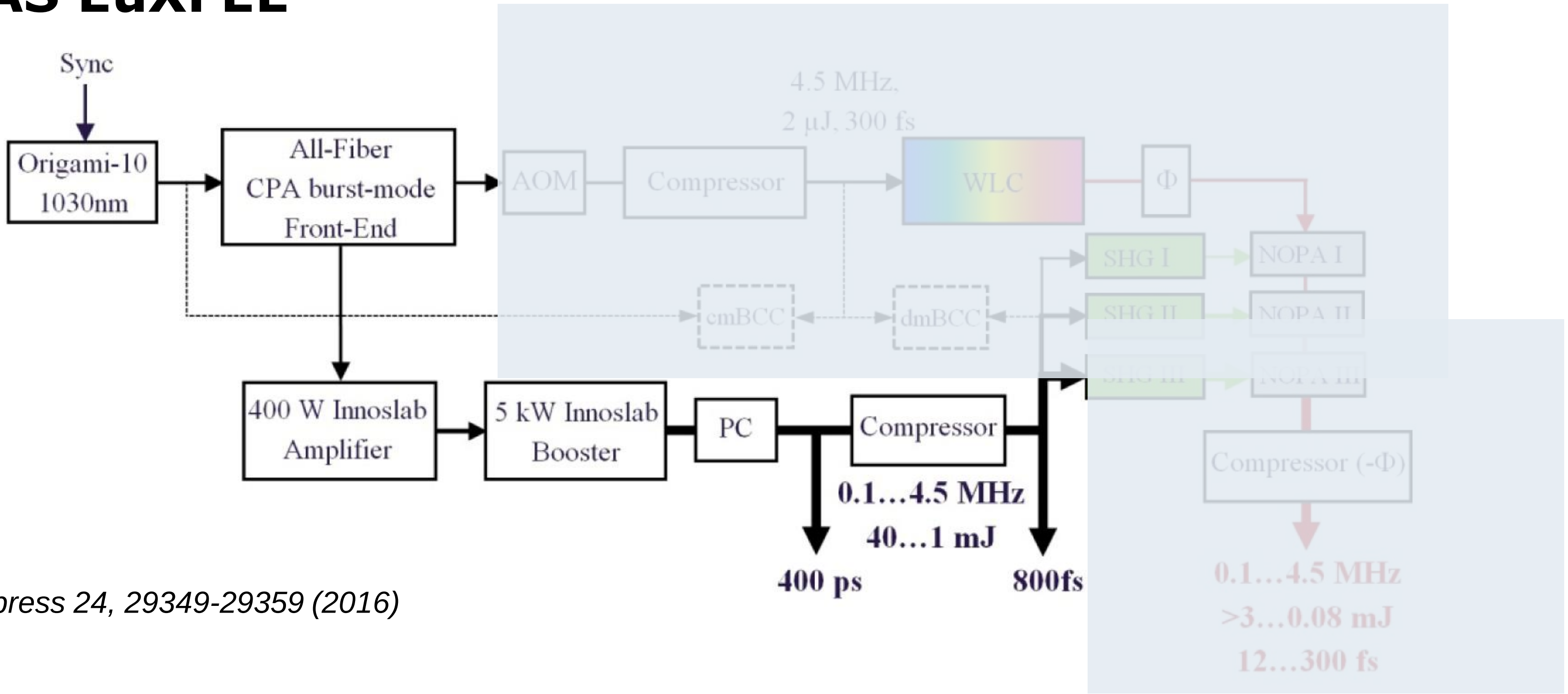
- Accelerator–based THz generation, see THz@PITZ
- Laser–based THz light sources

THz radiation requirements at EuXFEL:

- **Broadband**, single-cycle THz pulses
- **Narrowband**, multiple-cycle THz pulses
- **Large THz pulse energies supporting high-field (E and B) THz pulses**
- **THz/mid-IR spectral range from 0.1 THz to 30 THz**
- **Tunable THz central frequency**
- **CEP-stable THz light pulses**
- **Variable THz polarization**

Utmost importance of a high intensity, ultrashort laser source as a THz driver!

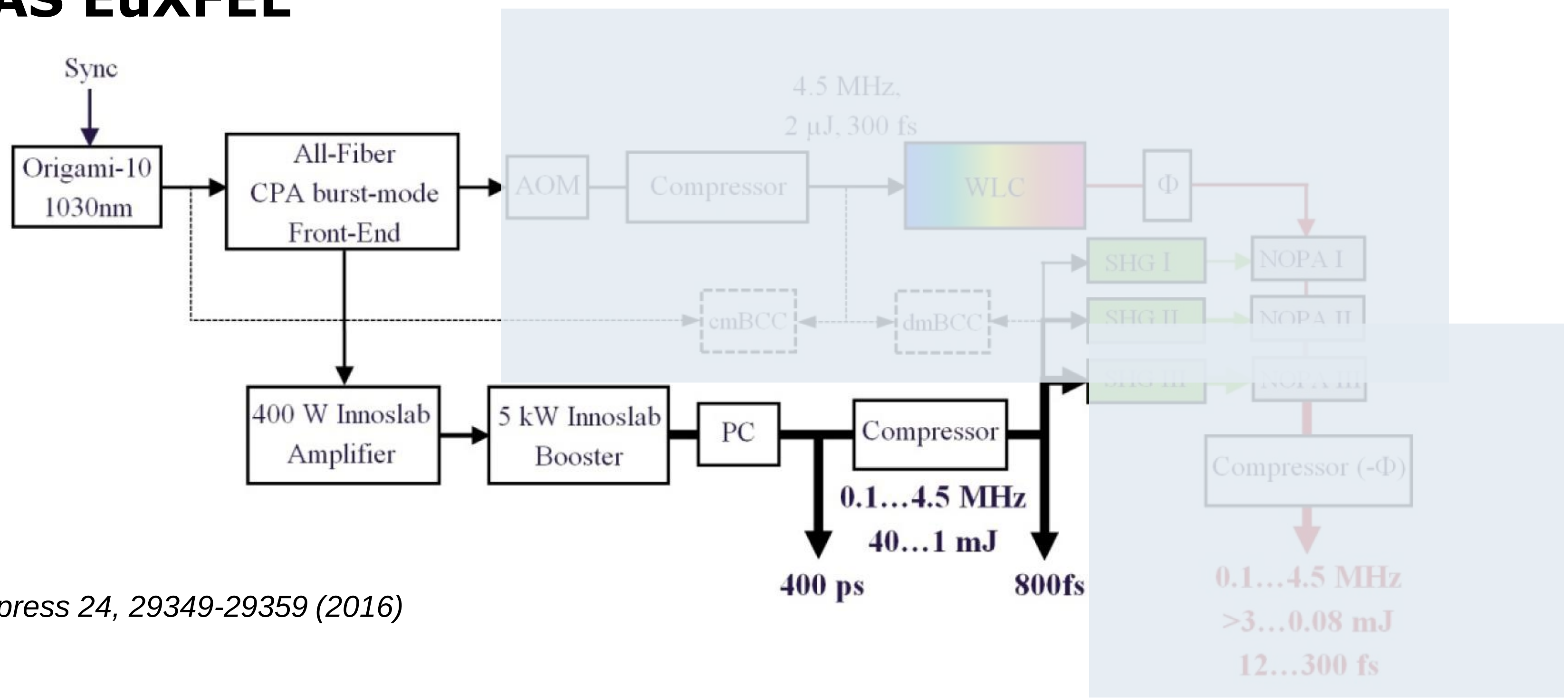
PP laser @ LAS EuXFEL



M. Pergament et al., Optics Express 24, 29349-29359 (2016)

- Laser output at 1030nm: **800 fs @ 0.1 to 4.5 MHz, 40 to 1 mJ/pulse**

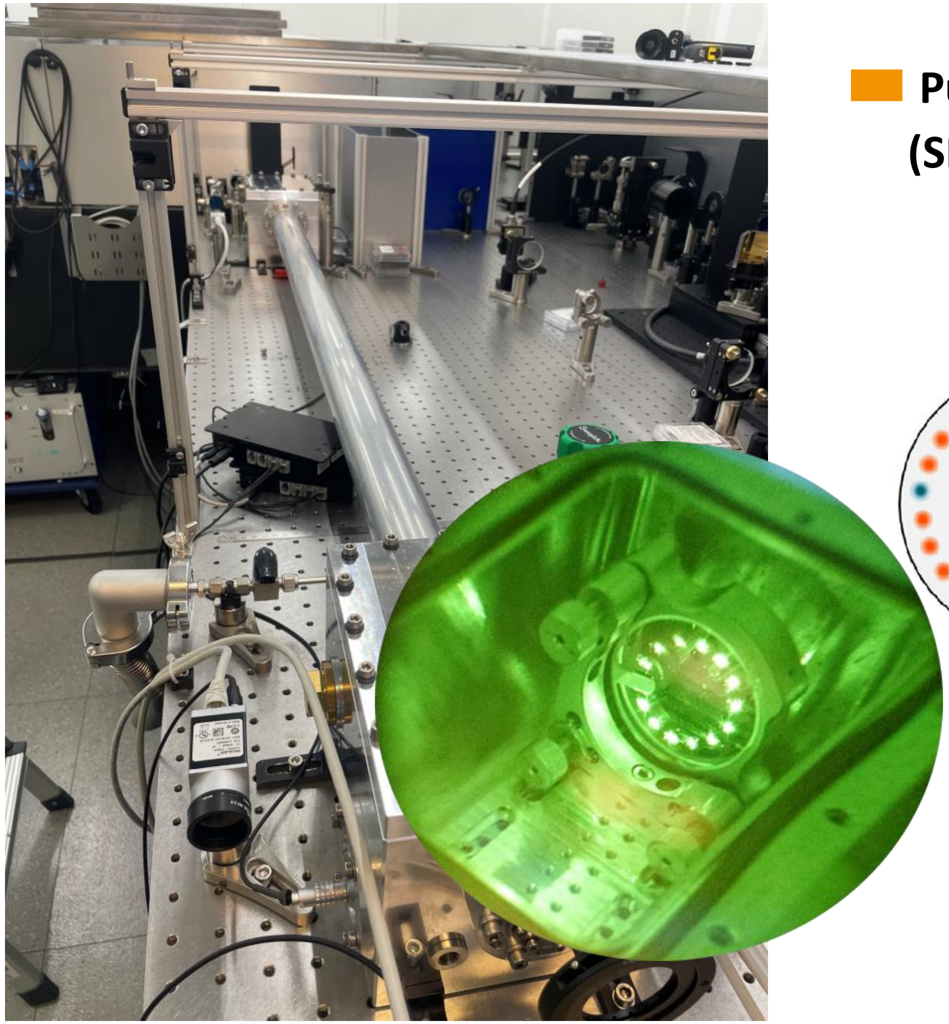
PP laser @ LAS EuXFEL



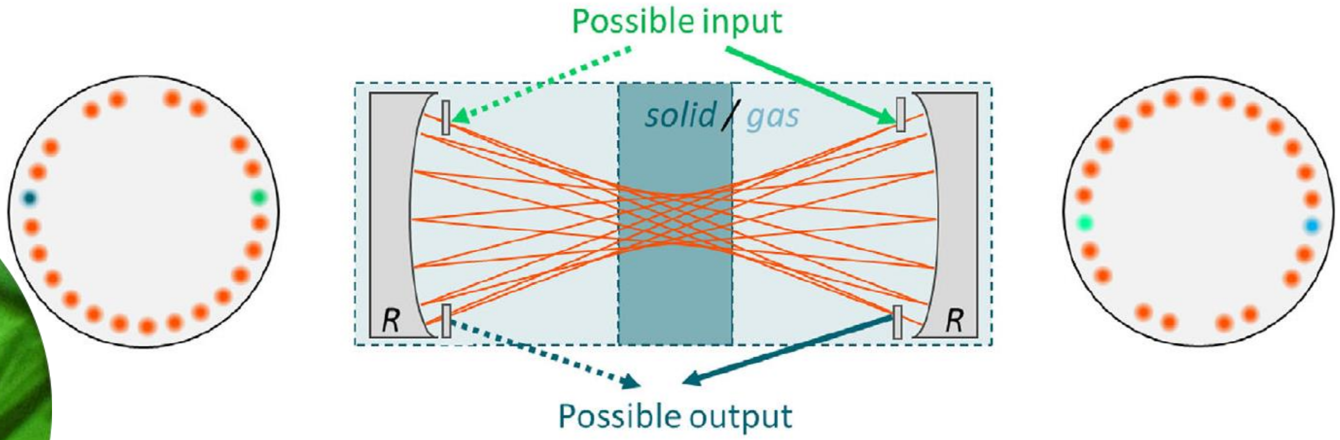
M. Pergament et al., Optics Express 24, 29349-29359 (2016)

- Laser output at 1030nm: **800 fs @ 0.1 to 4.5 MHz, 40 to 1 mJ/pulse**
- **Efficient THz generation (bandwidth, pulse energy etc) requires pulse compression <100 fs**
- **Compression scheme using multi-pass Herriott cell in Ar gas**

Compression of 1030nm laser beam @ 1.1 MHz; multi-pass Herriott cell



- Pulse compression by spectral broadening via self-phase modulation (SPM) in a Kerr medium followed by pulse chirp removal

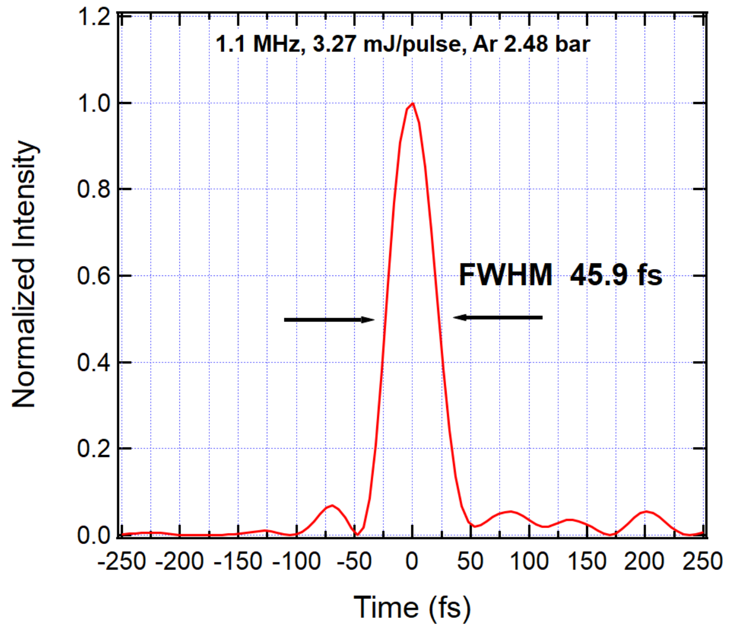


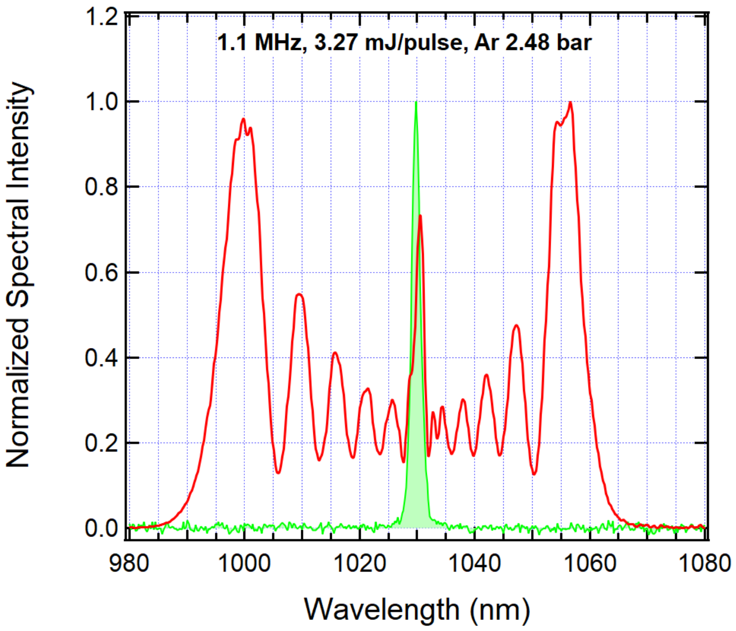
Laser Photonics Rev. 15, 2100220 (2021)

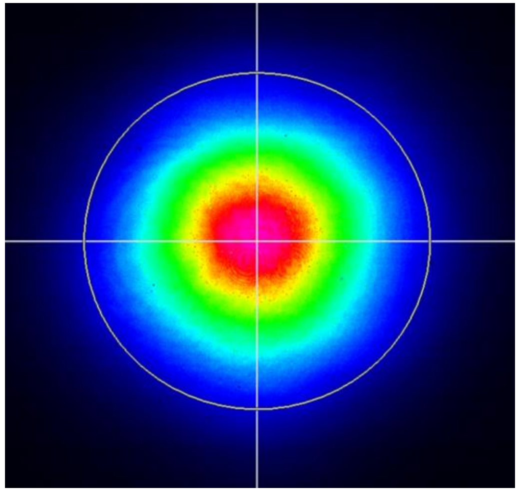
Herriott cell as installed in the R&D lab of LAS group

Compression of 1030nm laser beam @ 1.1 MHz; multi-pass Herriott cell

- Compression factor ~**20**; broadened spectrum supports **sub-40 fs @ 1.1 MHz**
- Compression setup transmission (HC + GTI's) about **92%**, i.e. ~**3 mJ/pulse**
- Excellent laser intensity profile after HC
- Compressed pulse duration of **45±5 fs**

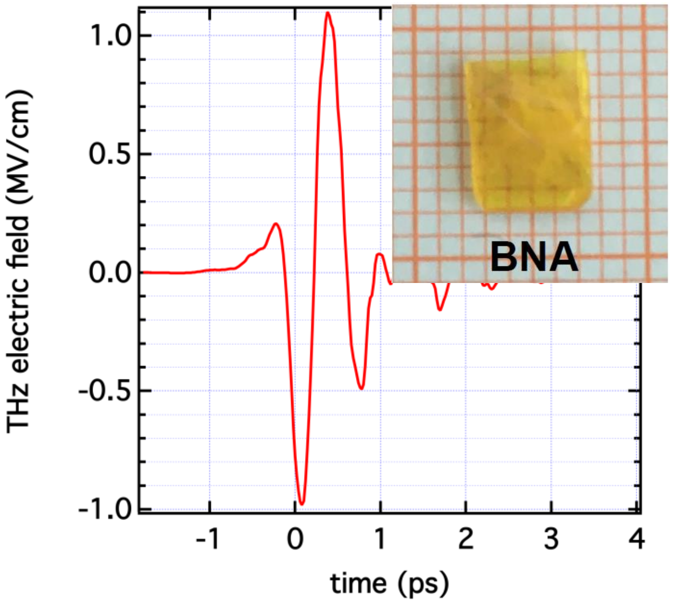




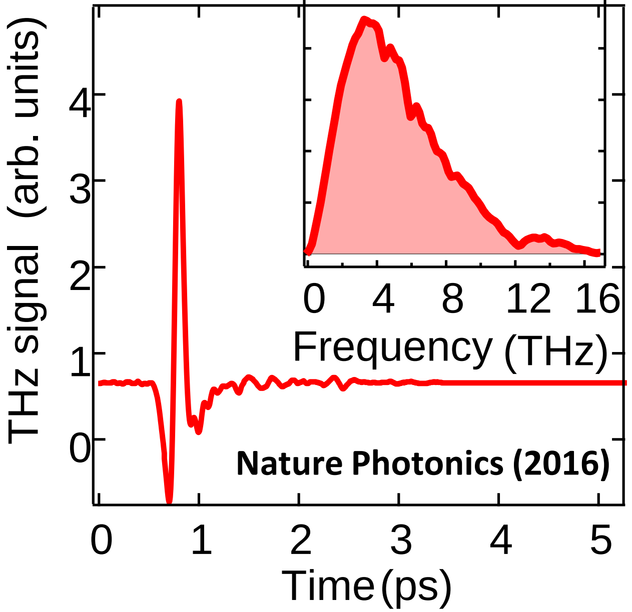


Broadband laser-based THz generation schemes at LAS, EuXFEL

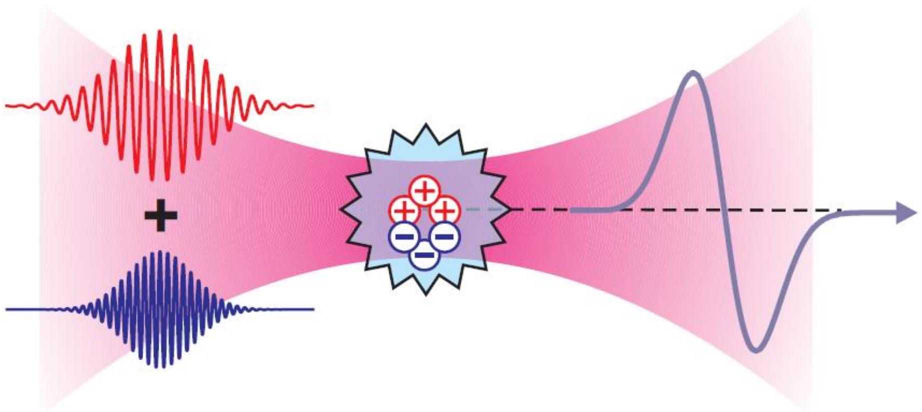
Organic crystals



Spintronic THz emitter

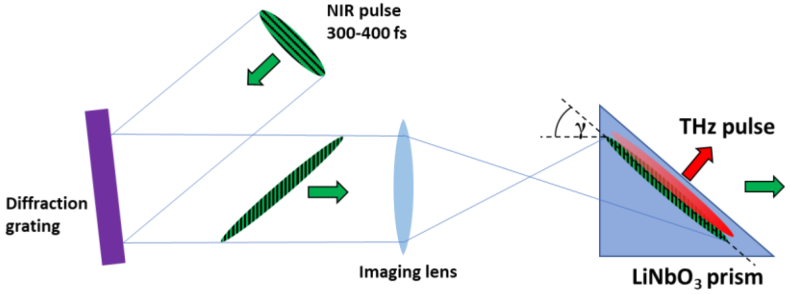


Two-color air/gas plasma



Laser & Photonics Review 4, 349 (2007);

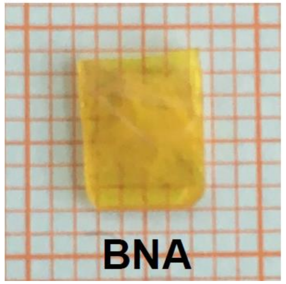
Lithium Niobate



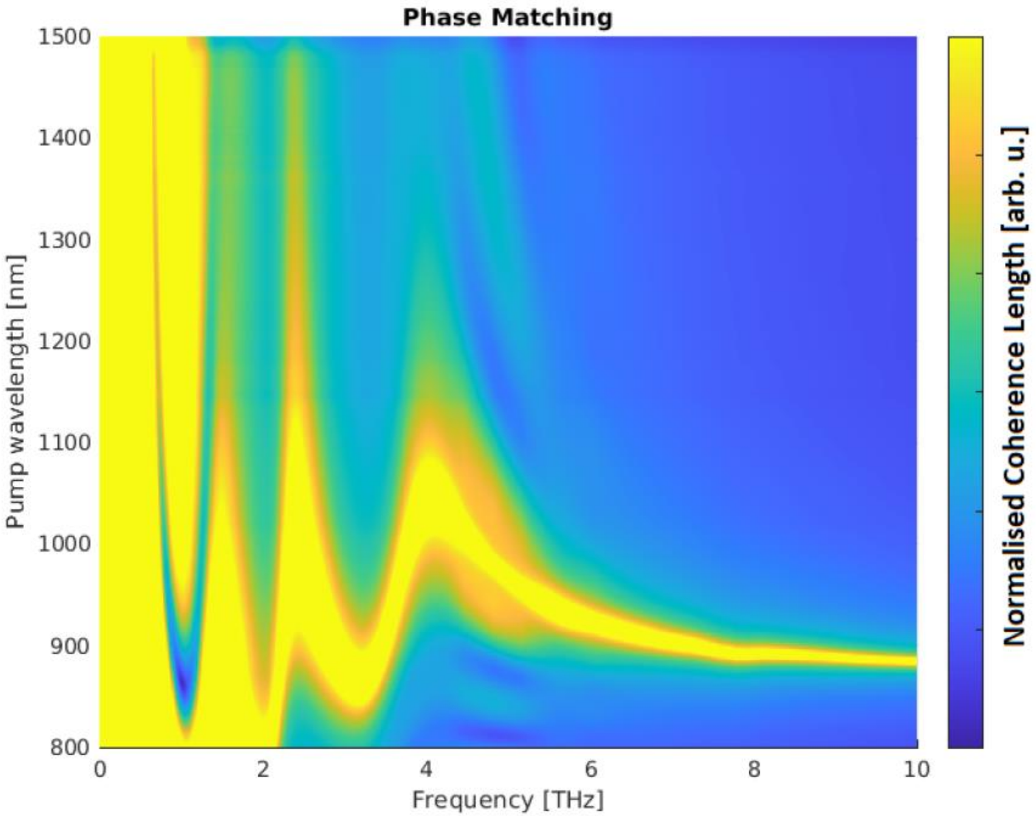
- **Four-fold approach:** THz source(s) will deployed depending on the required spectral range, field strength etc (user defined): 0.1 – 2 THz and 0.1 – 30 THz
- Driven by the pump-proble laser's spectrally broadened and compressed (**40-400 fs**) high power beam (**1030 nm**)

1. THz generation in organic crystals

BNA (N-benzyl-2-methyl-4-nitroaniline)



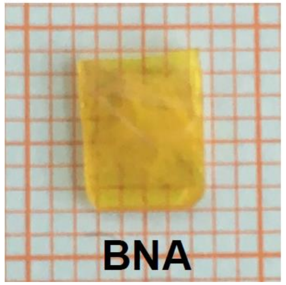
- Optimal phase matching around 1000 nm
- Energy conversion efficiencies about 0.8%
- THz crystal of choice @ 1030nm pumping



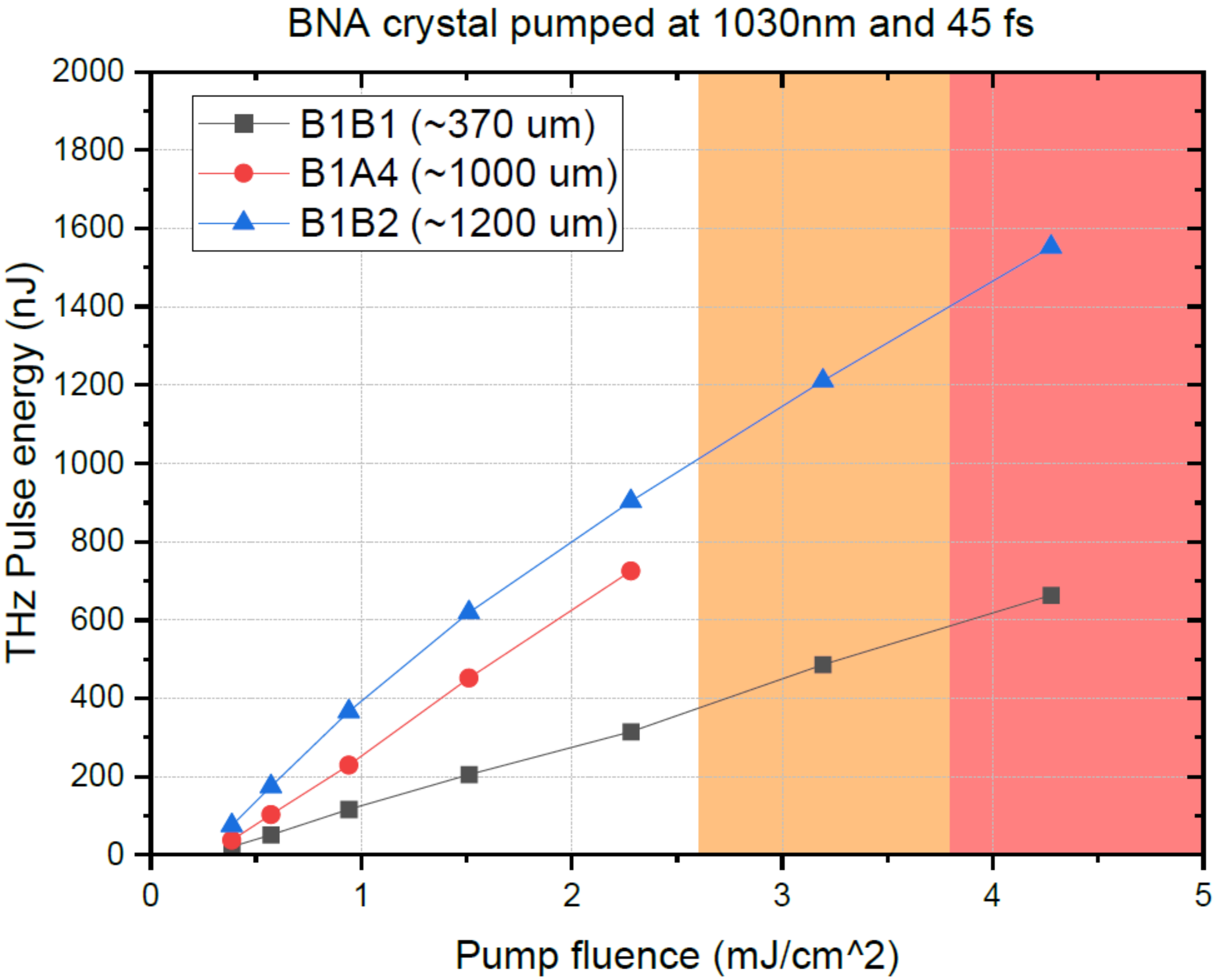
arXiv:2109.04274

1. THz generation in organic crystals

BNA organic crystals

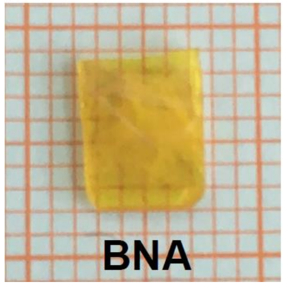


- BNA with different thicknesses
- Near-IR Power-in/ THz power-out test
- 45 fs @ 1030nm and 112 kHz RR



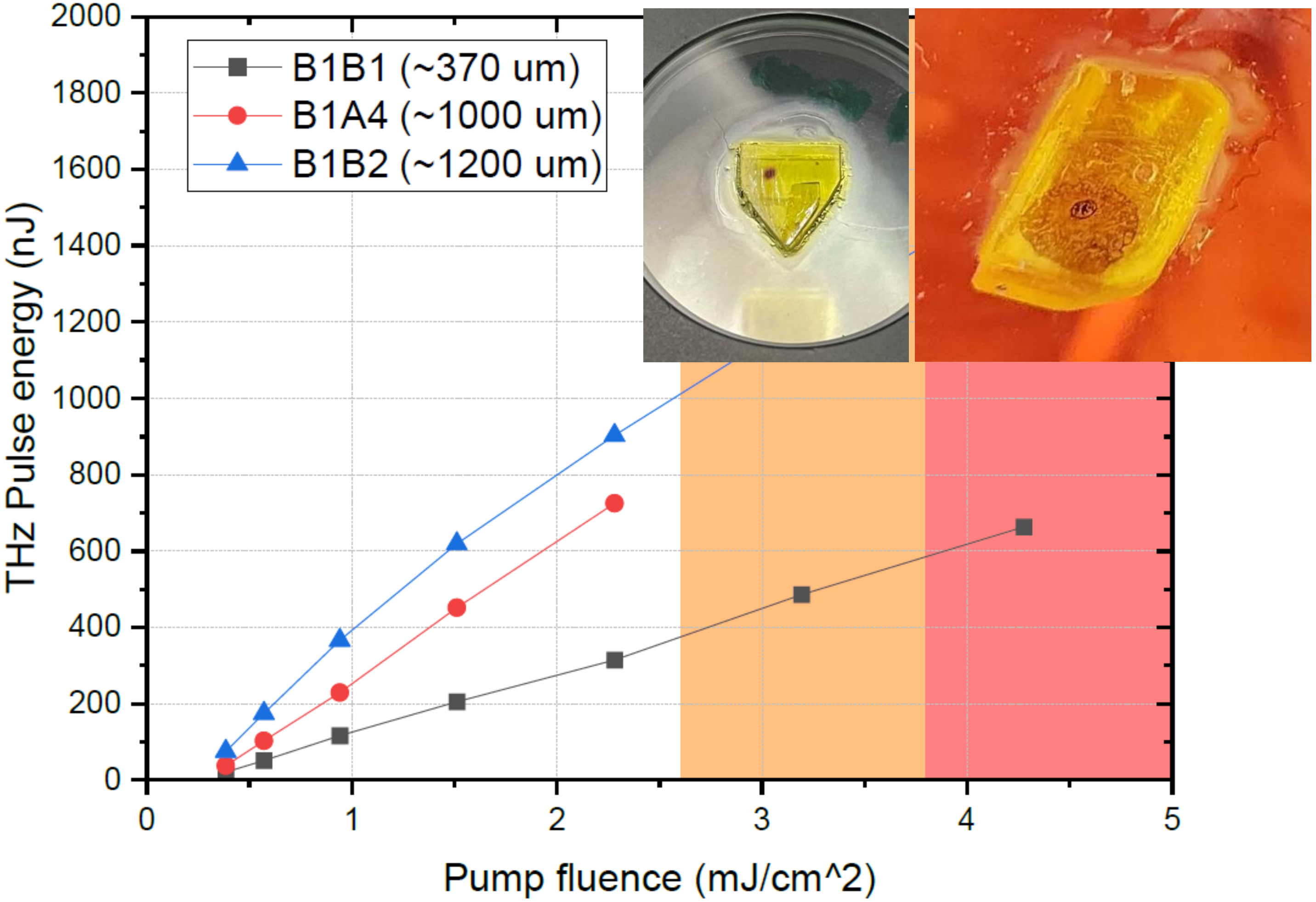
1. THz generation in organic crystals

BNA organic crystals



- THz pulse energies above **1 µJ/pulse**
- ‘Slow’ and ‘fast’ damage above 3 and 4 mJ/cm^2
- ‘Slow’ damaged xtals still usable (~10% less intensity)
- Accounting for THz air absorption (~45%) and reflective losses (~5%)

BNA crystal pumped at 1030nm and 45 fs



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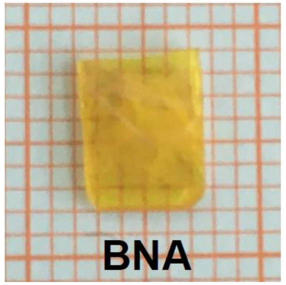
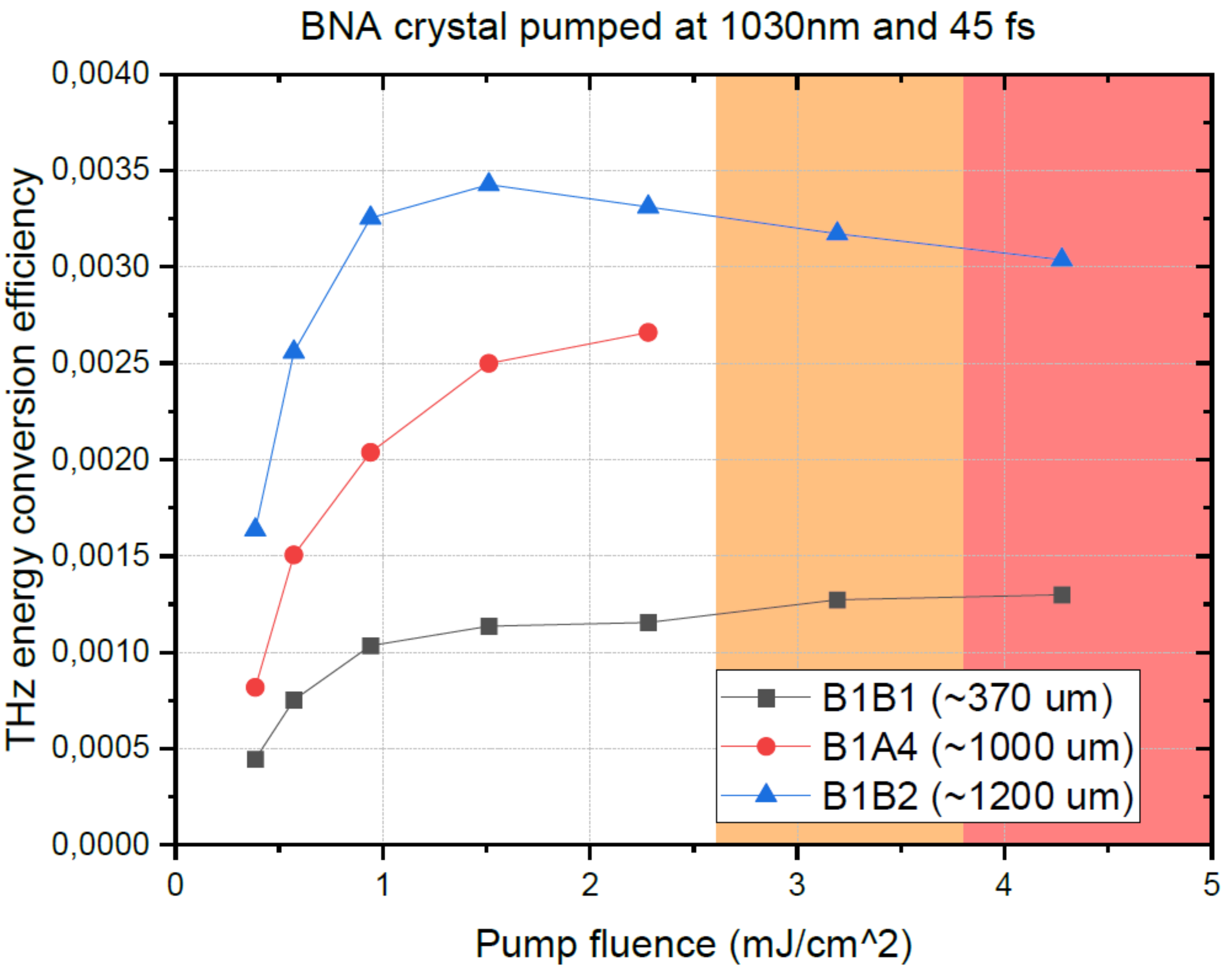
BNA organic crystals

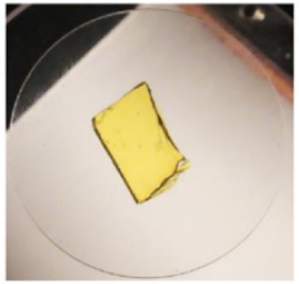


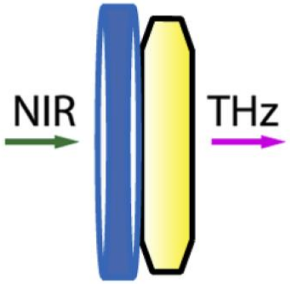


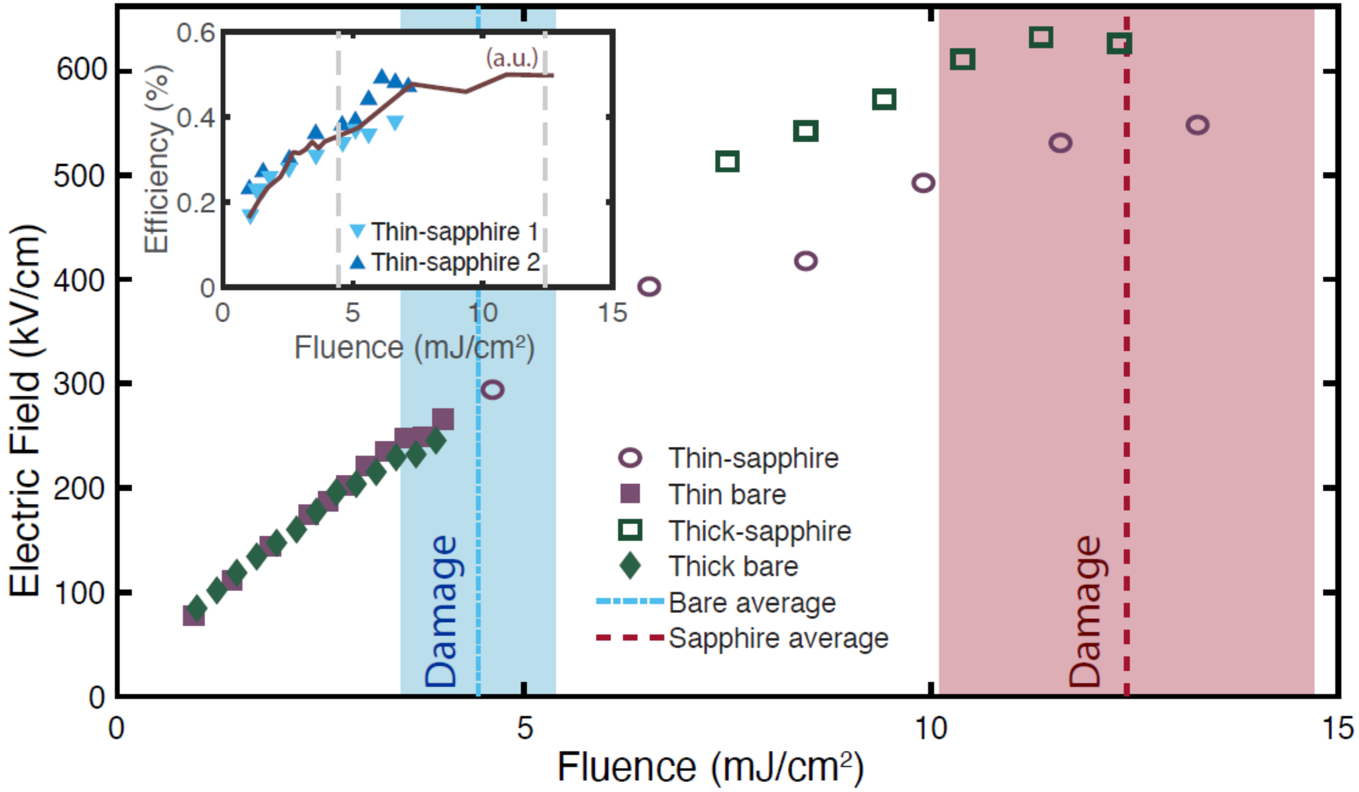
- Energy conversion efficiency of 0.35%
- Expected conversion efficiency of 0.8% (literature work @ 1 kHz RR)

1. THz generation in organic crystals

BNA organic crystals



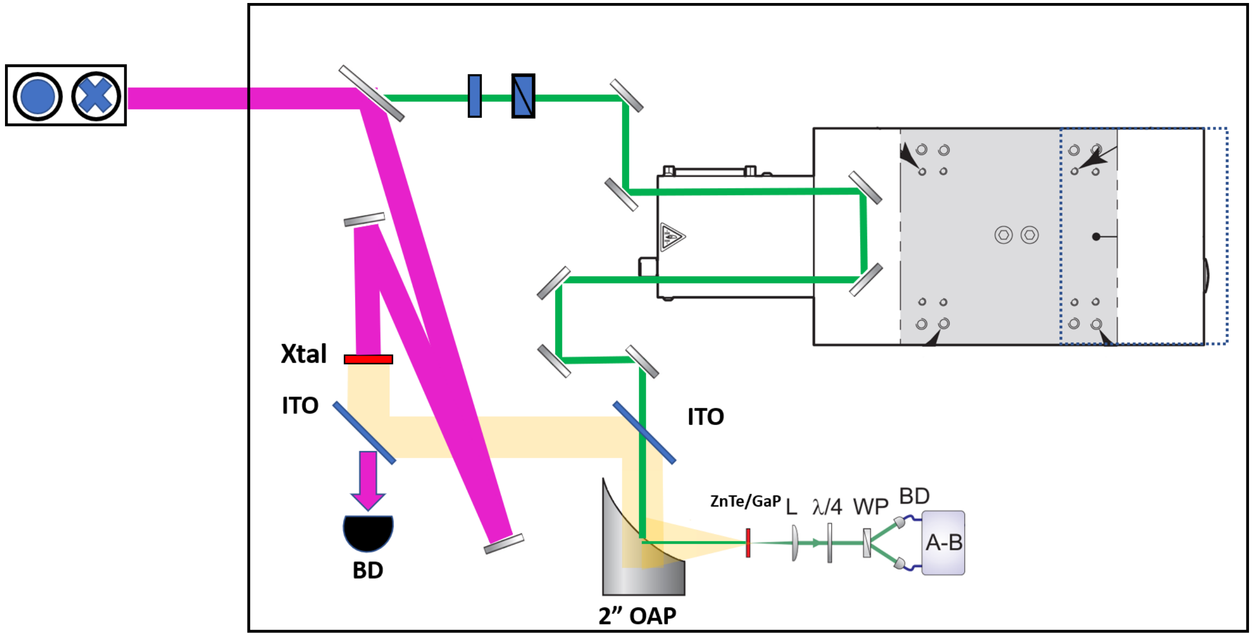


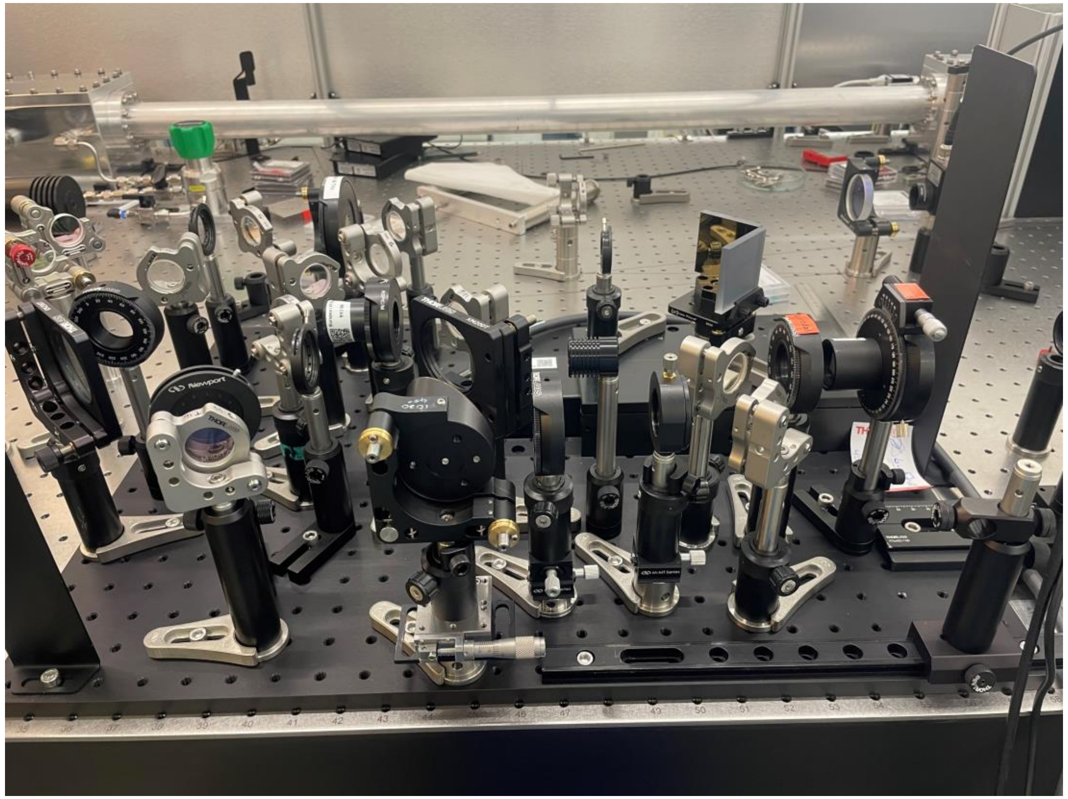


- Purchased **fused BNA on sapphire plates**
- Improves BNA cooling, accommodates larger fluences without crystal damage

Optics Express 29, 38084 (2021)

THz generation and detection setups

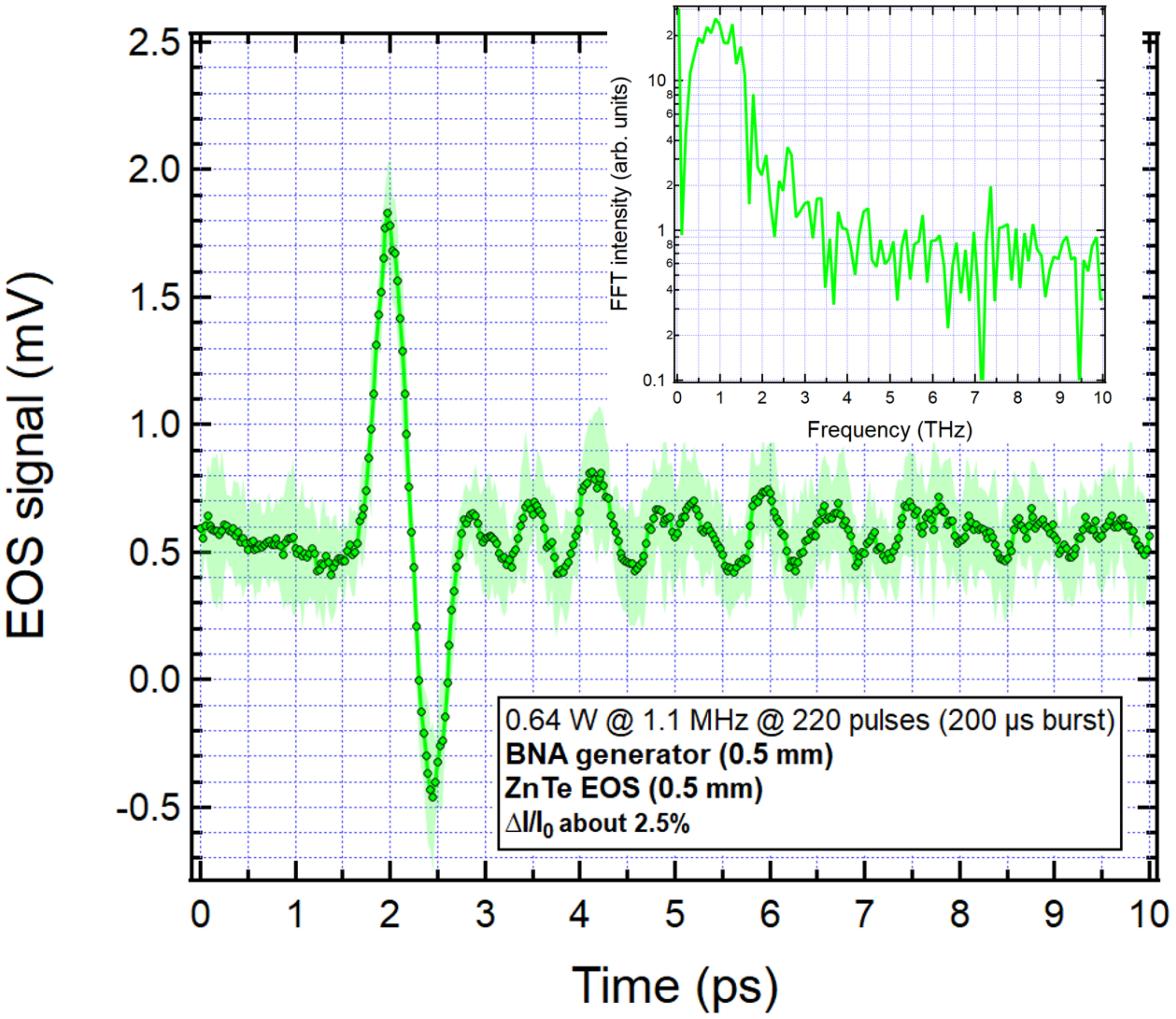




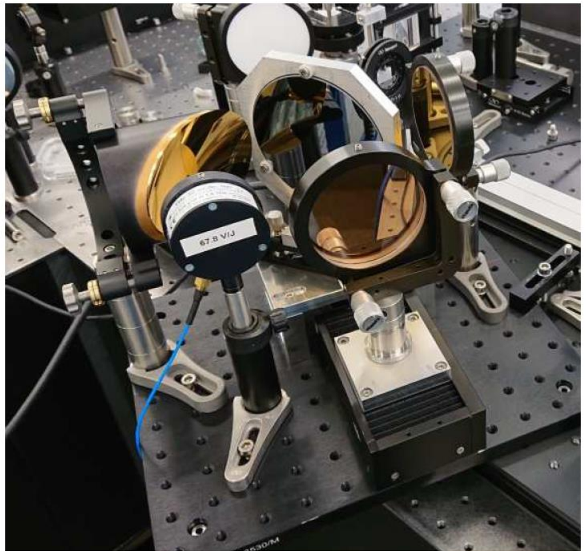
- BNA THz generator; ZnTe/GaP EOS detection
- Commission the BNA generators @ 1030nm & 1.1 MHz
- Measure and optimize THz spectrum + THz field strength

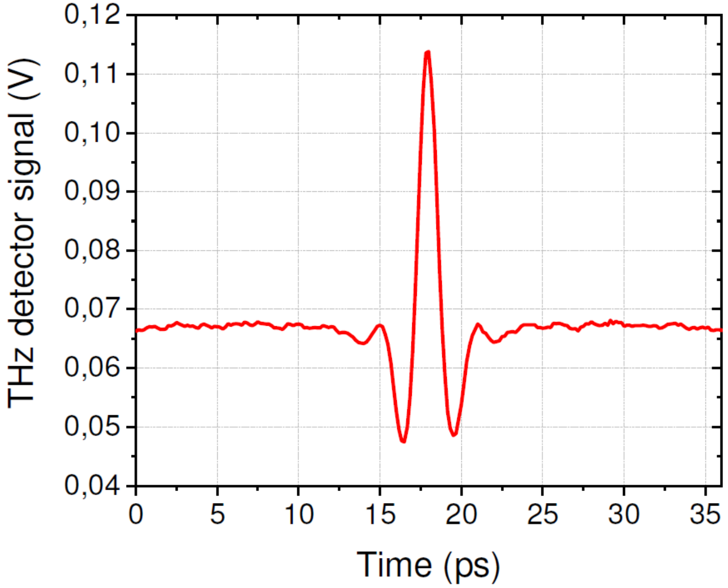
THz setup as installed in the R&D lab of LAS group

THz generation and detection setups



Michelson interferometer



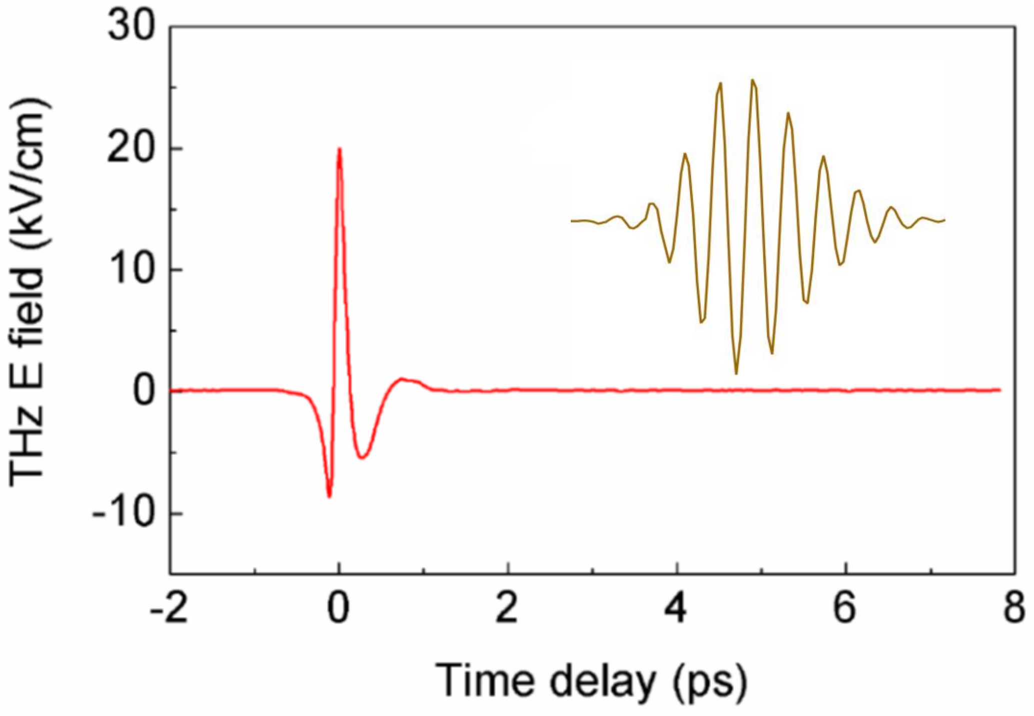


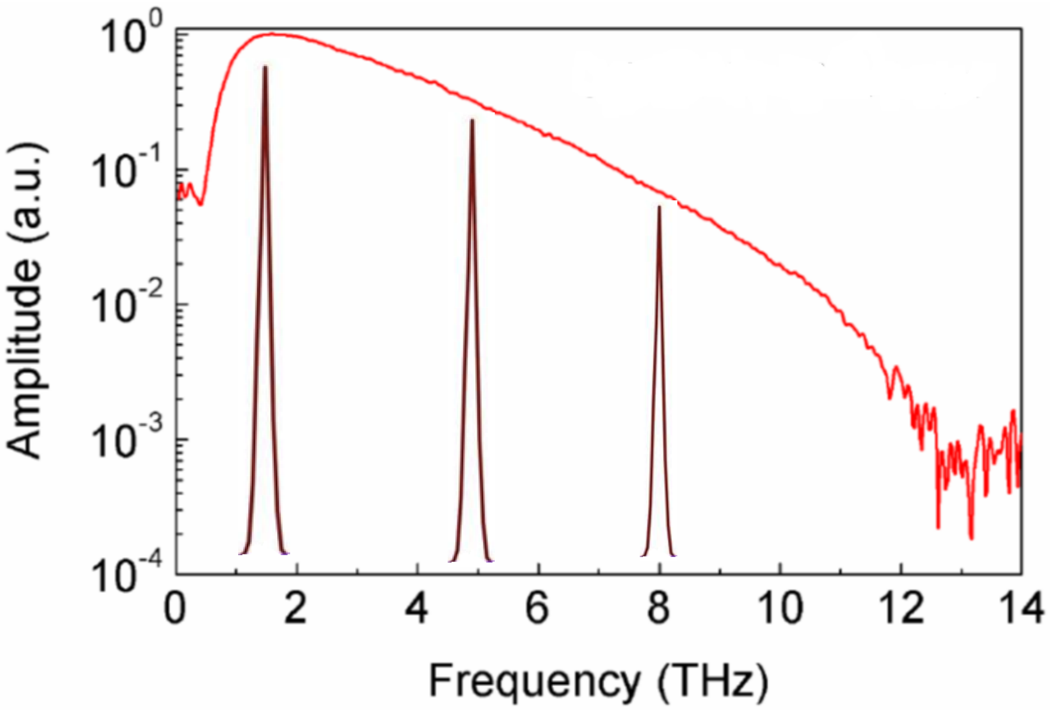
Narrowband, tunable laser-based THz generation schemes at EuXFEL

Three-fold approach:

1. Narrowband filtering of broadband THz (0-30THz):

Least complex…





Optics Express 18, 2872 (2010)

Narrowband, tunable laser-based THz generation schemes at EuXFEL

Three-fold approach:

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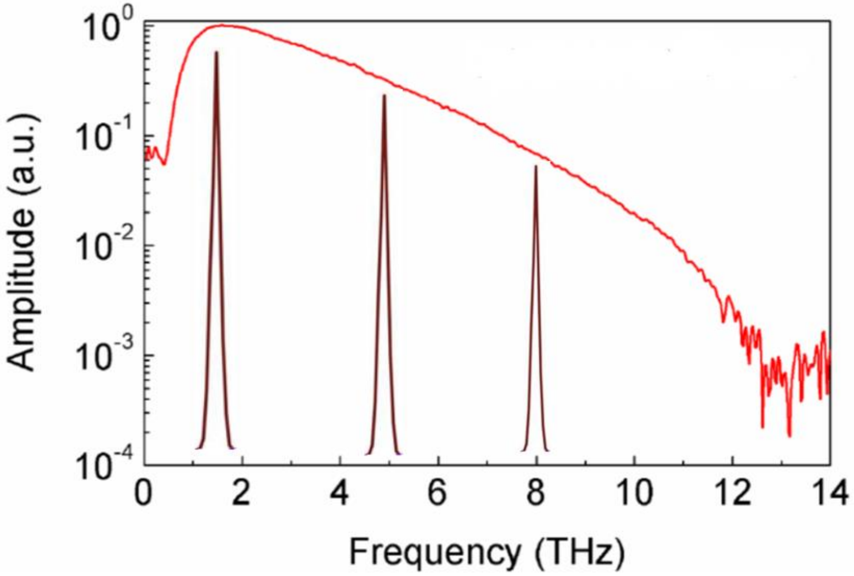
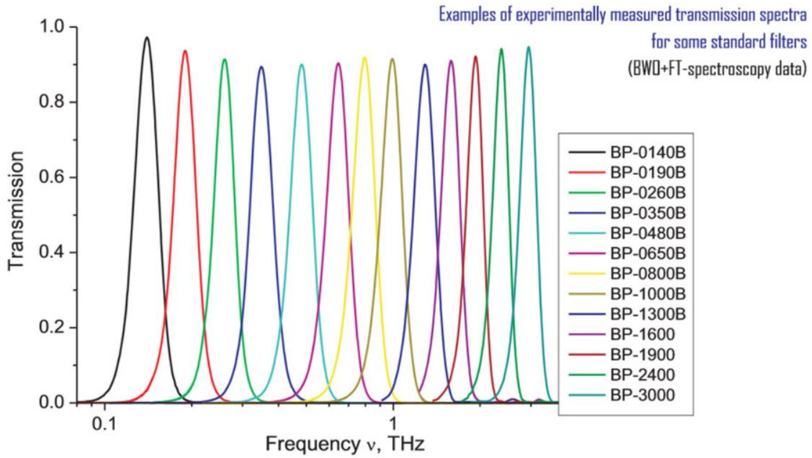




- **Bandpass THz filters, 84% to 97% transmission**
- **Variable bandwidth 1% to 20%**
- **Tunable central frequency, 0.2 THz to 20 THz**

www.terahertz.co.uk/qmci; www.soliton-gmbh.de;...

Narrowband, tunable laser-based THz generation schemes at EuXFEL

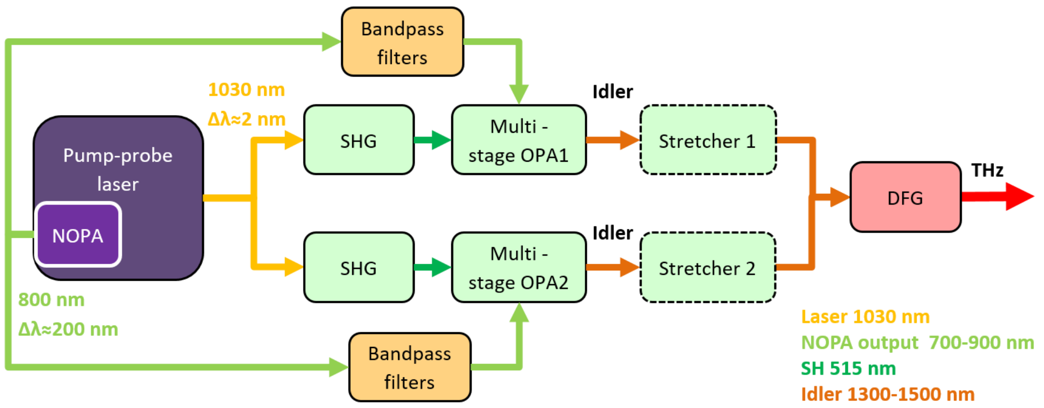
Three-fold approach:

1. Narrowband filtering of broadband THz (0-30THz):

- Least complex…

2. Organic-crystal-based difference frequency generation (DFG) of the idlers of two 515nm-pumped OPAs, wing-seeded by a broad-band NOPA:

- Makes use of NOPA (800nm) and pump (1030nm) beams of pump-probe laser.

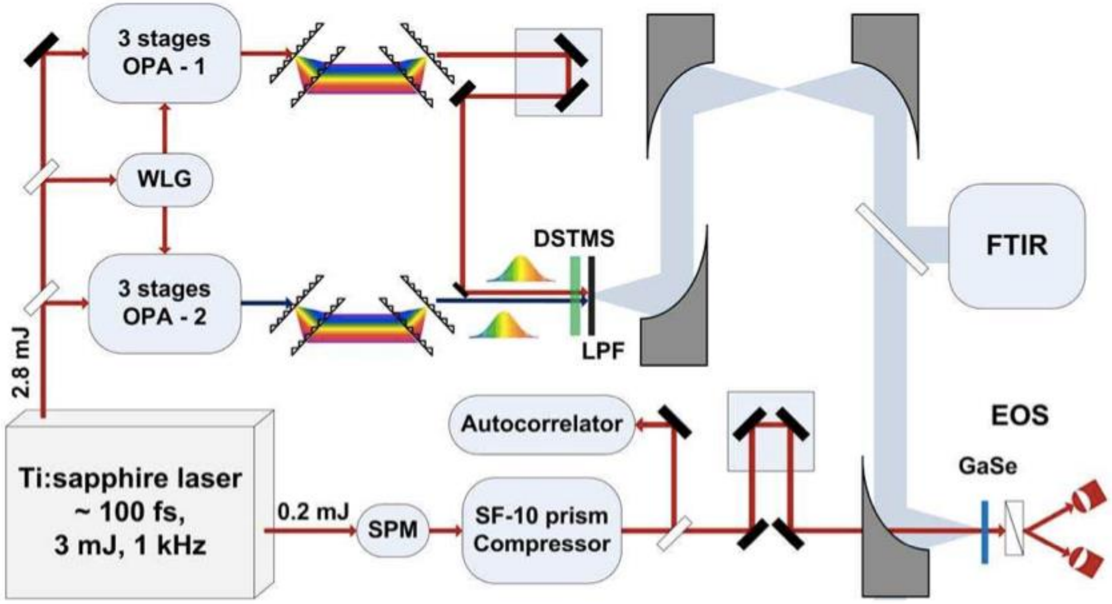


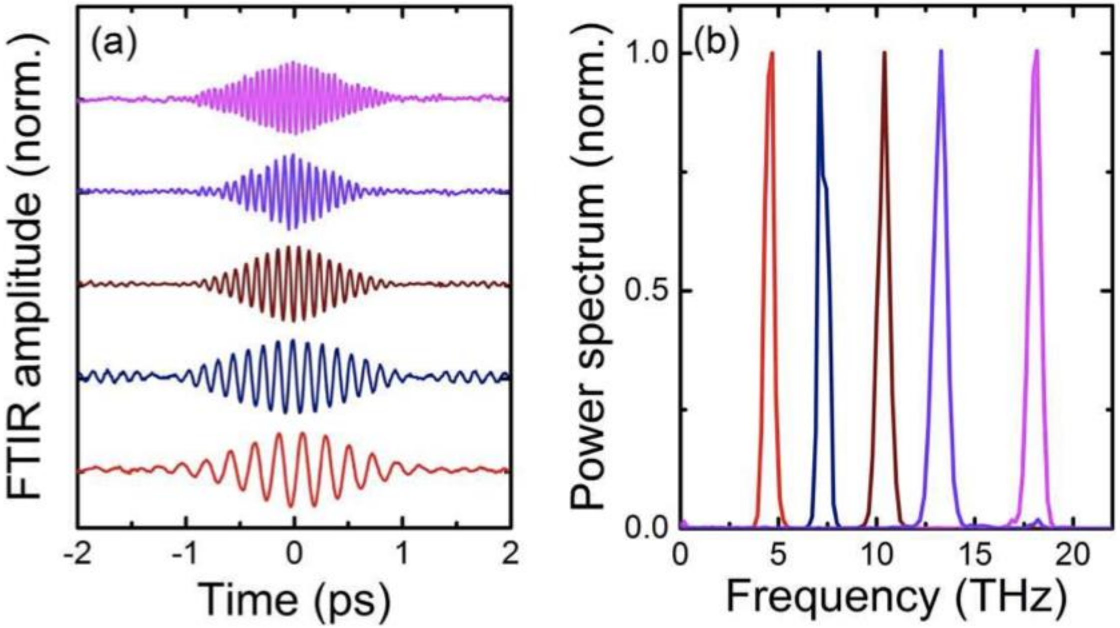
3. Difference frequency generation (DFG) of the signals of two 1030nm-pumped KTA OPAs, seeded by a supercontinuum:

- Driven by SCS (EuXFEL), Politecnico di Milano and MPI-MPSD, Hamburg and LAS (EuXFEL)

Narrowband, tunable laser-based THz generation schemes at EuXFEL

2. Organic-crystal-based difference frequency generation (DFG) of the idlers of two 515nm-pumped OPAs, wing-seeded by a broad-band NOPA:



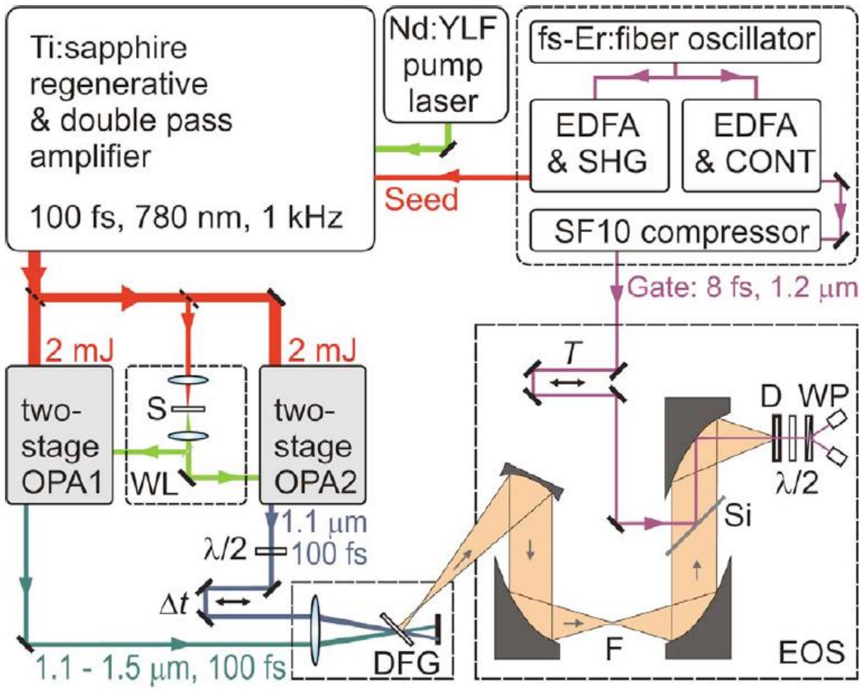


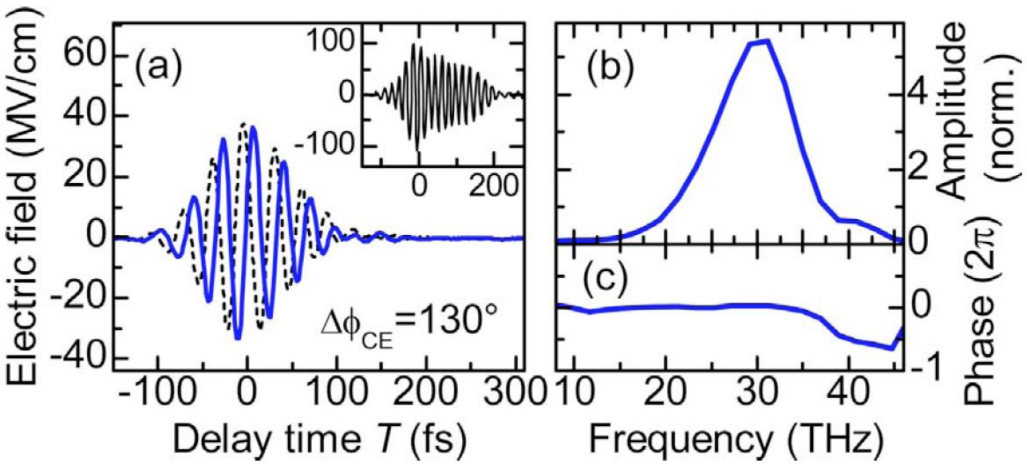
B. Liu et al., *Optics Letters* *42*, 189 (2017)

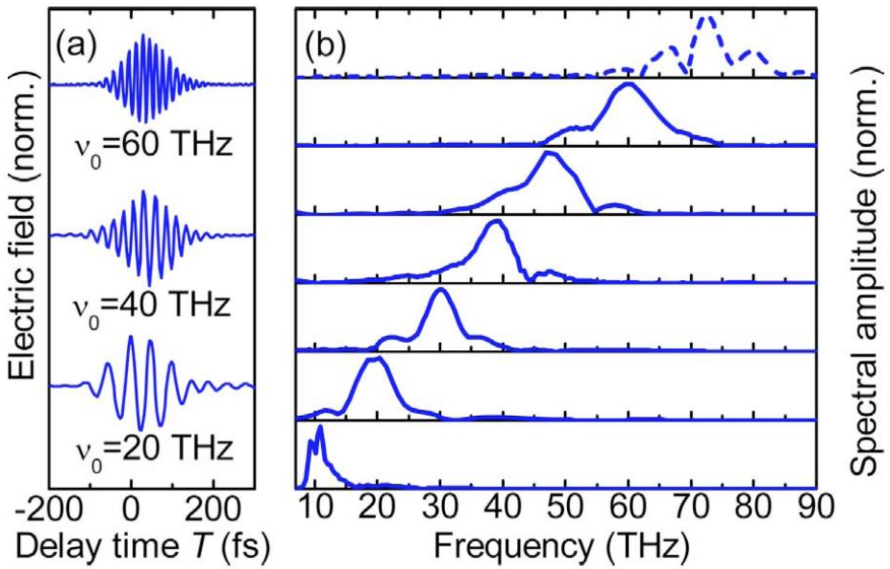
- 4THz to 18 THz from DSTMS
- ~0.1% conversion efficiency
- Up to 2µJ/pulse
- Up to 3.5 MV/cm THz fields

Narrowband, tunable laser-based THz generation schemes at EuXFEL

3. GaSe-based difference frequency generation (DFG)



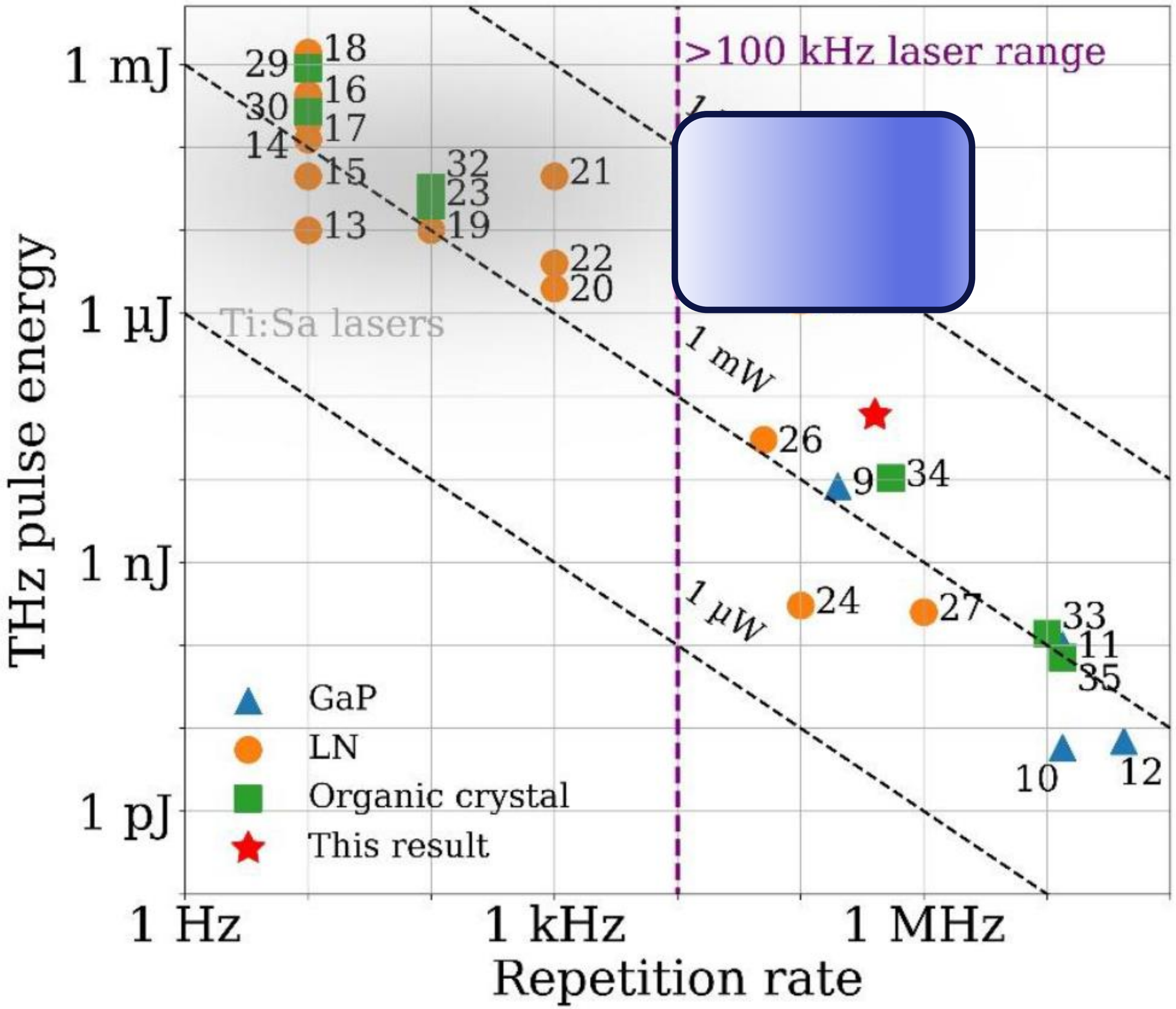




A. Sell et al., *Optics Letters* *33*, 2767 (2008)

Summary: Future Laser-based THz generation schemes at LAS, EuXFEL

- **Broadband, single-cycle** and **narrowband, multiple-cycle** THz sources **to be installed and commissioned at LAS**
- Envisioned **high THz fields (> 1 MV/cm)** in the **0.1 to 30 THz range at high rep-rates** (**0.1 to 1.1 MHz)**
- Implementation of such THz schemes at the XFEL end-stations tailored by user requirements
- Combined THz & X-ray pump-probe measurements



Optics Express 31, 7922 (2023)