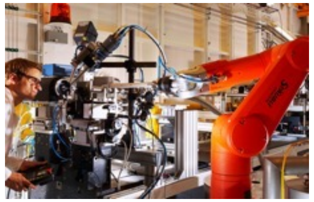
Progress in THz Acceleration

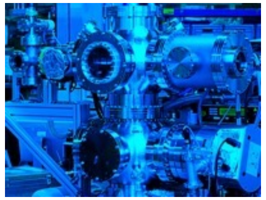


PETRA III / IV

6 GeV Highest Brightness Synchrotron

European XFEL

17.5 GeV X-Ray FEL
Atto - Femtosecond
Hard X-ray Source



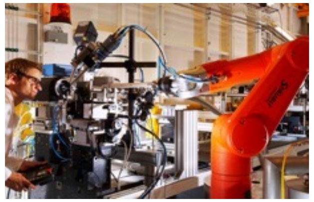
FLASH 2020+

VUV & Soft X-ray
Free-Electron Laser
Femtosecond Pulses

Franz X. Kärtner

Center for Free-Electron Laser Science
Ultrafast Optics and X-rays Group
DESY Photon Science Division
and Universität Hamburg

Compact Electron & X-ray Sources and Beam Manipulation and Diagnostics



PETRA III / IV

6 GeV Highest Brightness Synchrotron

European XFEL

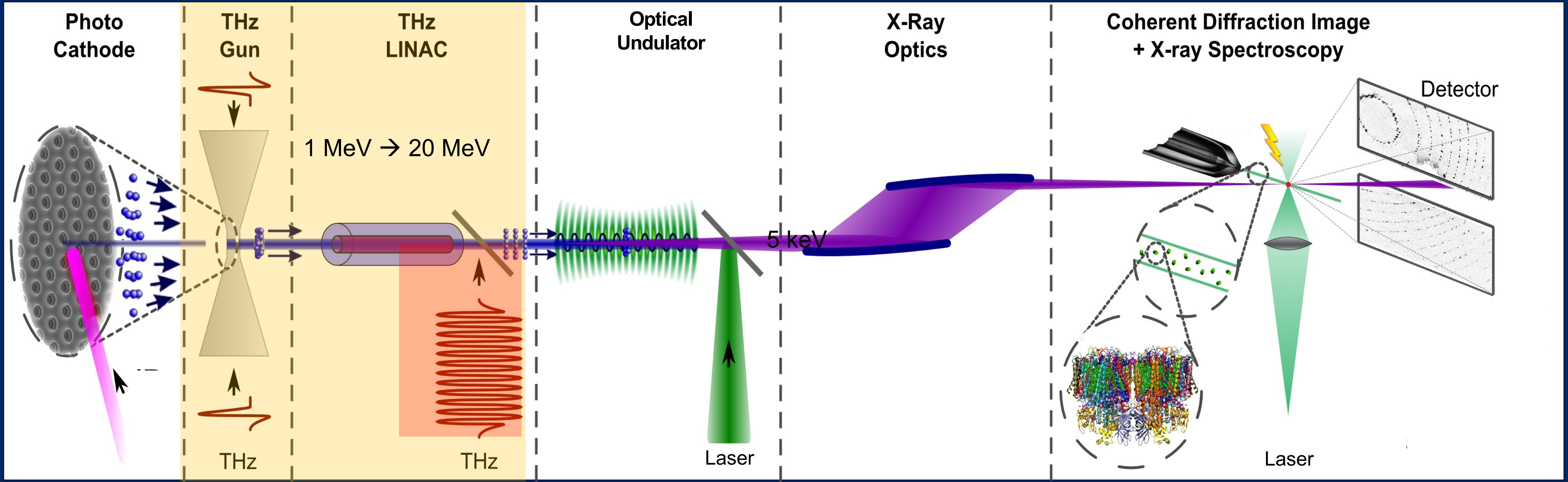
17.5 GeV X-Ray FEL
Atto - Femtosecond
Hard X-ray Source

- Compact sources → broaden user community
- Added value at end stations
- Underlying technologies have many applications
- Diagnostics and beam modification in RF accelerators
- High power THz Sources

THz Acceleration and Compact X-ray Sources

AXSIS: Attosecond X-ray Sources – Imaging and Spectroscopy

@ 300 GHz: 1 mJ-SC 20 mJ-MC @ 1 μm: 200 mJ – 1 J

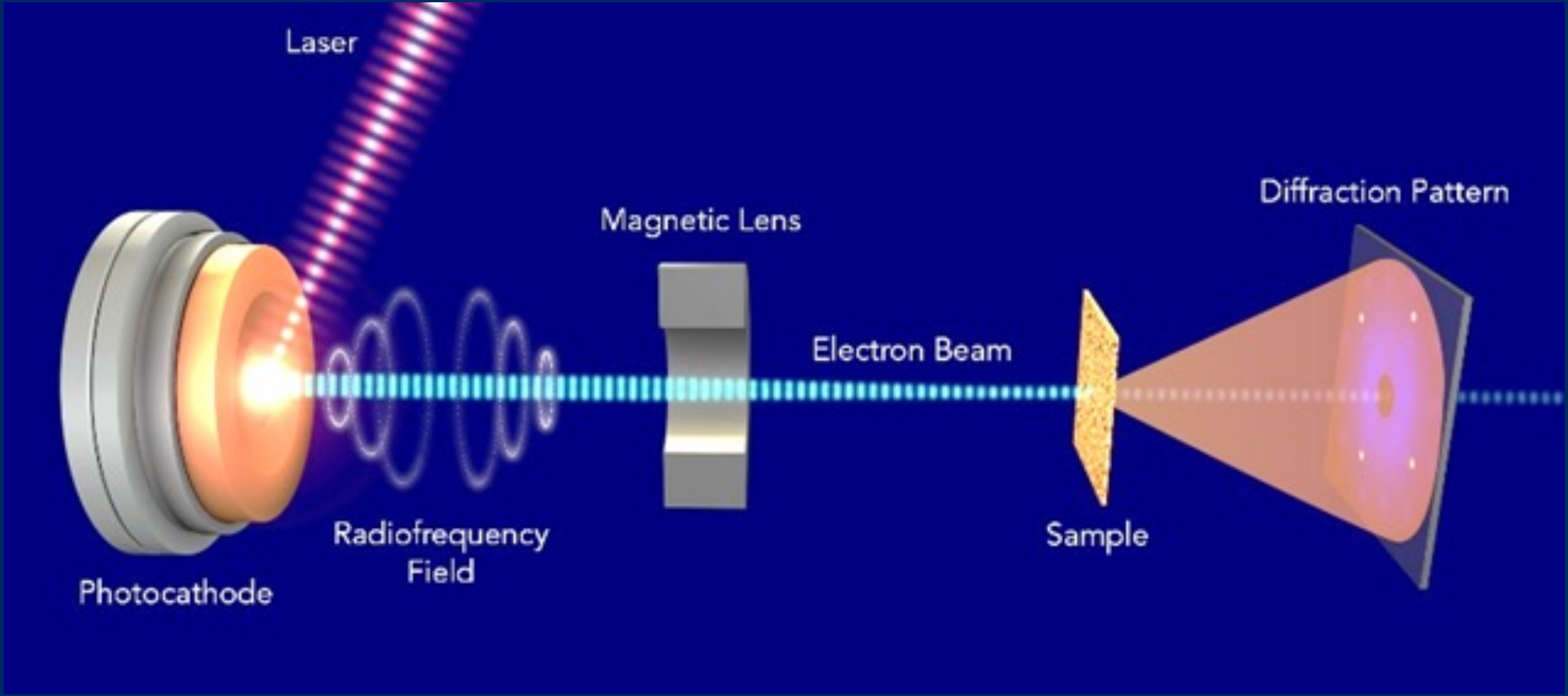


FXK. et al., doi:10.1016/j.nima.2016.02.080

Laser-based THz-generation, acceleration and optical undulator

1-J-ps Lasers, fs-level auto-synchronization, kHz operation

Ultrafast Electron Diffraction



Schematic UED Setup: SLAC National Accelerator Laboratory

https://www6.slac.stanford.edu/news/2015-08-05-slac-builds-one-of-worlds-fastest-electron-cameras.aspx

Why THz accelerators?

RF accelerators

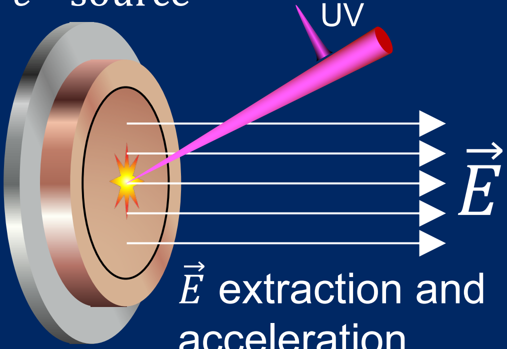
$E_0 \sim 30\ \mathrm{MV/m}$

$\lambda_{RF} \approx 10\ \mathrm{cm}$

[1] Kilpatrick RSI 28, 824 (1957)
[2] Dolgashev APL 97, 171501 2010
[3] Forno, et al. PRAB. 19, 011301 (2016)

$$\left|\vec{E}\right|_{breakdown} \sim \tau^{-5\,\ldots-6}$$

e^- source



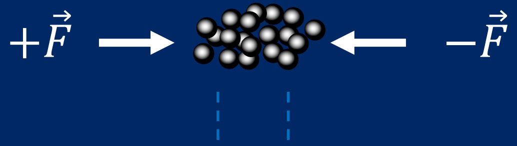
$\vec{E}$ extraction and acceleration

µs → ps

or

0.1 GV/m → 1 GV/m

e^- bunch



$\sim 1\ \mathrm{fs},\ 1\mu m$

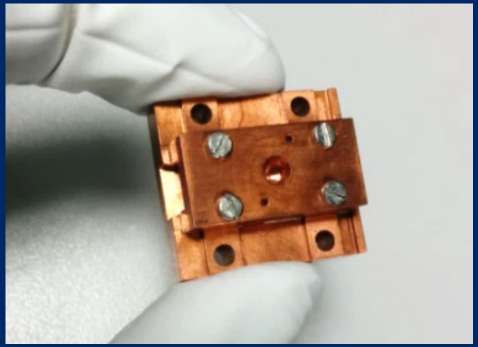
4D Brightness

$$B_{4D} \propto \frac{|E_0|^n}{MTE}$$

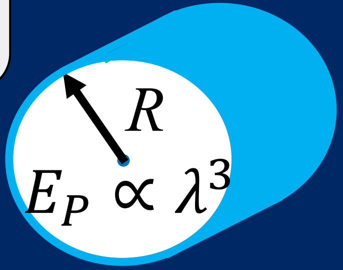
THz accelerators

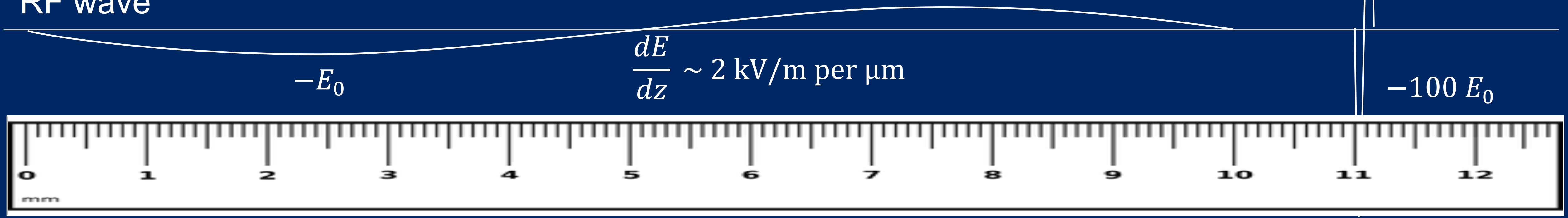
$E_0 \approx 1\ \mathrm{GV/m}$

$\lambda_{THz} \approx 1\ \mathrm{mm}$



THz wave

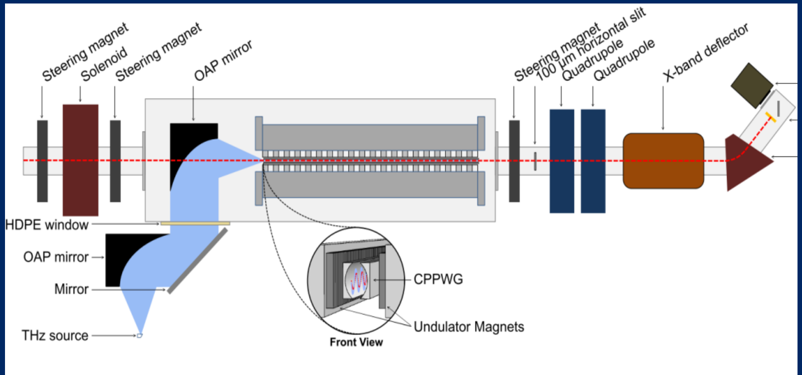


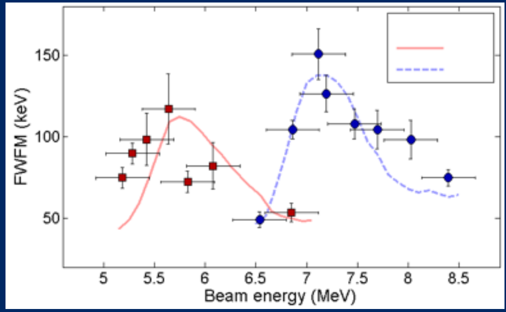


THz acceleration and beam manipulation takes up speed!

THz-powered iFEL

E. Curry et al., PRL 120, 094801 (2018)

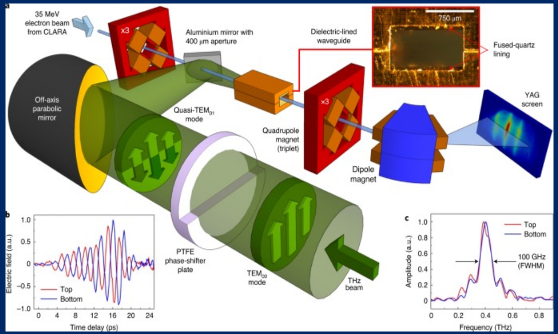


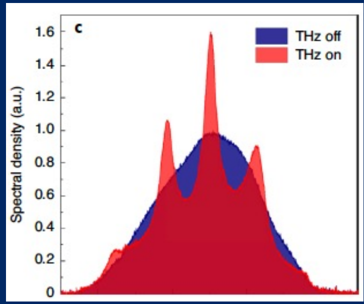


$E_{in} = 5\ \text{MeV}$
$\Delta E = \pm 75\ \text{keV}$
$E_{THz} = 1\ \mu\text{J}$

Acceleration

M. Hibberd et al., Nat. Photon. (2020)

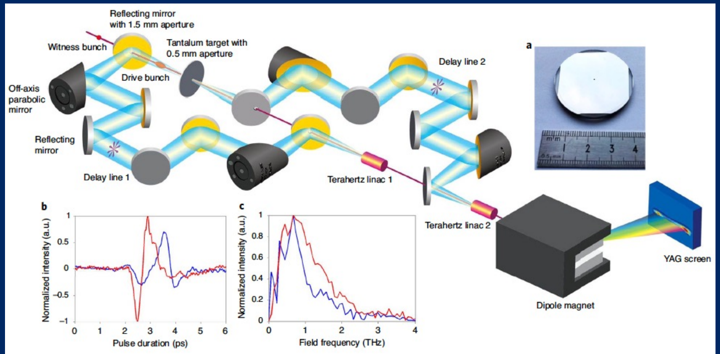


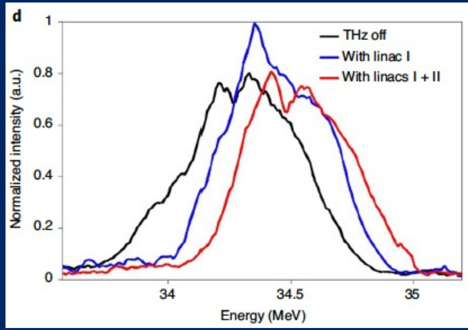


$E_{in} = 35\ \text{MeV}$
$\Delta E = \pm 10\ \text{keV}$
$E_{THz} = 2\ \mu\text{J}$

Acceleration & Staging

H. Xu et al., Nat. Photon. (2021)





$E_{in} = 34.3\ \text{MeV}$
$\Delta E = 150\ \text{keV}$
$E_{THz} = 132\ \mu\text{J}$

Many Others:

- *Kealhofer et al., Science 359, 459 (2016)*
- *Walsh et al., Nature Comm. 8, 421 (2017)*
- *Zhao et al., PRX 8, 021061 (2018)*
- *Li et al., Phys. Rev. Accel. Beams 22, 012803 (2019)*
- *Lenz et al., arXiv:2605.00125v2 (2026)*

Many more devices:

- *Guns*
- *Streaking*
- *Deflectors*
- *Compressors*

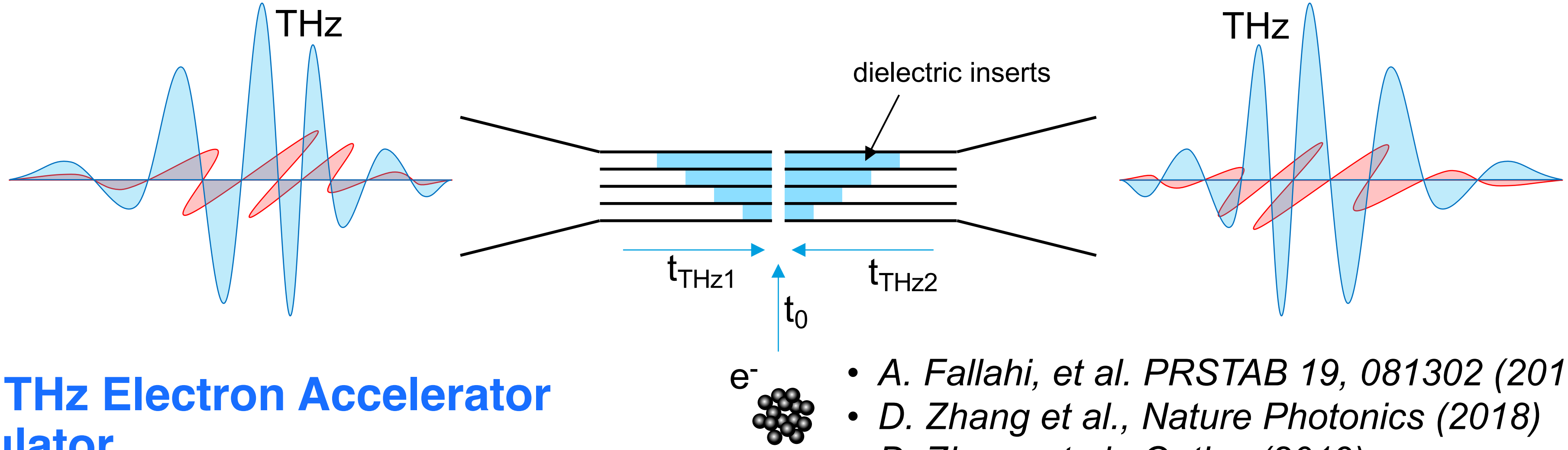
Outline

- Single and multi-cycle THz sources by optical rectification
- Amplifier for multi-cycle THz waves – Phlystron
- Advances in THz guns
- Dielectrically loaded metal waveguide accelerators
- THz accelerator facility
- Hollow Surface Plasmon-Polariton accelerator - HoSPPA
- Summary

THz - electron interaction geometries:

Transverse Geometry

- Single (few)-cycle THz
- Tuning: dielectric L, h

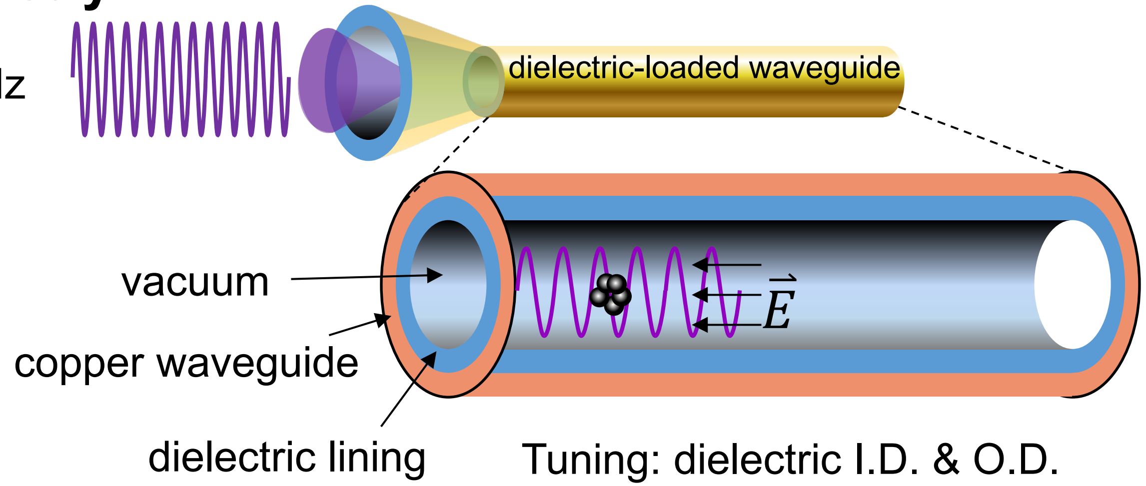


STEAM – Segmented THz Electron Accelerator and Manipulator

- *A. Fallahi, et al. PRSTAB 19, 081302 (2016)*
- *D. Zhang et al., Nature Photonics (2018)*
- *D. Zhang et al., Optica (2019)*

Co-propagating Geometry

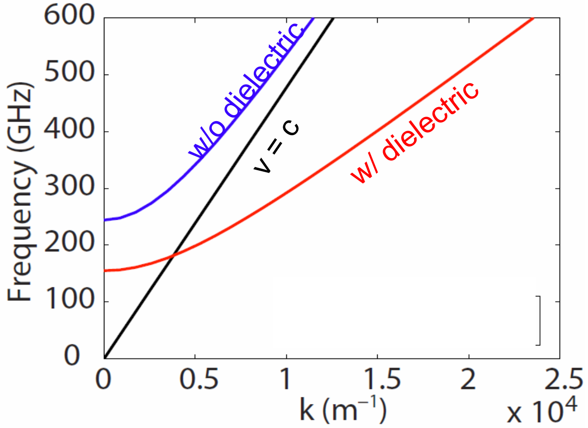
- Narrowband (multicycle) THz
- Tuning: dielectric inner and outer diameter



Tuning: dielectric I.D. & O.D.

DLW – Dielectrically Loaded Waveguide

DLW Dispersion Relation

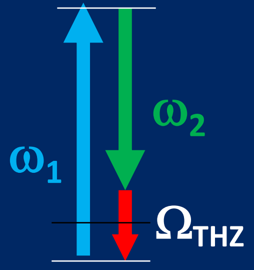


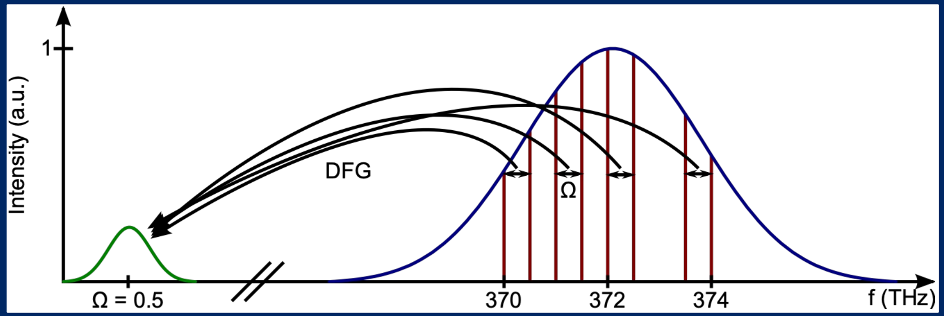
L.J. Wong et al., Opt. Exp. ***21****, 9792 (2013)*

Optical THz Generation based on χ(2) – Nonlinearity

Conservation of energy: $\Delta\omega = \omega_1 - \omega_2 = \Omega_{THZ}$

DFG process



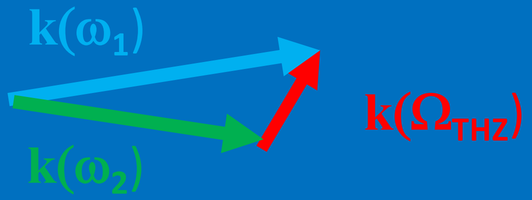


Optical bandwidth
> THz frequency

Conservation of momentum:

Non-collinear Phase Matching

$LiNbO_3$: $n_{opt} \approx 2$ and $n_{THZ} \approx 5$



Single-cycle THz generation by Tilted Pulse-Front Technique

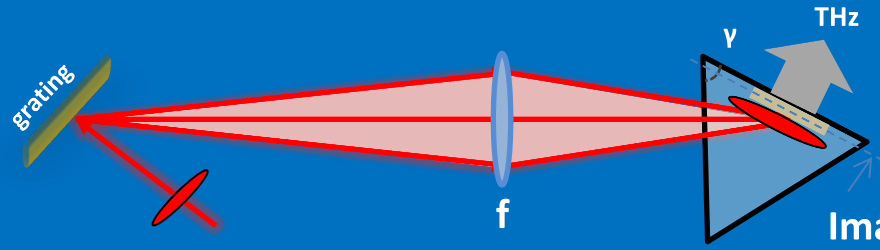
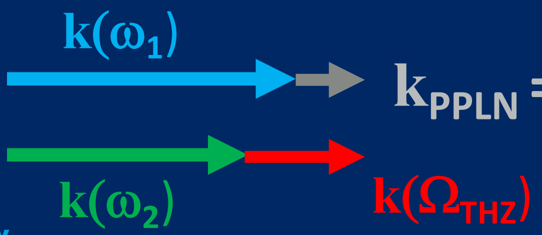


Image of grating

J. Hebling et al,
Opt. Express 21, 1161 (2002)

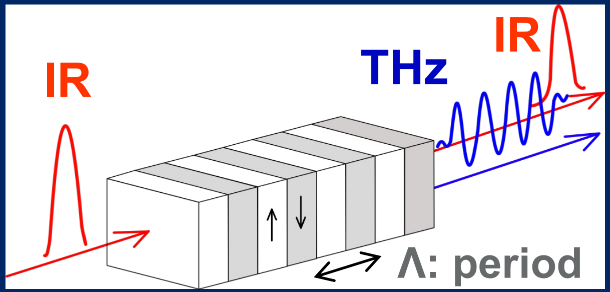
~ 1 % efficiency

Collinear Phase Matching



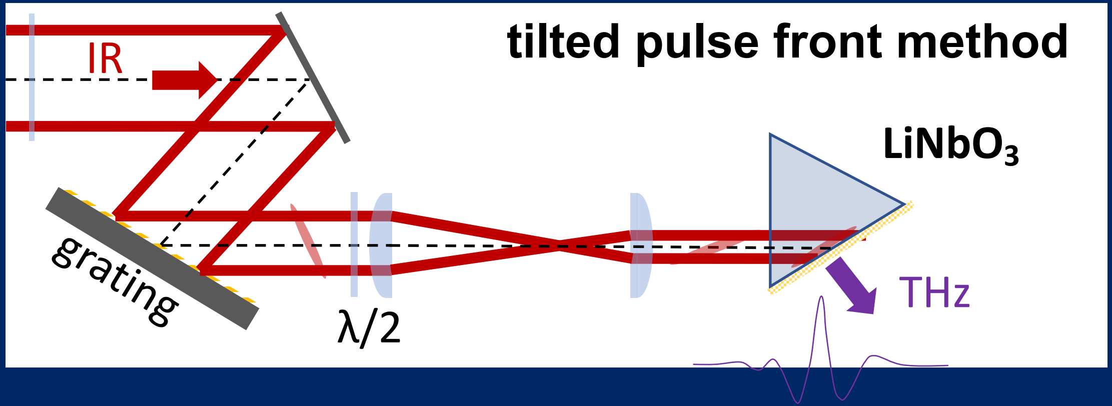
$$k_{PPLN} = \frac{2\pi}{\Lambda}$$

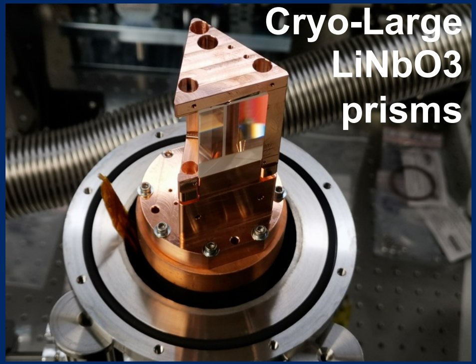
Multi-cycle THz generation using Periodically-Poled Lithium Niobate



> 1 % efficiency

mJ - scale single-cycle THz sources

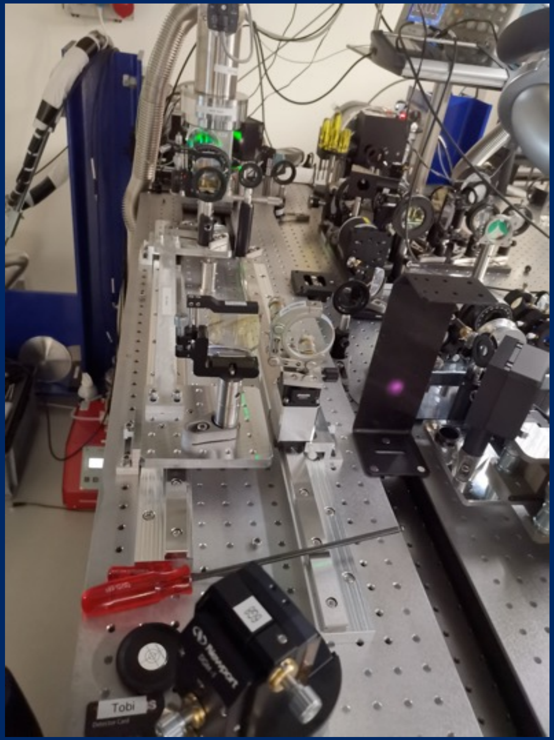


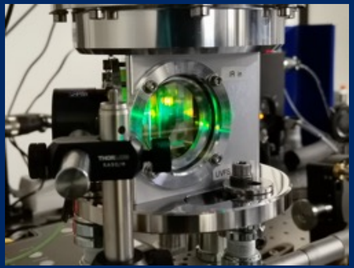


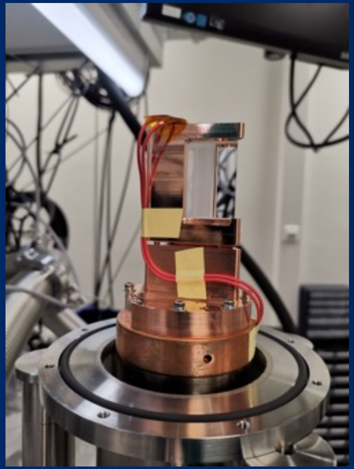
Single - Cycle THz Generation

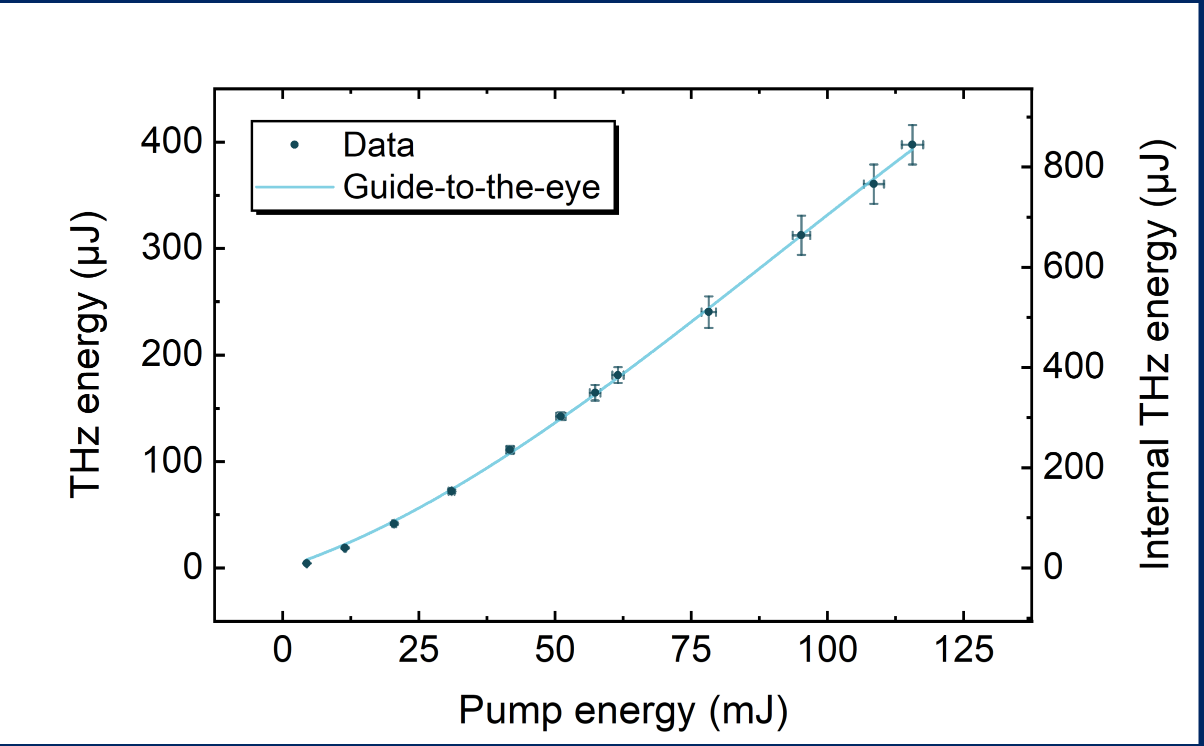
- ~ 0.5% conversion eff.
- 200 mJ → **1 mJ THz @ 50 Hz**

*T. Kroh et al., Opt. Exp, **30**, 24186 (2022)*



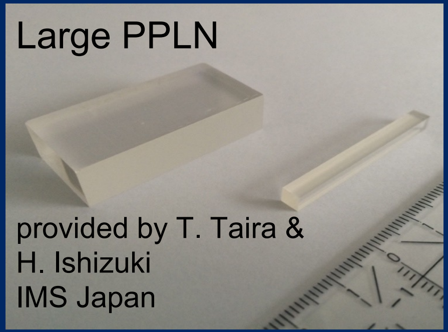




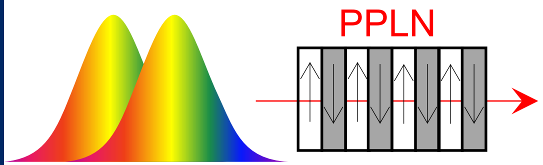


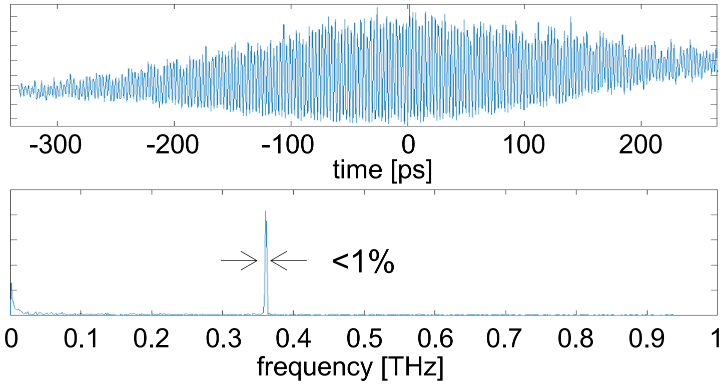
X. Wu et al., Generation of 13.5-mJ Terahertz Radiation from Lithium Niobate, Science Adv. 2023 (1 Hz)

Summary of multi-cycle THz development



Chirp & Delay



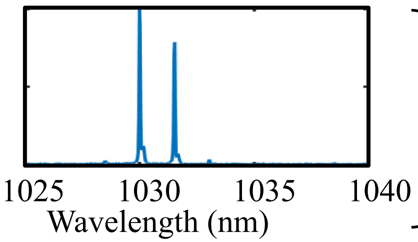


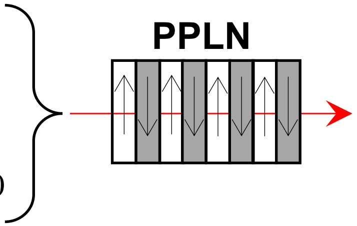
Record Narrowband THz Gen.

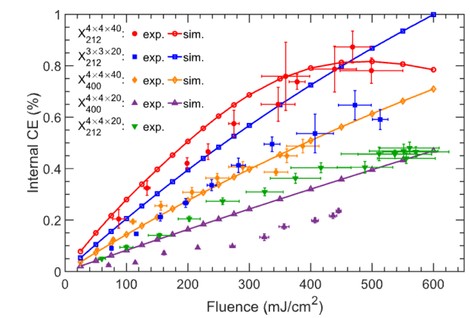
- 0.24% conversion eff.
- 1J Ti:S → **600 μJ THz**

S. Jolly et al., Nature Commun. ***10****, 2591 (2019)*

Custom 2-Line Laser



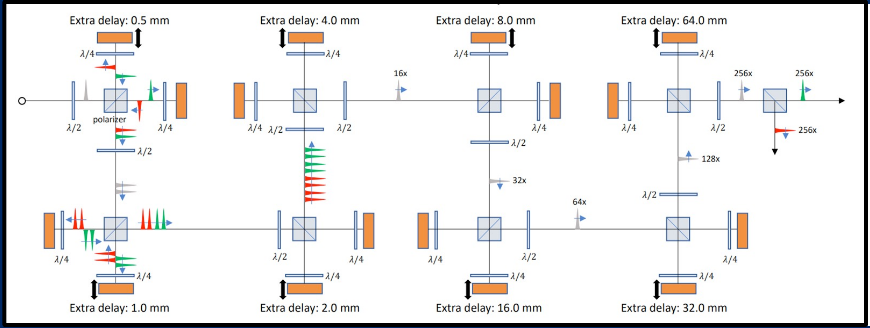


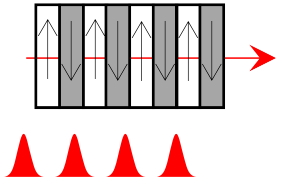


Record Narrowband THz Eff.

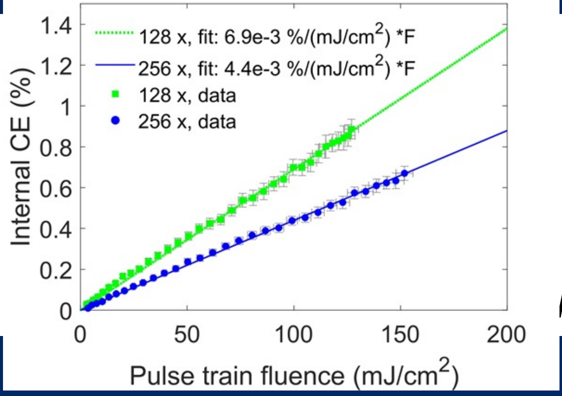
- 0.9% conversion eff. (500 GHz)
- 10 mJ Yb:YAG → **45 μJ THz**

H. T. Olgun et al., Opt. Lett. ***47****, 2374 (2022)*





Up to 256 pulses



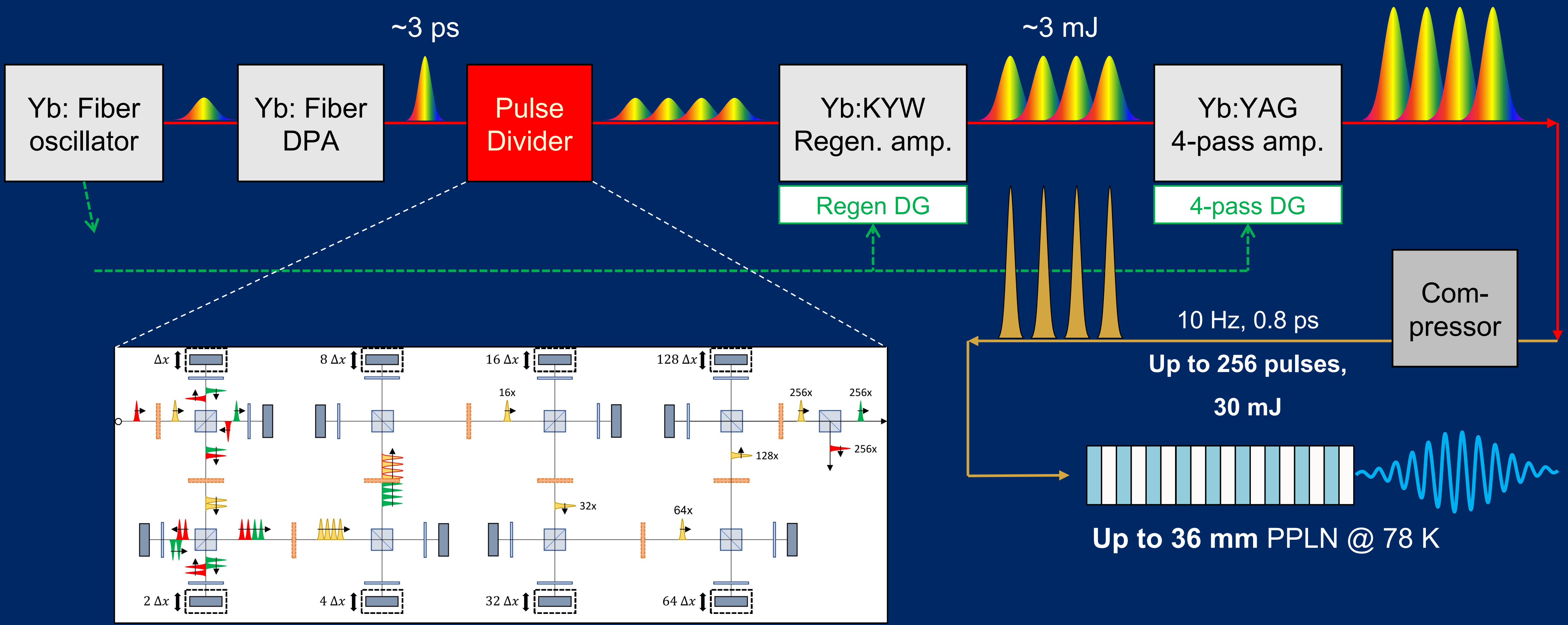
Exquisite Parameter Control

- periodicity of train
- \# of pulses in train
- duration of each pulse
- here 300 GHz

N. Matlis et al., Opt. Exp. ***31,*** *44424 (2023)*

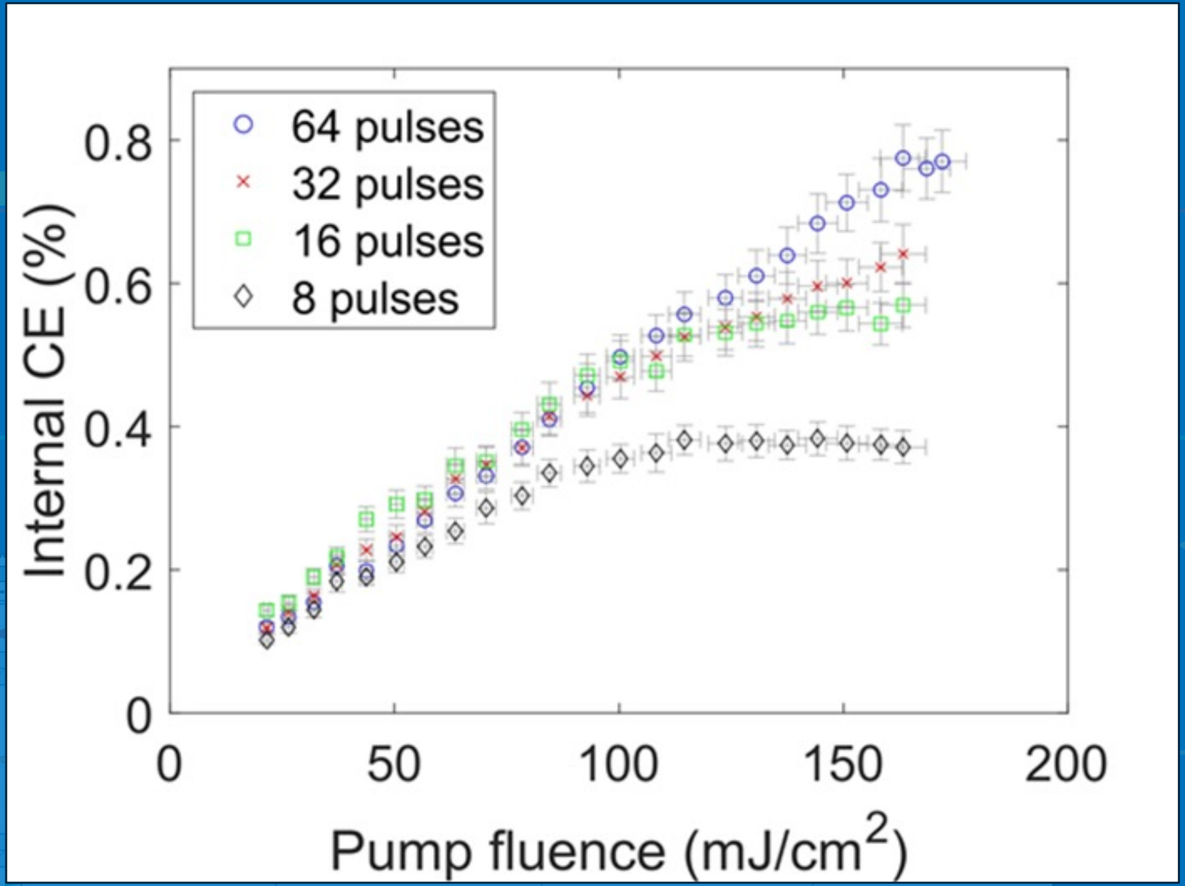
THz generation with tunable pulse trains

- Pulse train laser @ 1030 nm



THz generation with tunable pulse trains

- Pulse train laser @ 1030 nm



Efficiency remains < 1 %
(here 36 mm PPLN, 355 GHz)

But, pulse train approach allows control over THz pulse shape and length
$(\tau_{THz} \propto N_{train})$

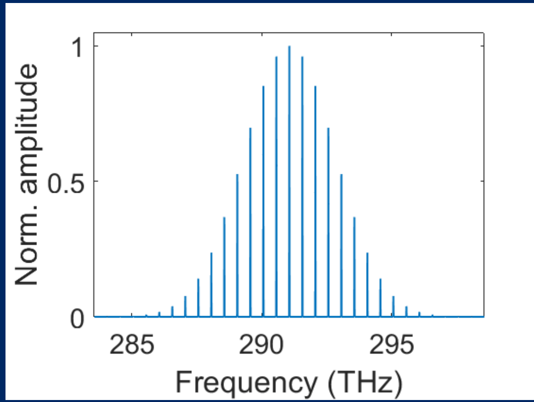
How to create 10 mJ-level THz rate pulse trains?

10 mJ-level THz energies require pump pulses ~1 Joule with sub-ps duration

High-energy laser technologies

Gain material	Yb:YAG / Yb:YLF	Nd:YAG	Ti:Sa
Pulse energy E_p	**~ 500 mJ**	Multiple J	Multiple J @ **< 10 Hz**
Pulse duration	< 500 fs	**~ ns**	> 20 fs
Wavelength	1030 nm	1064 nm	~ 800 nm
Cost	€€	€	**€€€**

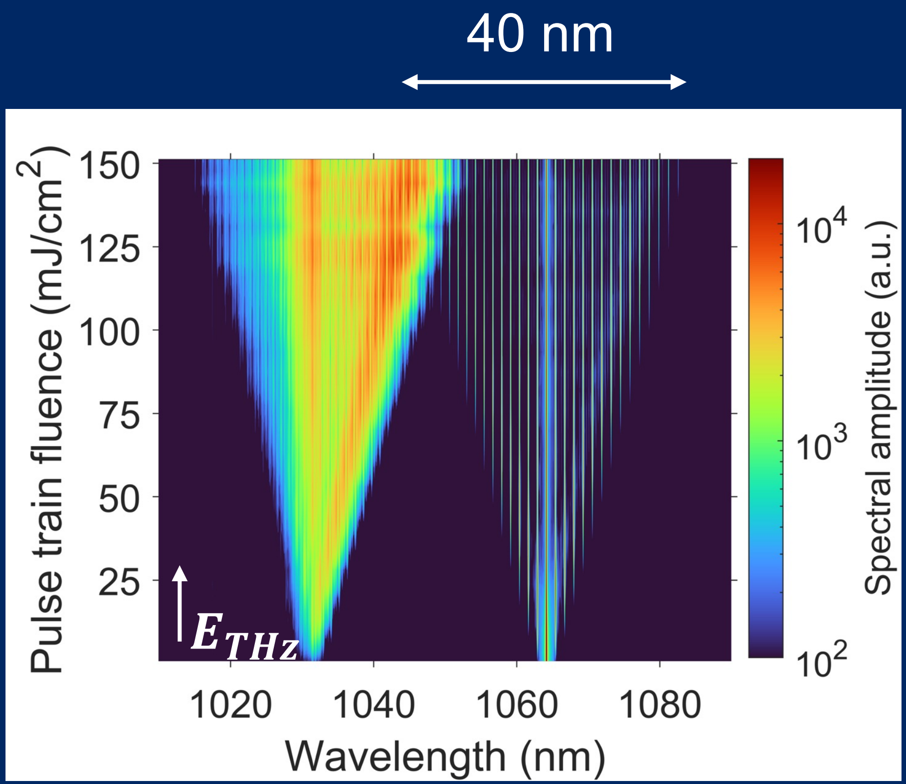
$\Delta f = f_{THz}$

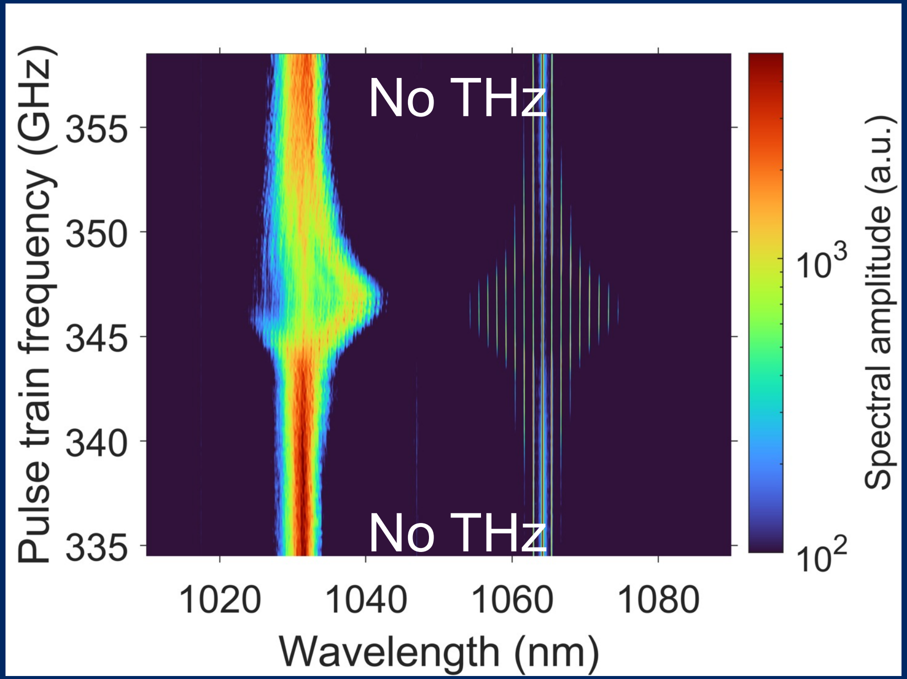


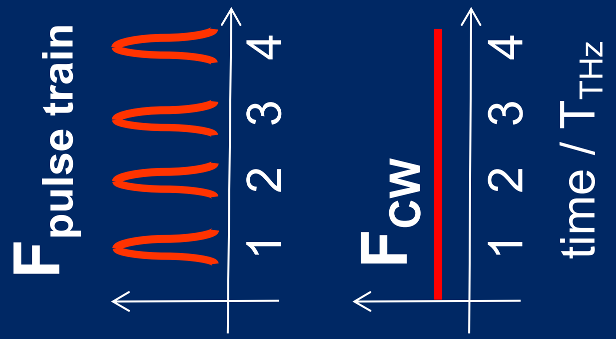
We can create 10-mJ-level THz rate pulse trains
by **modulating a Nd:YAG laser pulse** (multi-line spectrum)
→ Need intense THz pulses with ns duration!

THz-induced modulation

In 5 cm PPLN using 256 pulses: $\theta \propto r_{33}\boldsymbol{E_{THz}}L \cdot \sin(\omega_m t)$



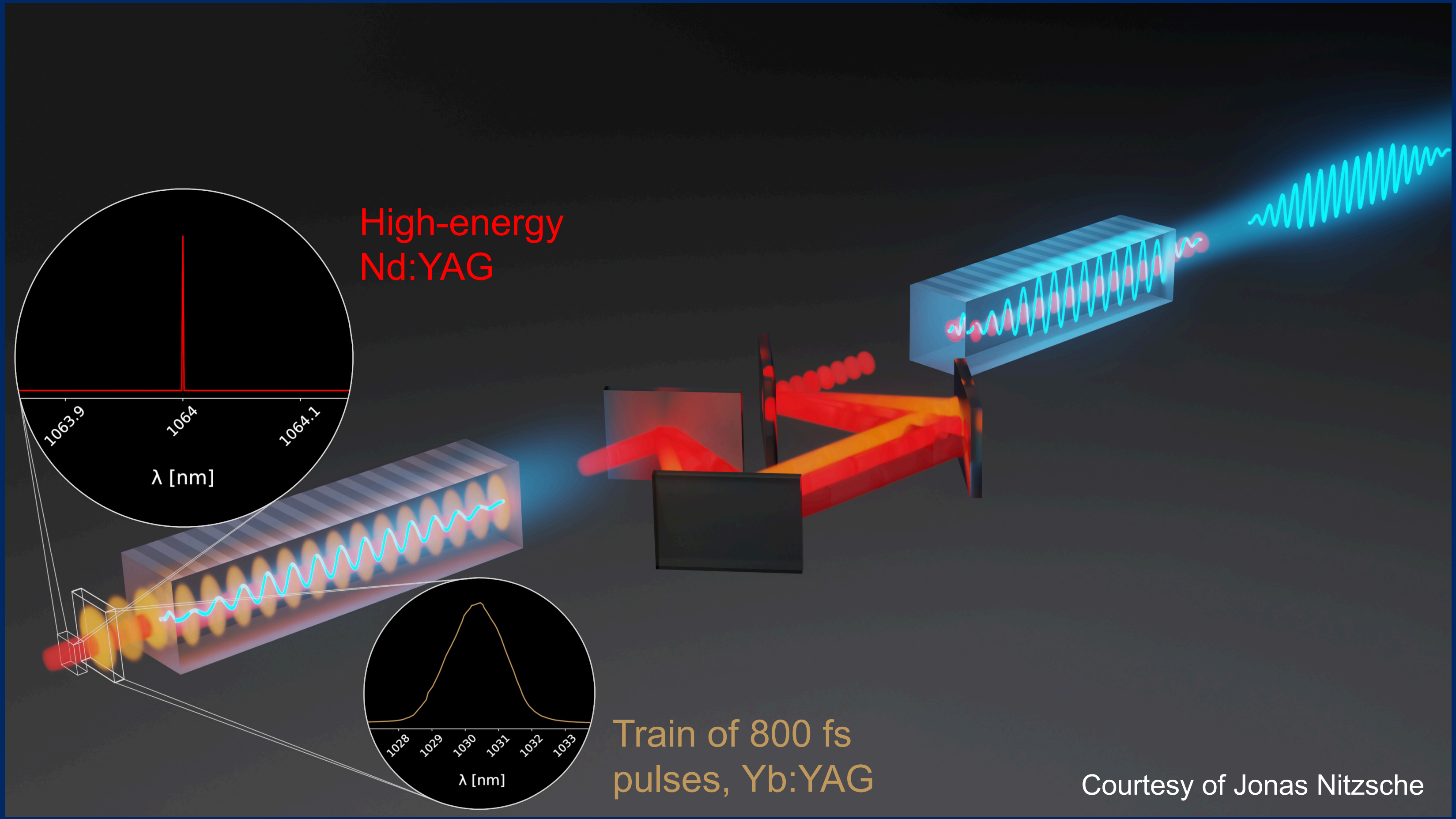




$\Delta\lambda = 1.27$ nm

$\rightarrow \boldsymbol{\Delta f = 335}$ **GHz** $(f_{THz} = 346$ GHz$)$

THz generation with a modulated narrowband laser



1. THz-induced traveling wave modulation in PPLN:

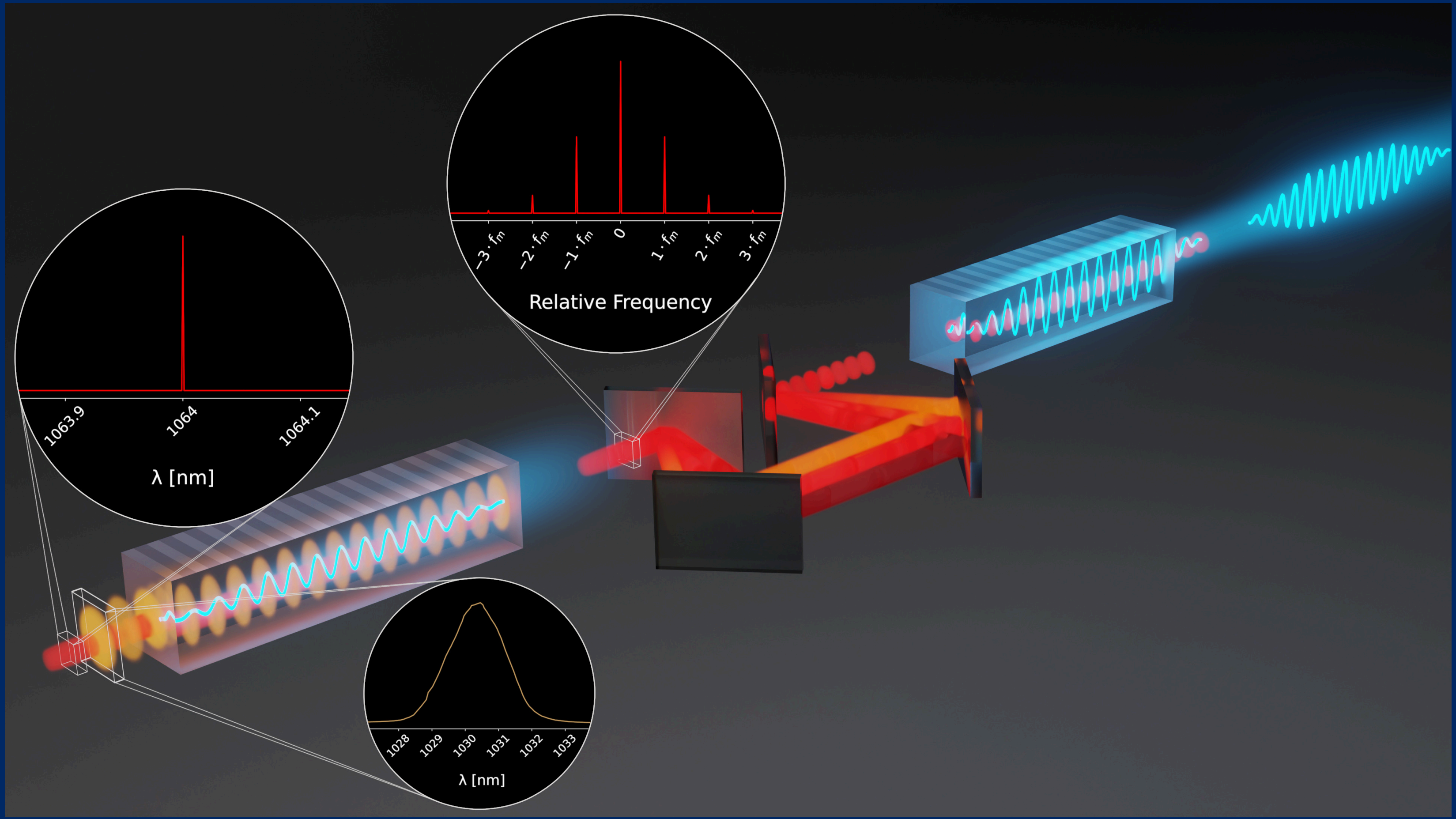
$$E_{op}(t) \propto e^{i\omega_0 t - i\boldsymbol{\theta}\sin(\omega_m t)}$$

with modulation depth

$$\boldsymbol{\theta} \propto r_{33} E_{THz} L$$

C. Rentschler et al., arXiv:2605.20118v1

THz generation with a modulated narrowband laser



1. THz-induced traveling wave phase modulation

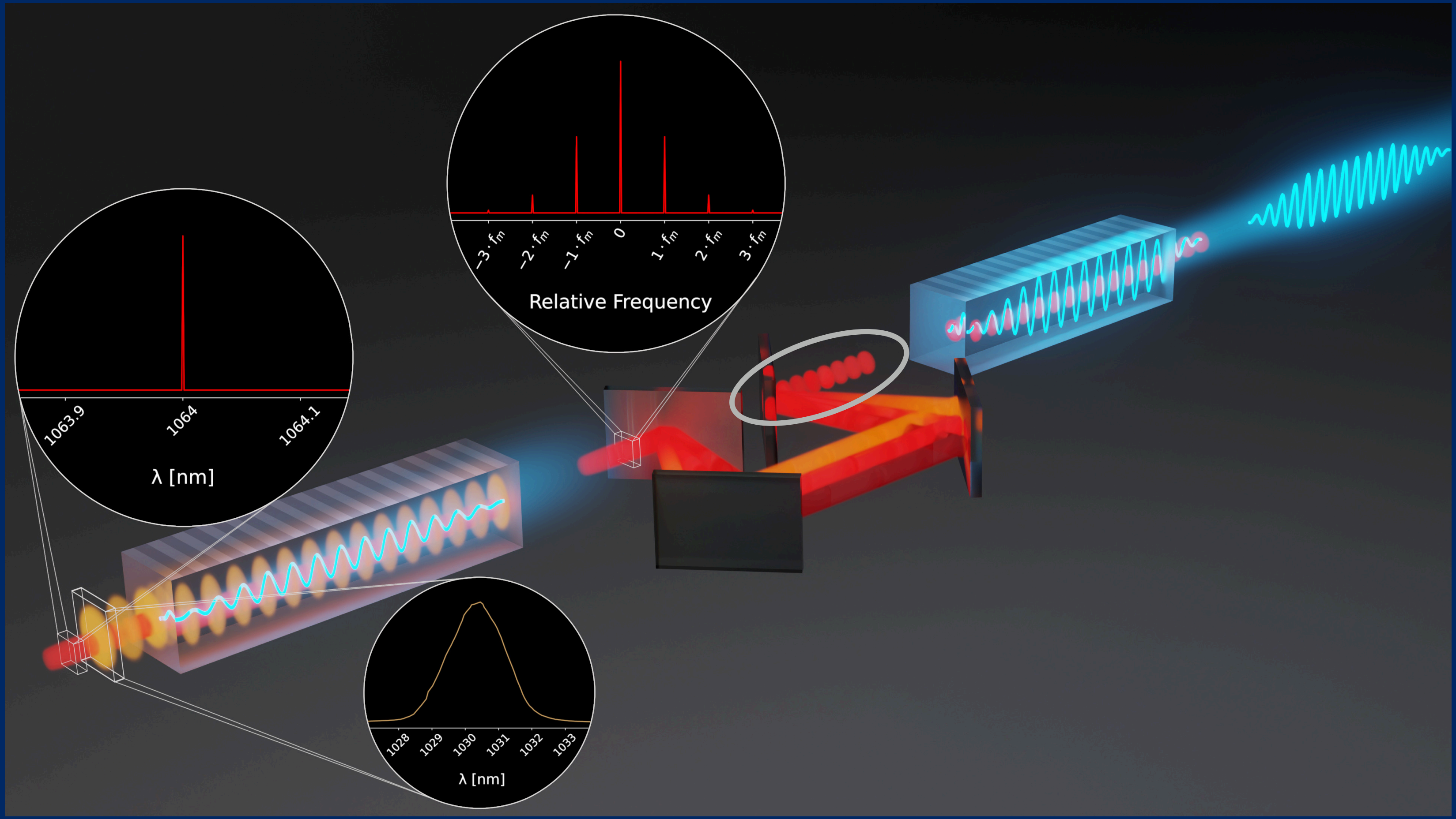
$$E_{op}(t) \propto e^{i\omega_0 t - i\boldsymbol{\theta}\sin(\omega_m t)}$$

$$= \sum_q J_q(\boldsymbol{\theta}) e^{i(\omega_0 - \boldsymbol{q}\boldsymbol{\omega_m})t}$$

with modulation depth

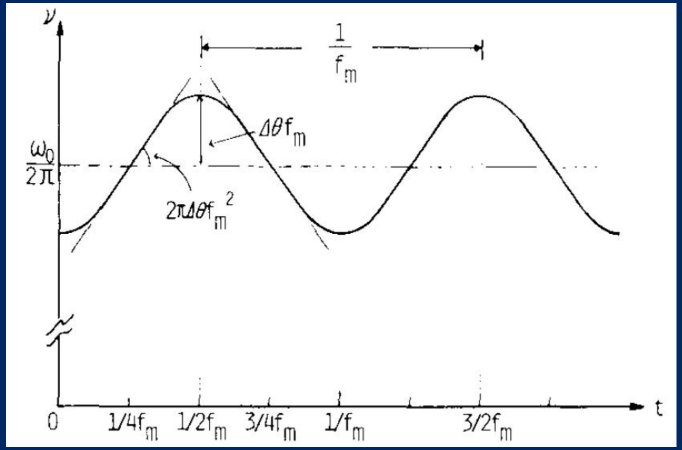
$\boldsymbol{\theta} \propto r_{33} E_{THz} L$

THz generation with a modulated narrowband laser

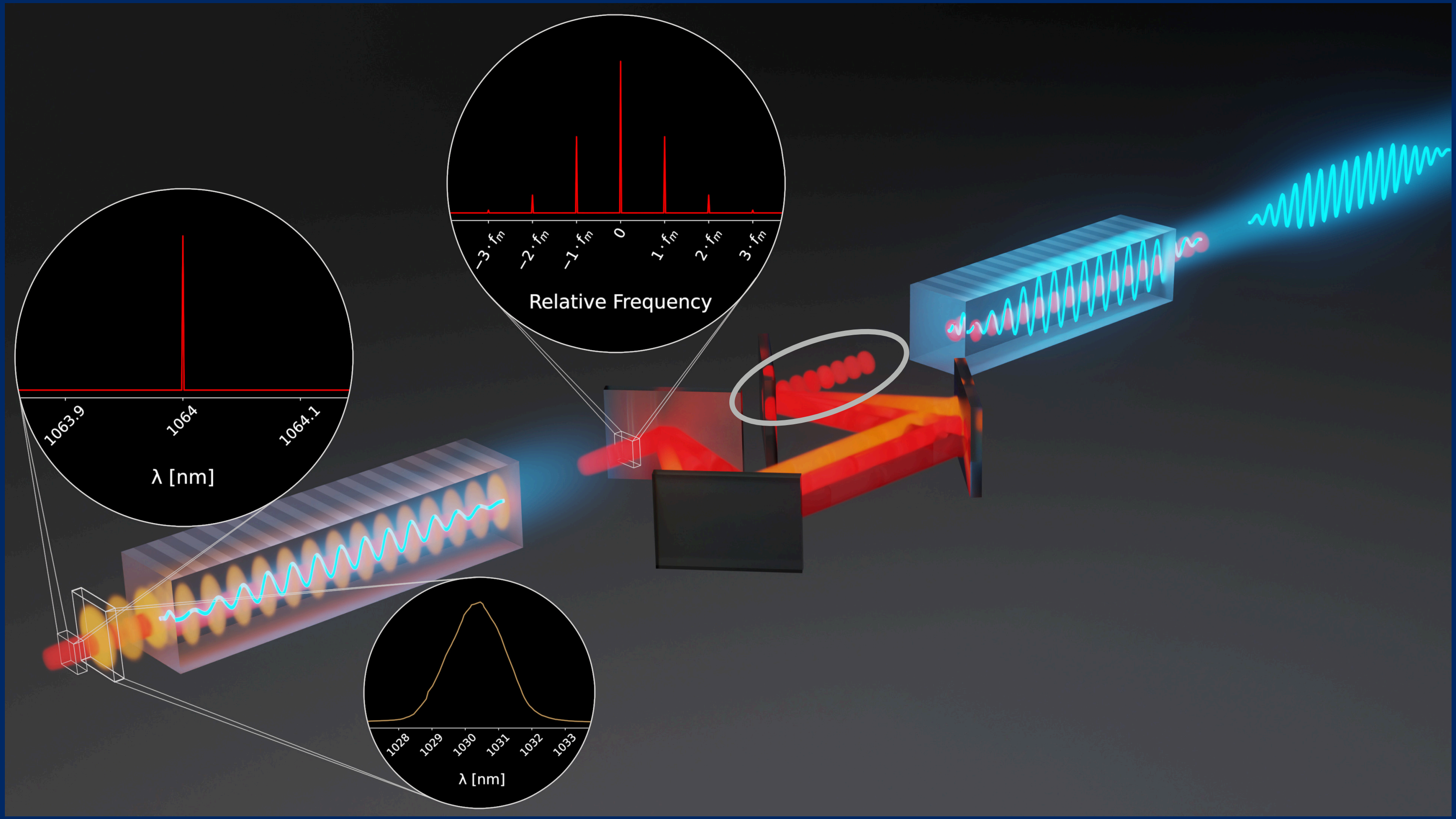


1. THz-induced traveling wave modulation in PPLN

2. Pulse “compression” → secondary pulse train

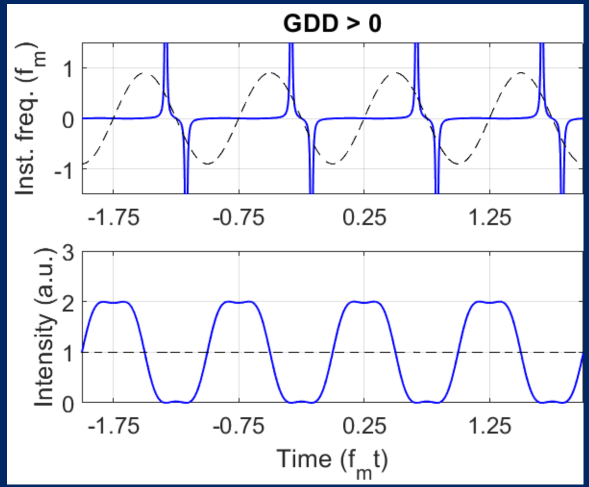


THz generation with a modulated narrowband laser

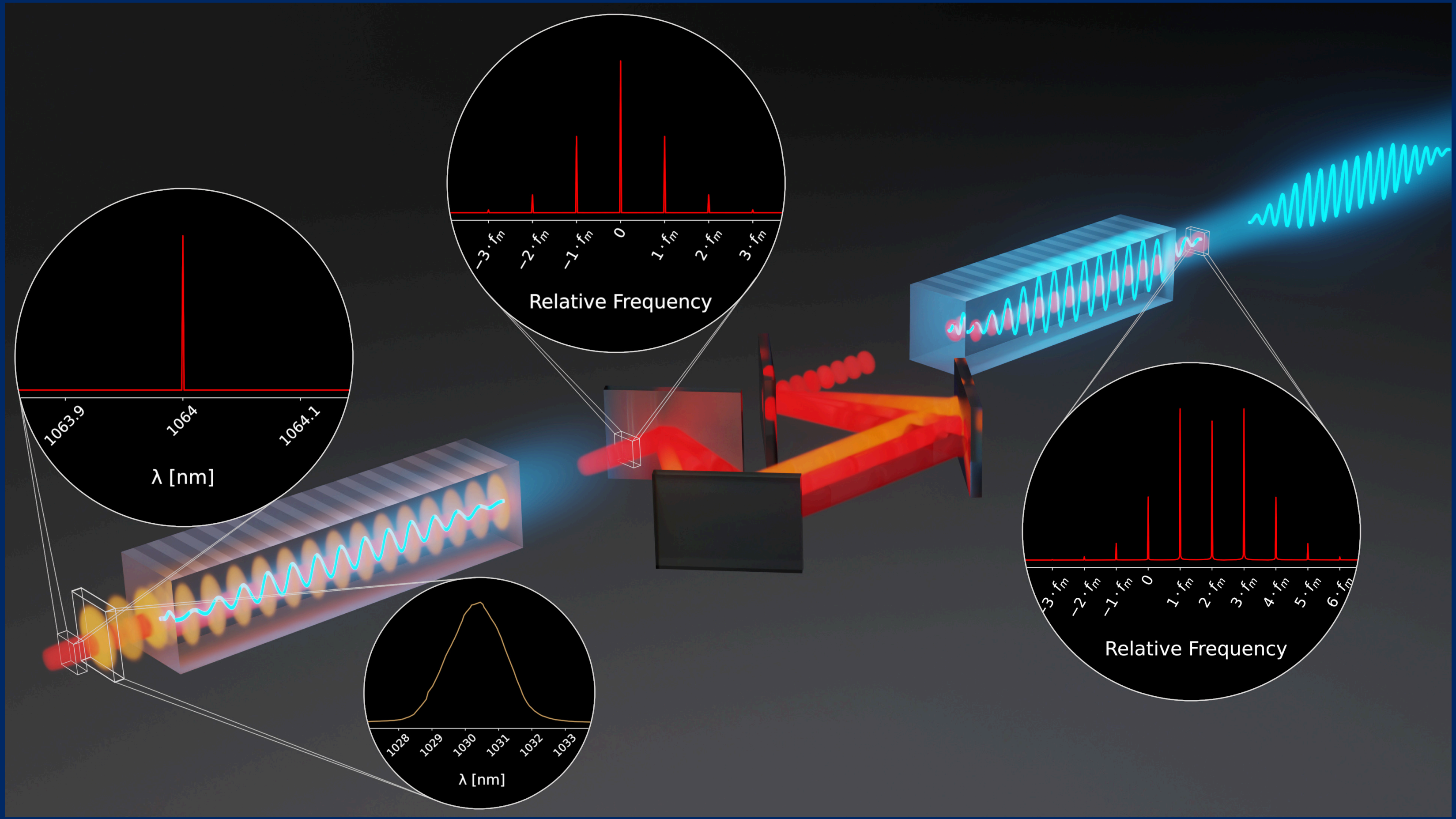


1. THz-induced traveling wave modulation in PPLN

2. Pulse "compression" with pos./neg. GDD:



THz generation with a modulated narrowband laser



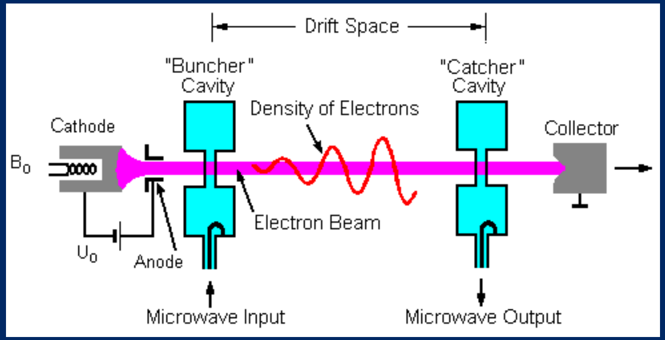
1. THz-induced traveling wave phase modulation in PPLN

2. Pulse “compression” with pos./neg. GDD:

3. THz generation in second identical PPLN

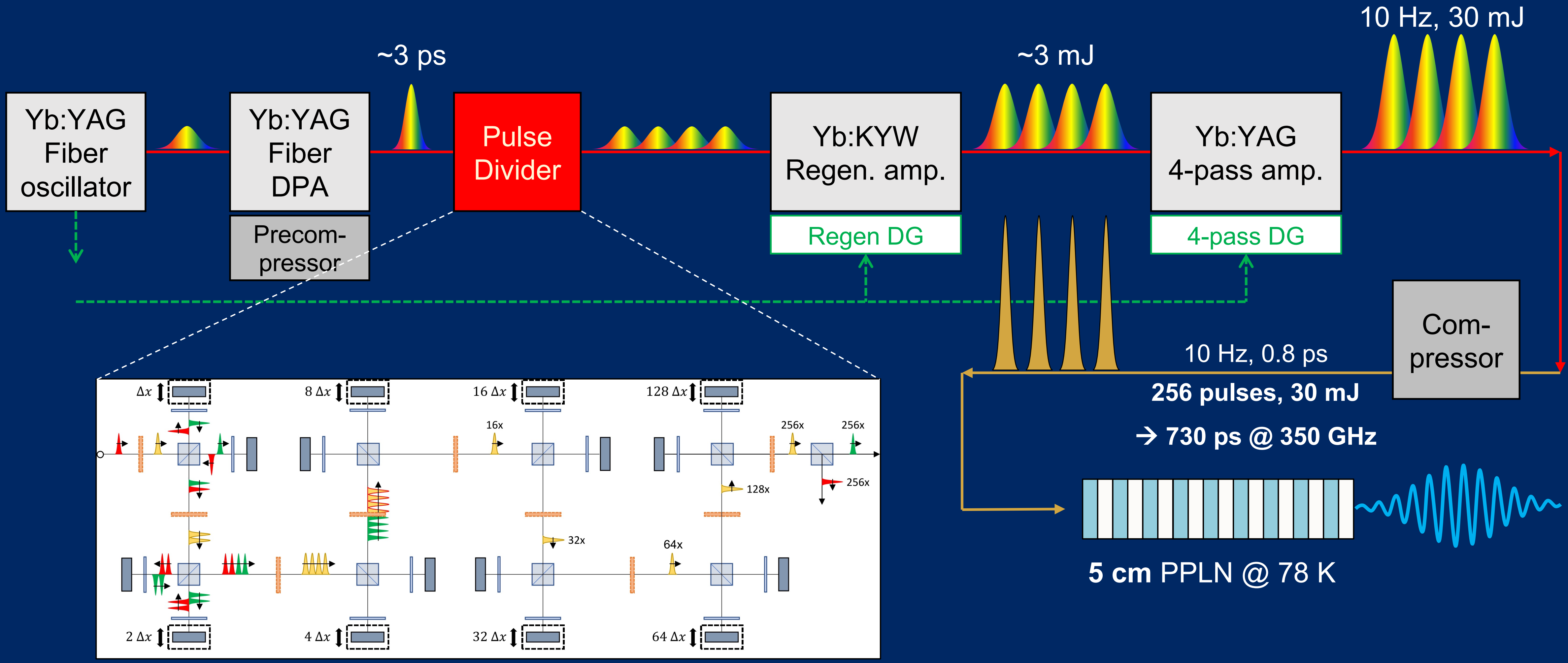
Similar to Klystron:

“Phlystron”



THz-induced modulation of a narrowband laser

- Pulse train laser @ 1030 nm synchronized with seeded narrowband laser @ 1064 nm



THz-induced modulation of a narrowband laser

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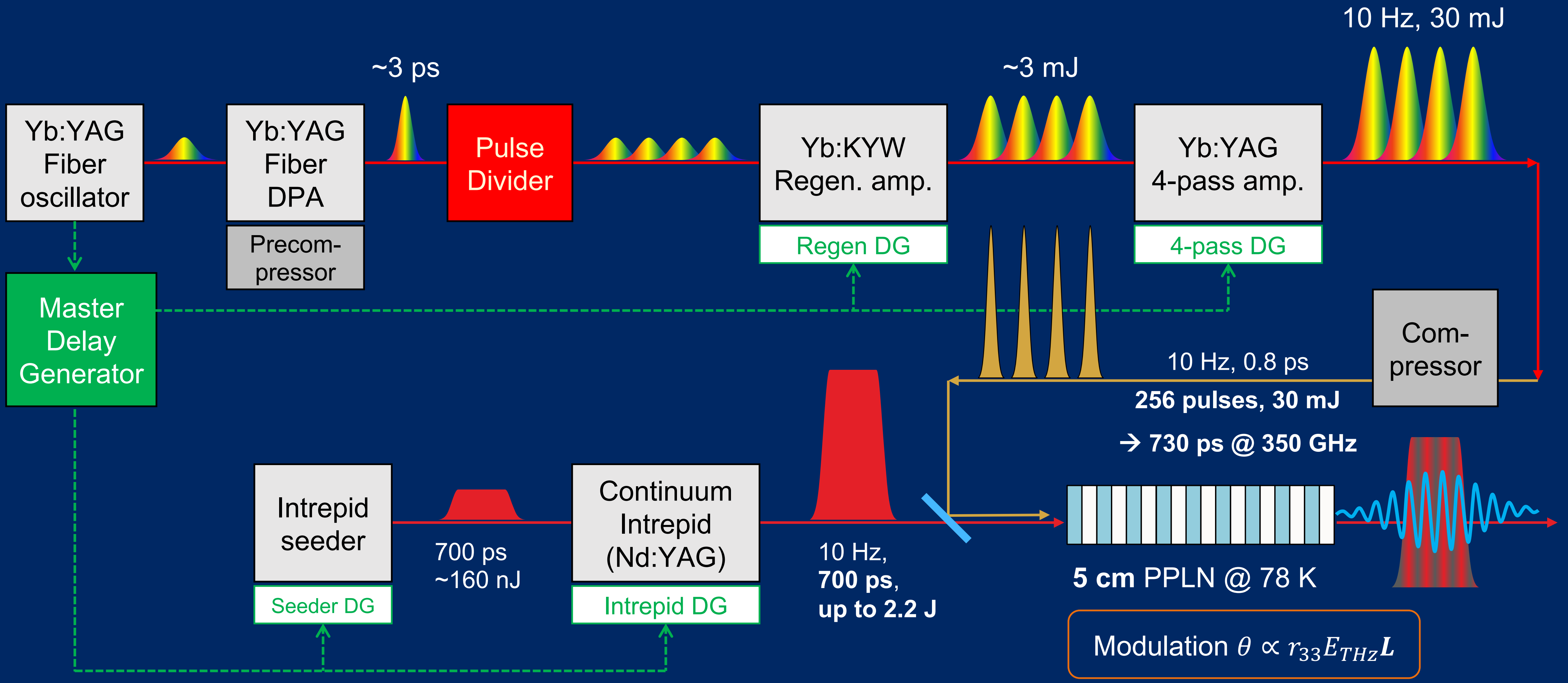
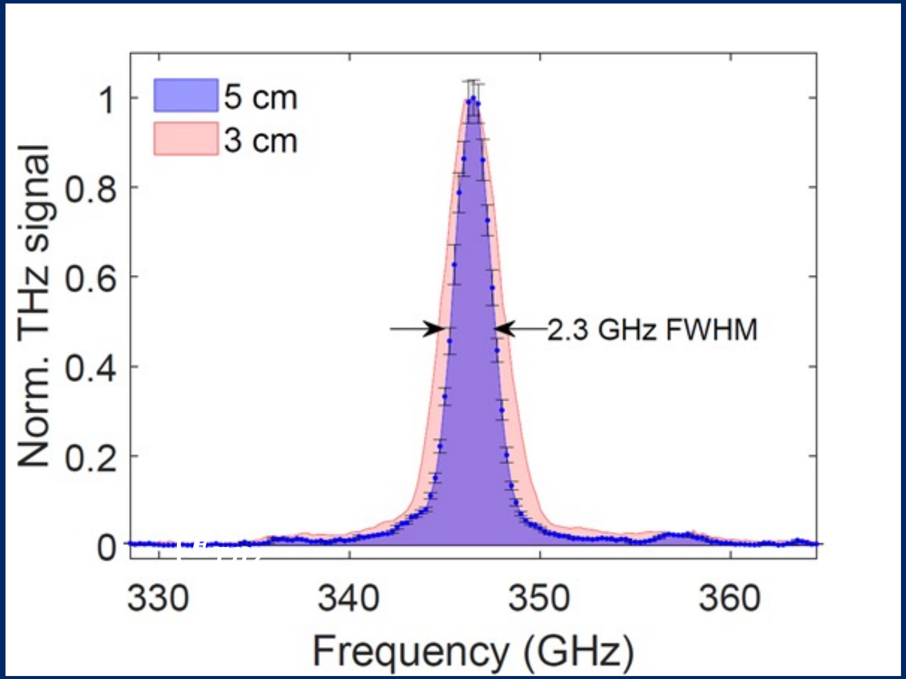


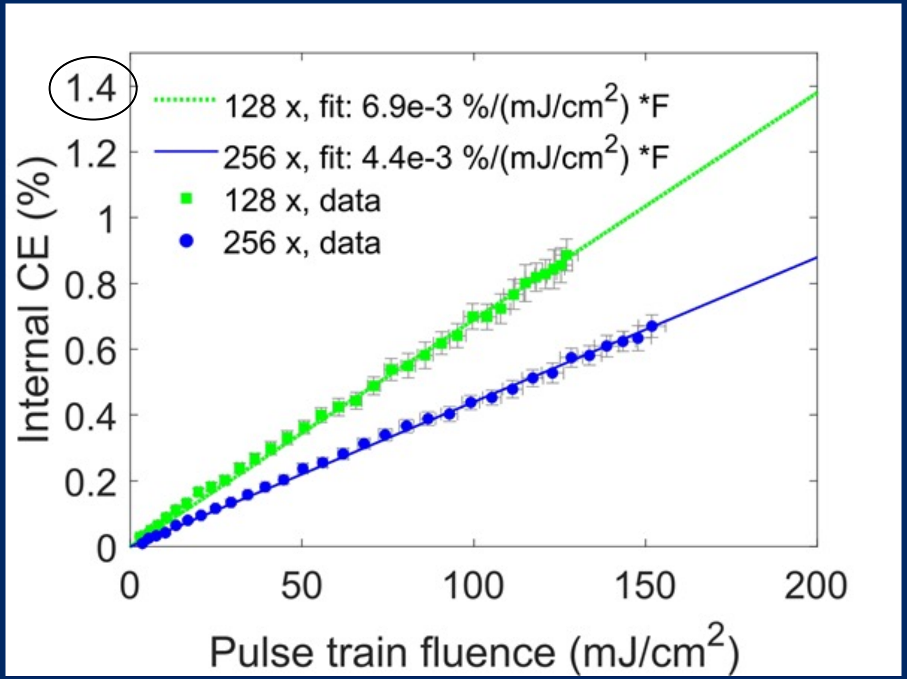
I. THz-induced modulation of a narrowband laser

Improved performance in 5 cm long PPLN

THz tuning curve: 256 pulses

•





$f_{THz} = 346.5\ \mathrm{GHz}$

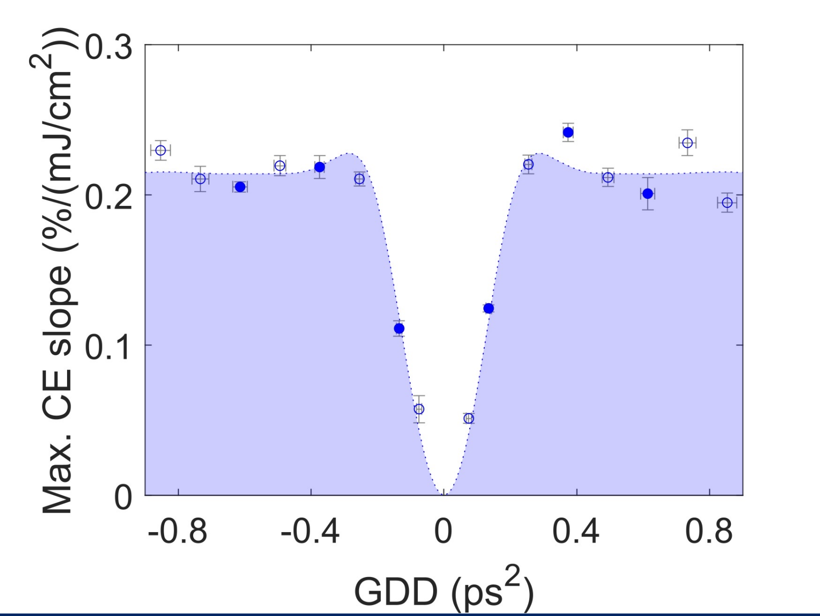
0.7 % rel. bandwidth

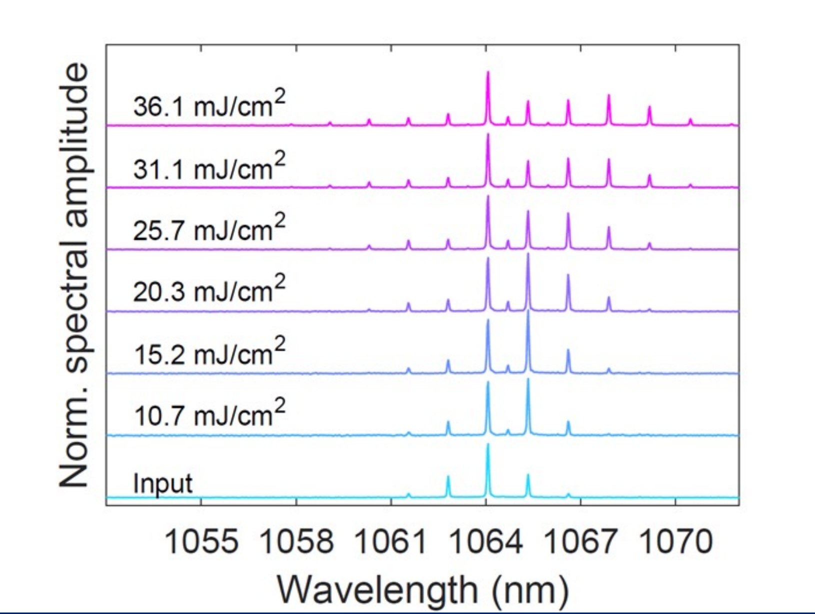
→ ~ 1 ns THz pulse duration

Max. performance: $\mathbf{7 \cdot 10^{-3}}\ \frac{\%}{\mathrm{mJ/cm^2}}$ (**128** pulses)

Two-Line DFG: $2 \cdot 10^{-3}\ \frac{\%}{\mathrm{mJ/cm^2}}$

THz generation performance of modulator pulse train





Maximum CE slope: $\frac{\partial\eta}{\partial F_0} = 2.4 \cdot 10^{-3} \frac{\%}{\mathrm{mJ/cm^2}}$

Optimum PT fluence: $F_{tr} \sim 18 \frac{\mathrm{mJ}}{\mathrm{cm^2}}$

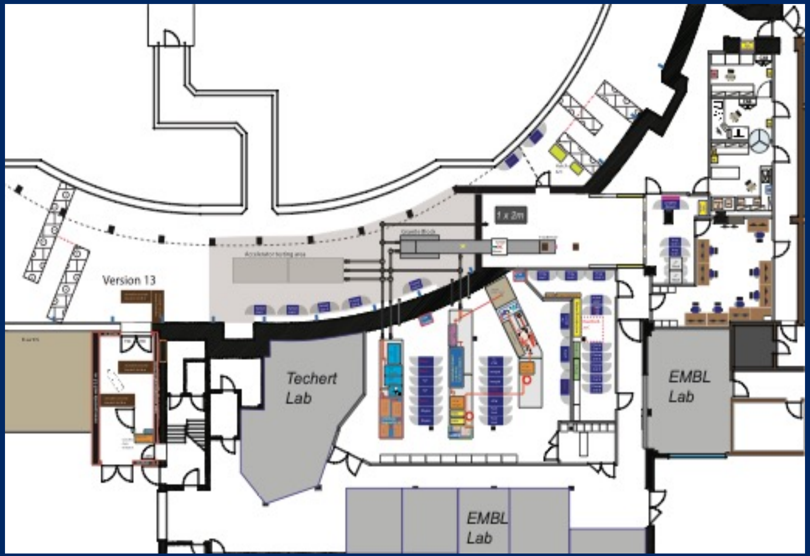
→ **only one sideband is enough**

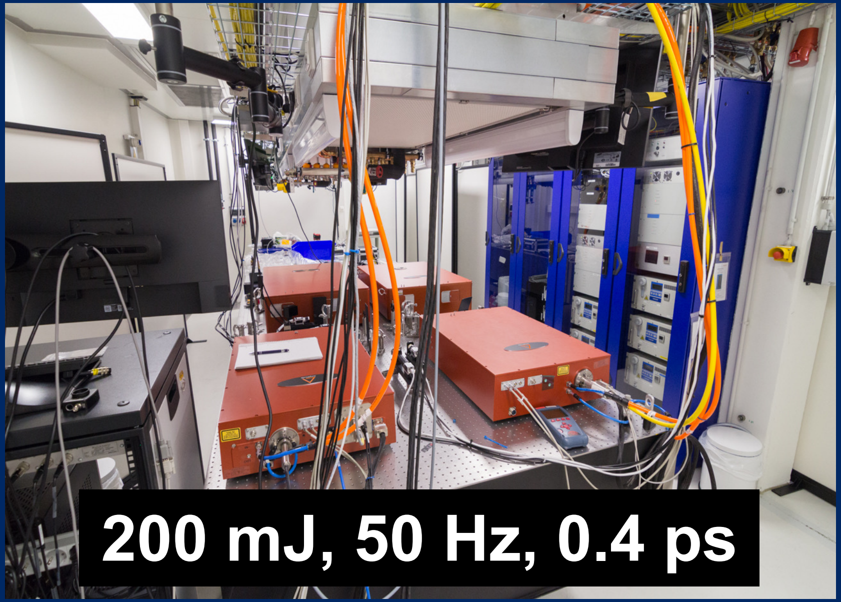
Modulate narrowband laser beam with **10 times higher fluence** ($F_{tot} \sim 200\ \mathrm{mJ/cm^2}$)

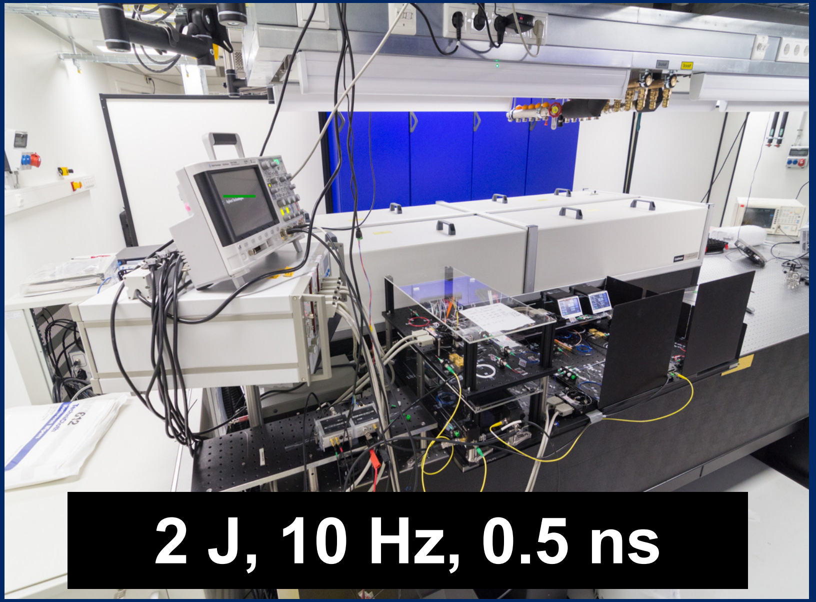
Amplification of equivalent THz – Input Signal by a factor of 3.3

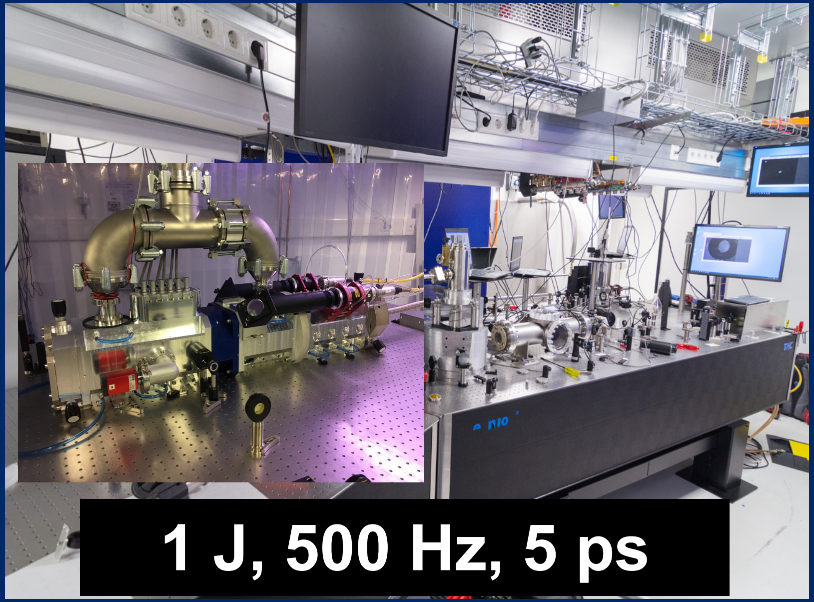
Detailed analysis shows gain of 5 possible, use of 2 μm laser → should enable 10-20 gain

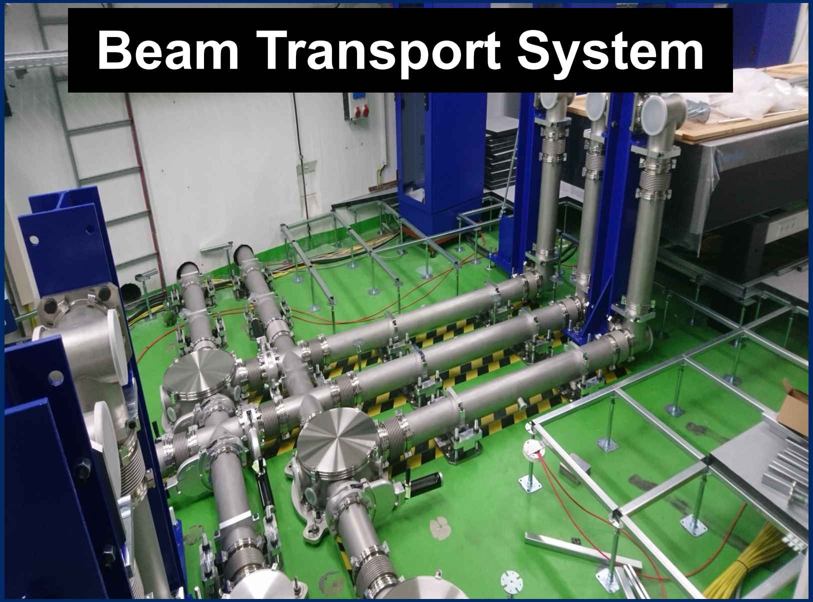
THz Accelerator Laboratory

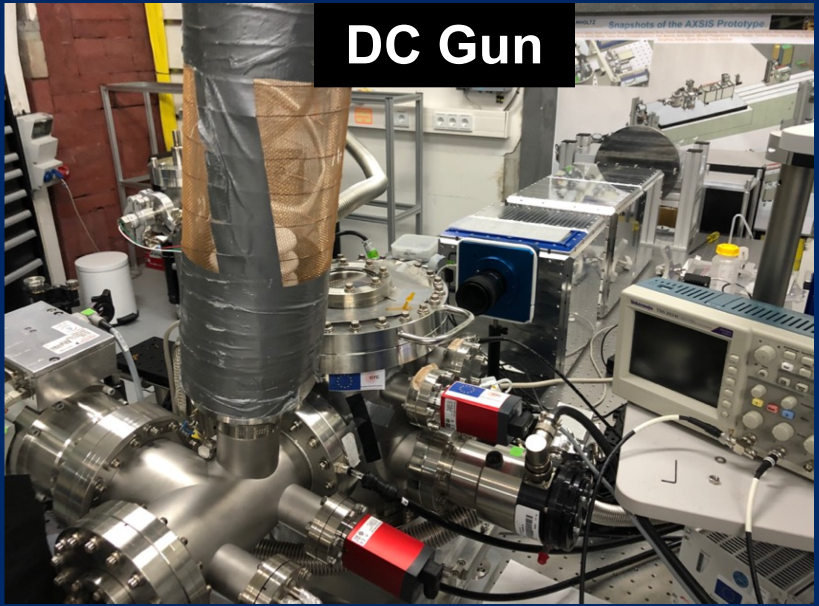




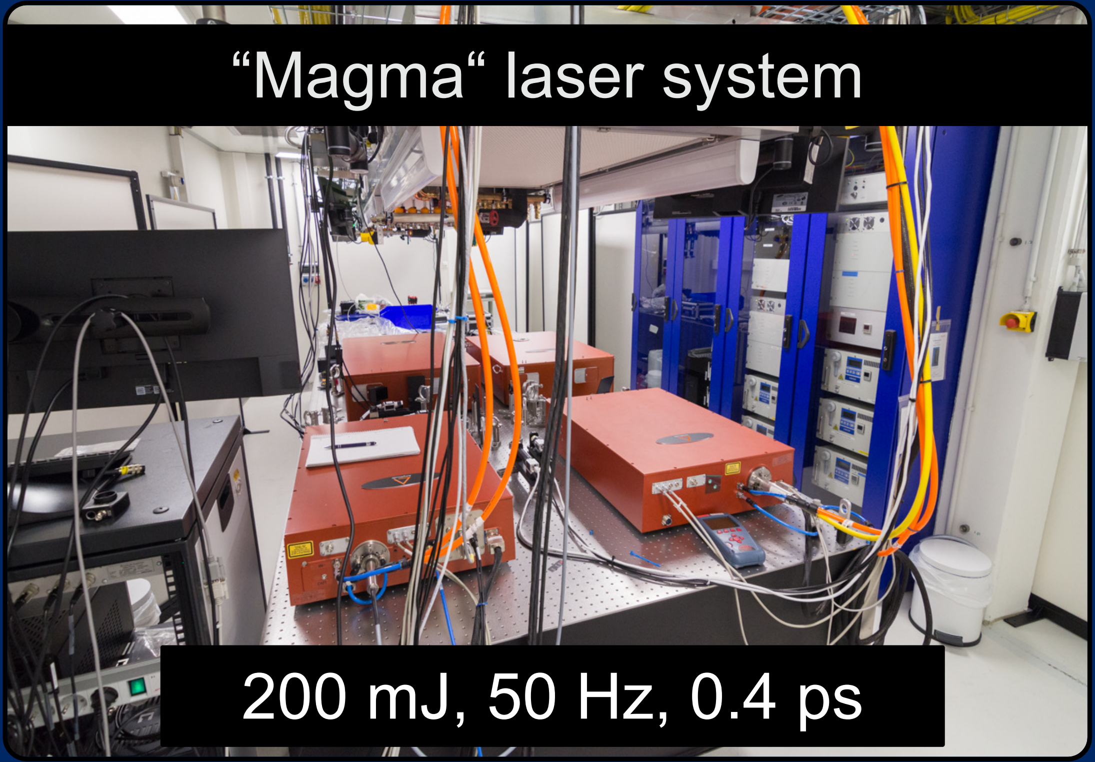




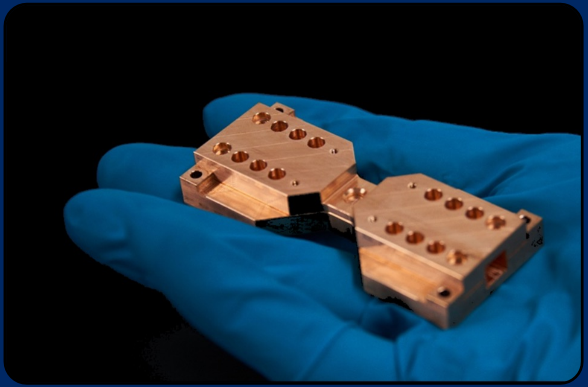




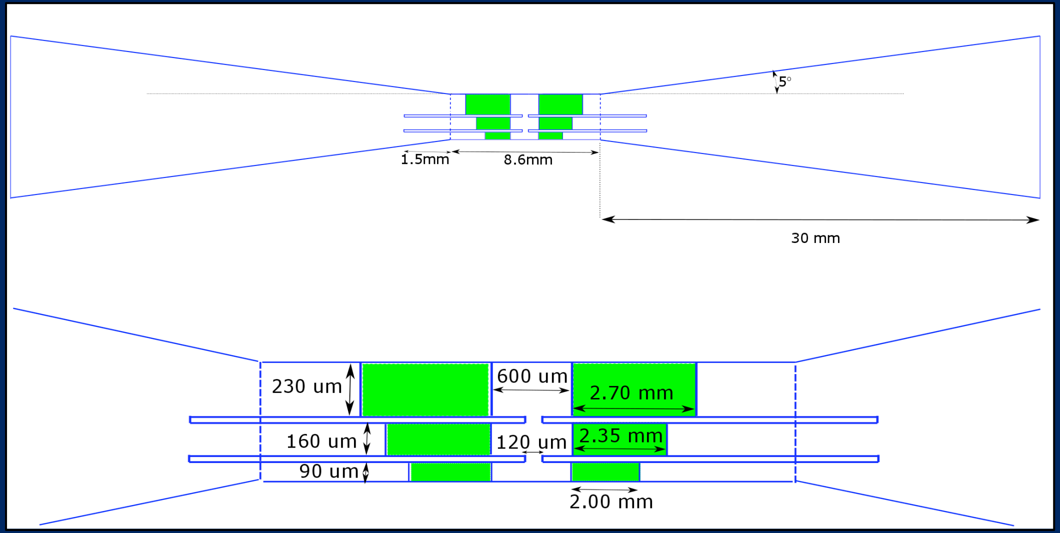
200 keV THz gun

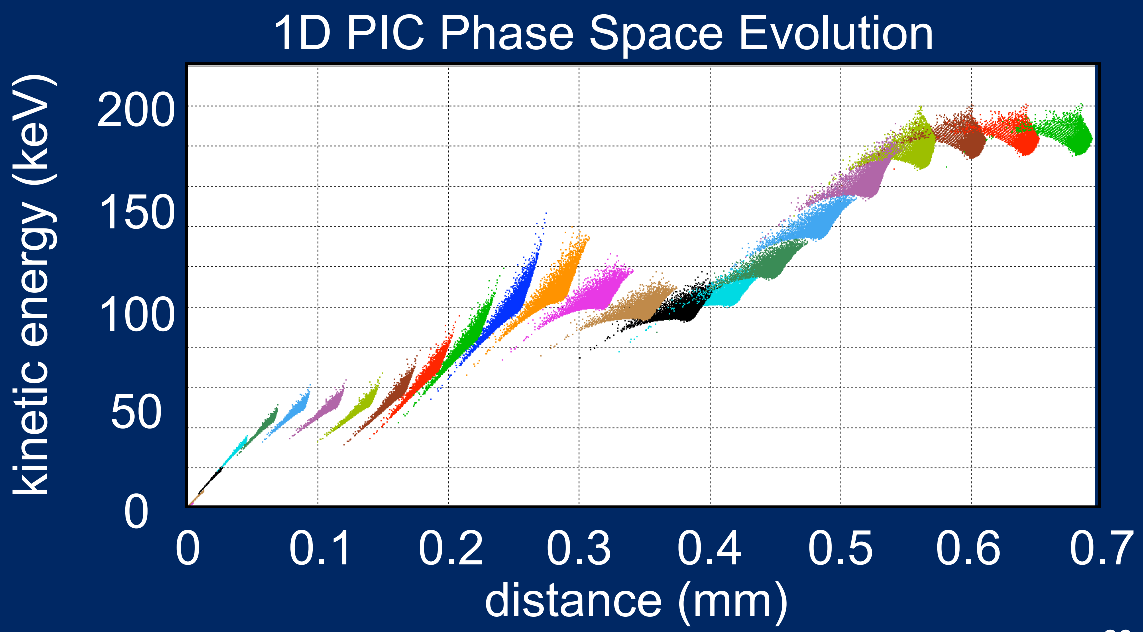


2 x 400 µJ THz pulses



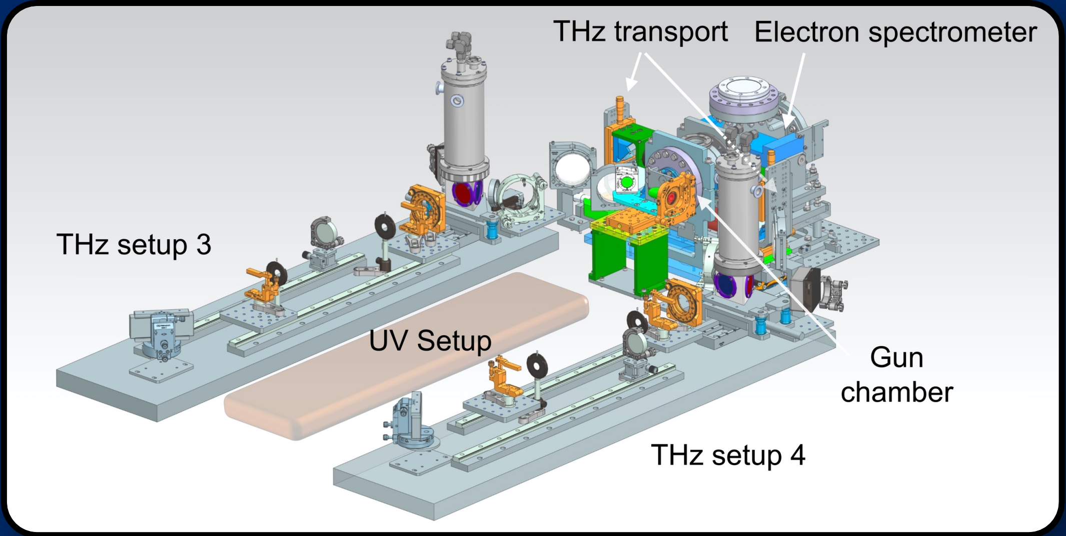
3-layer device

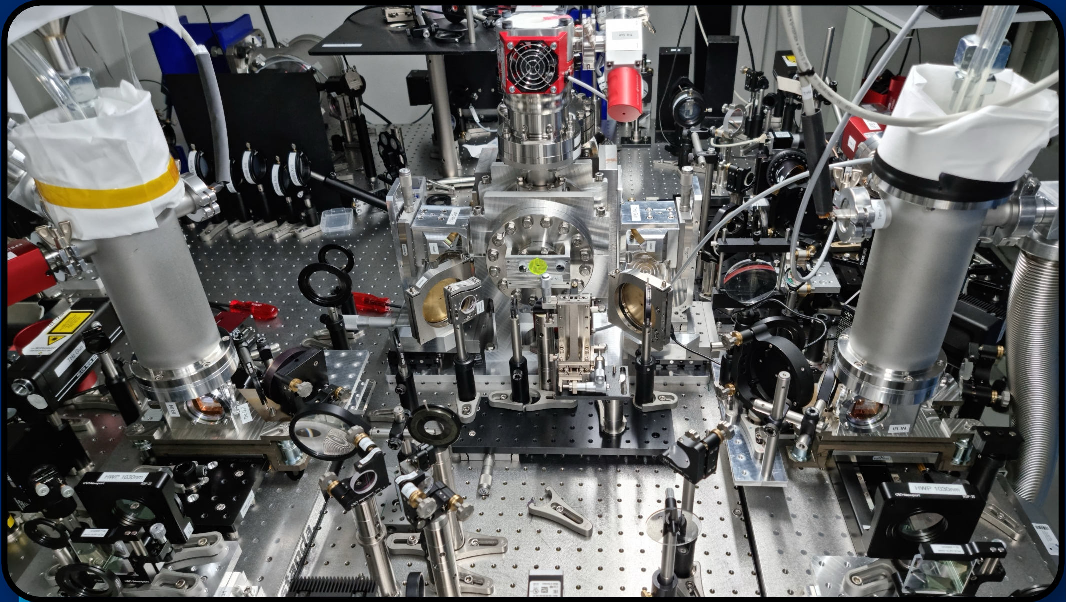




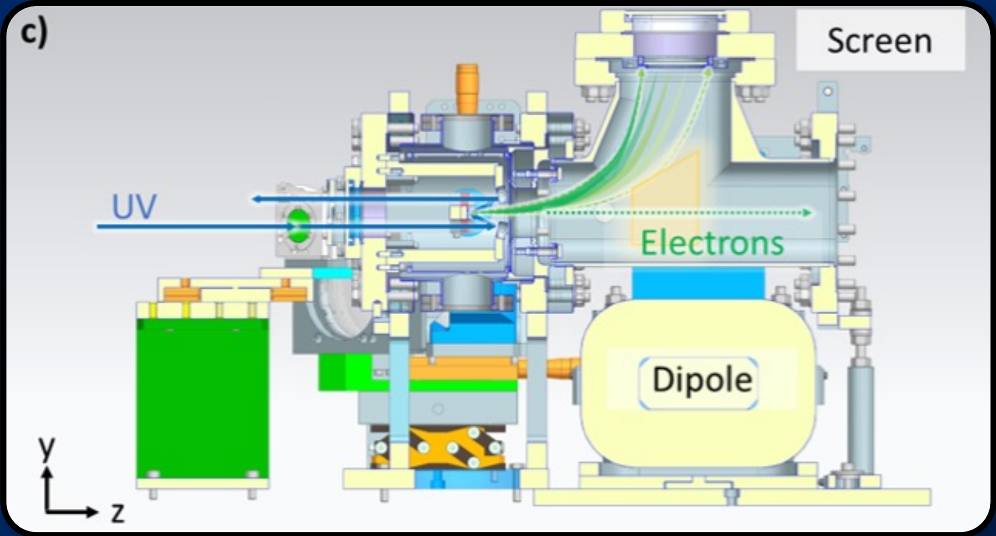
THz – gun test stand

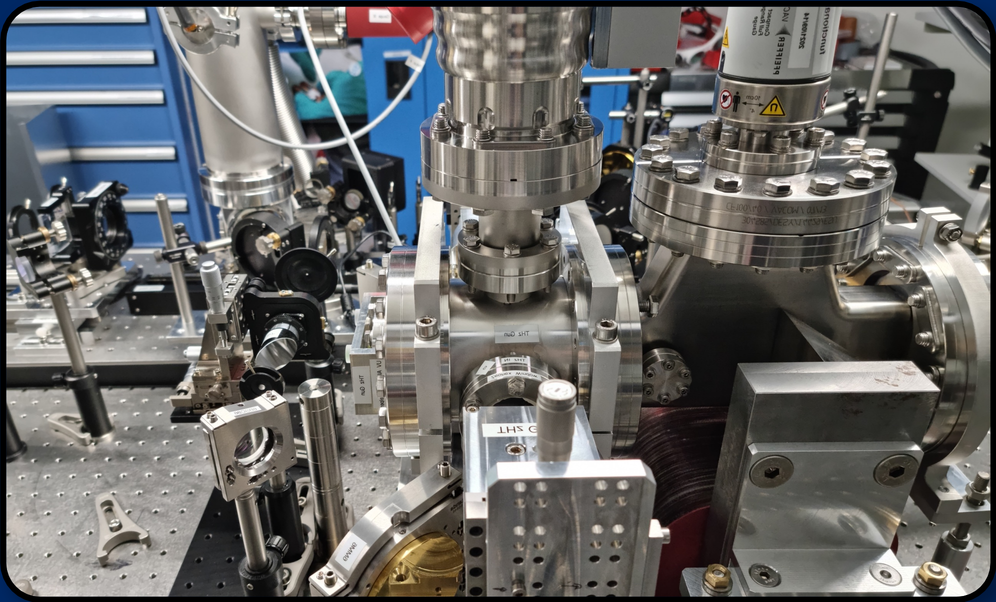
THz Gun Test Stand Layout





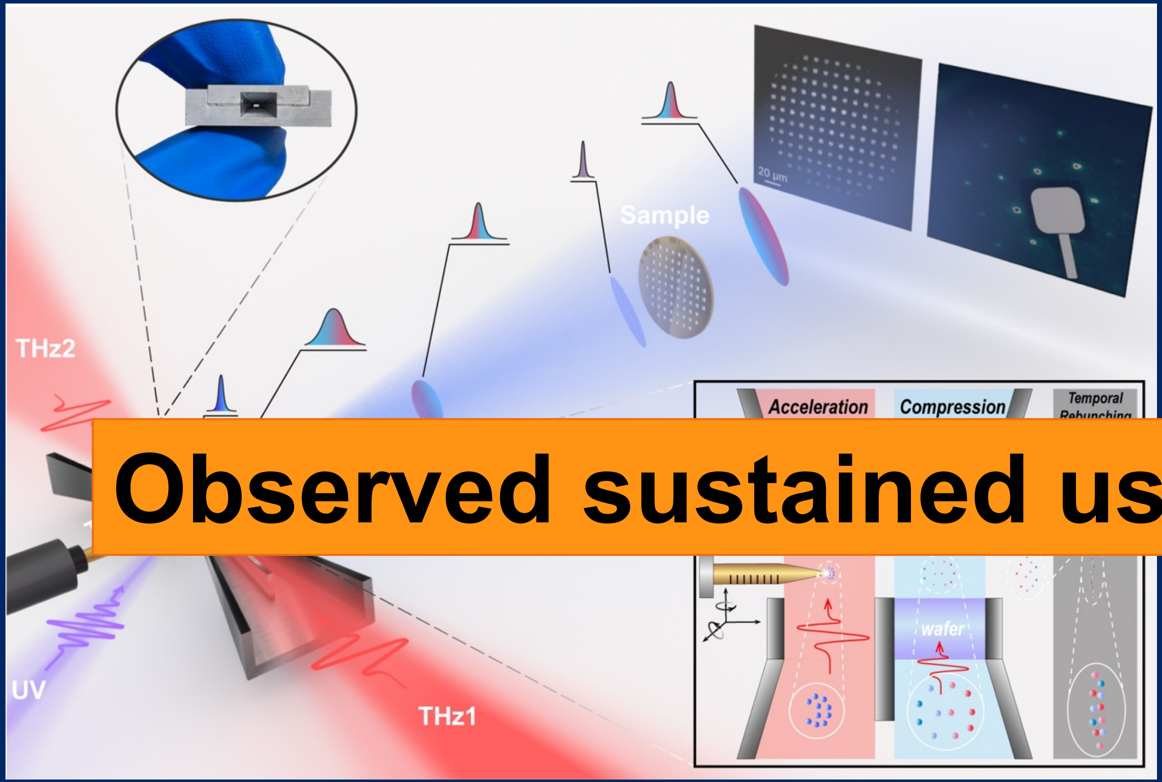
Magnetic Spectrometer Detail

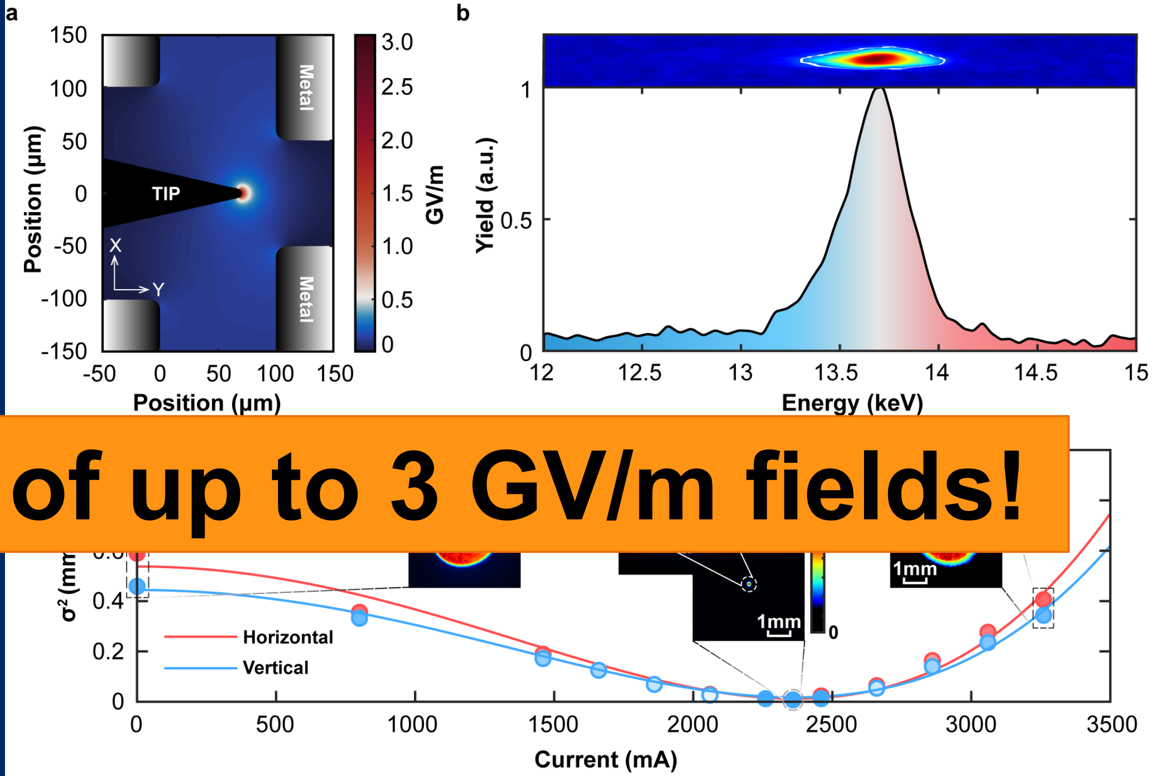




High gradient Terahertz-driven ultrafast photogun

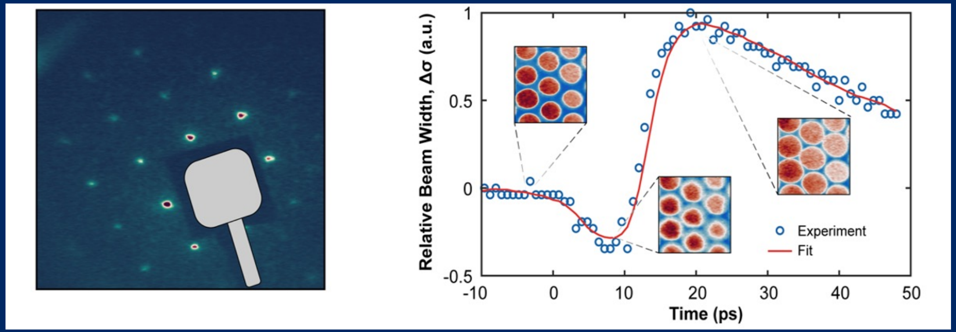
J. Ying, …..FXK, Donfang Zhang, Shanghai Jiao Tong University, Nature Photonics 18, pp. 758–765 (2024)





Observed sustained use of up to 3 GV/m fields!

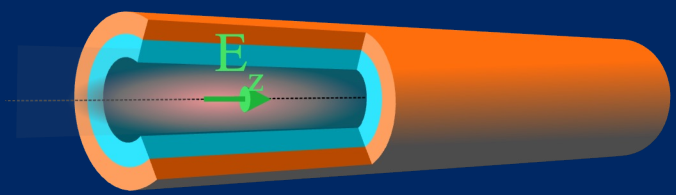
Electron diffraction from a 35 nm thick single-crystalline silicon film with fcc-structure.

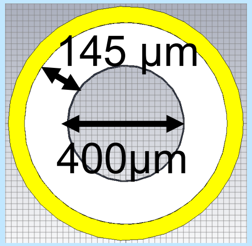
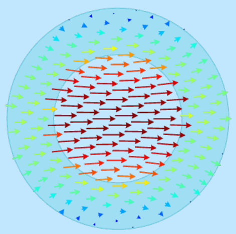
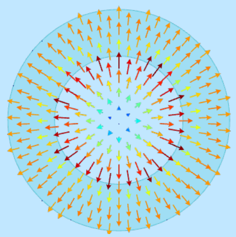
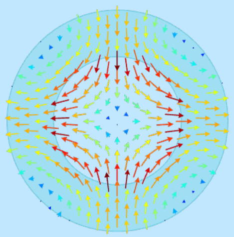
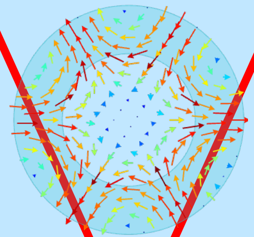


Measured relative beam diameter change as a function of laser-electron delay time when focussed through mesh.

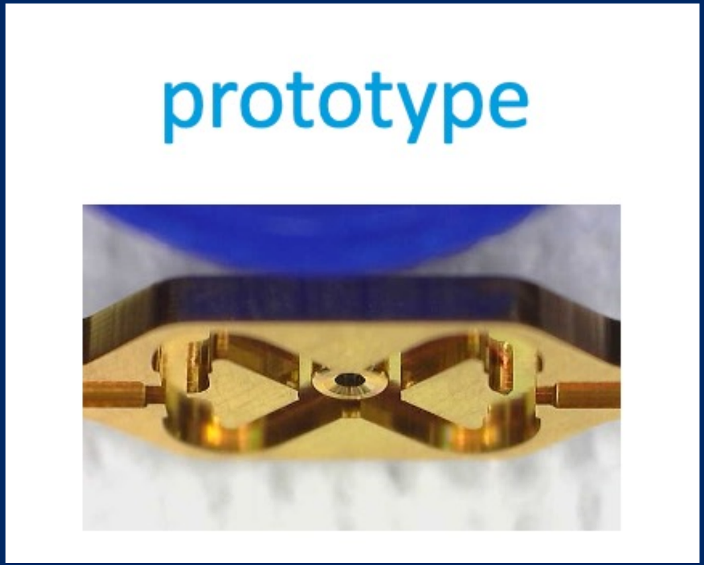
Dielectrically loaded Waveguide Accelerator (DLW-LINAC)

- Travelling wave as an accelerating field
- Electron should remain in a single half cycle
  - Phase velocity reduced below speed of light
  - Dielectric layer (Fused Silica / Sapphire) is added to the cylindrical waveguide
- Possible propagating modes inside the DLW at 300GHz

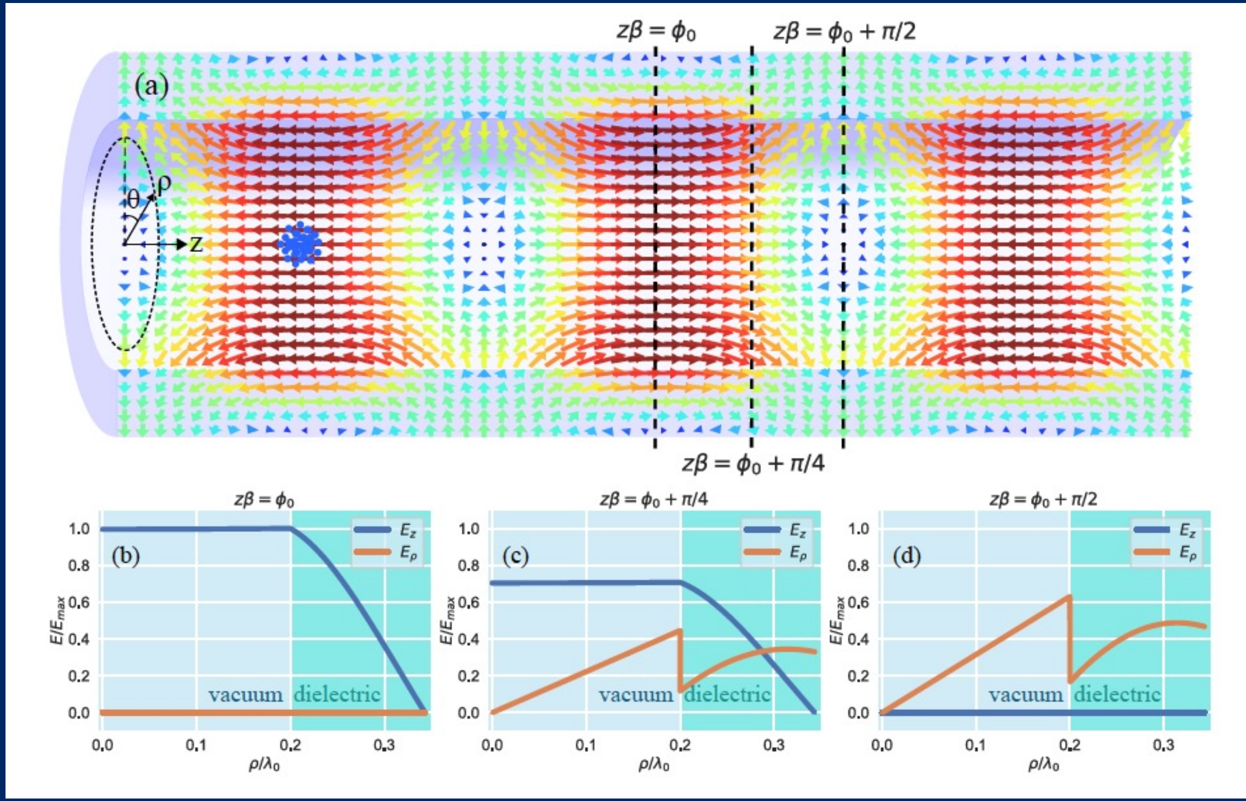


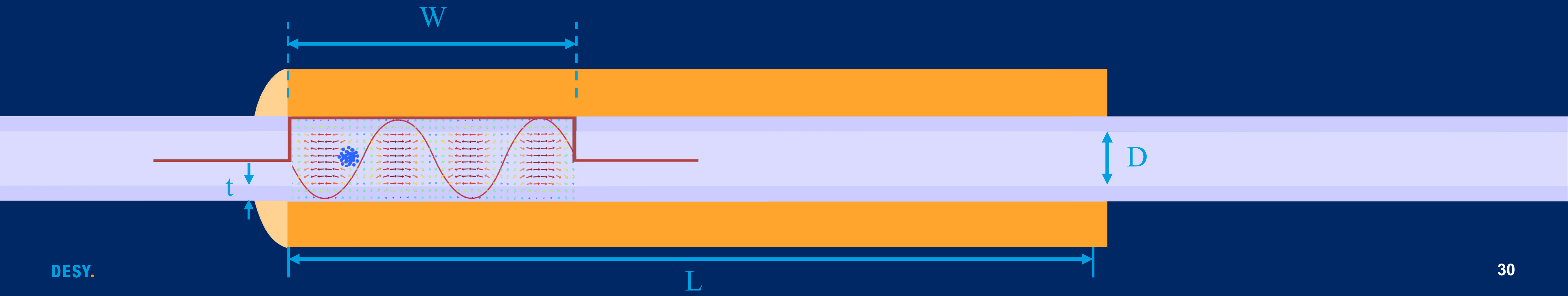
$n_{dielect.}$ = 1.94 				
Mode	HE_{11} (parasitic)	TM_{01} (desired)	HE_{21}(parasitic)	HE_{31}
Cut-off frequency	210 GHz	239 GHz	285 GHz	327 GHz
Propagation constant at 300 GHz	7641	6482	5678	0
Phase velocity/c_0 at 300 GHz	0.82	1	1.1	∞

LINAC coupler

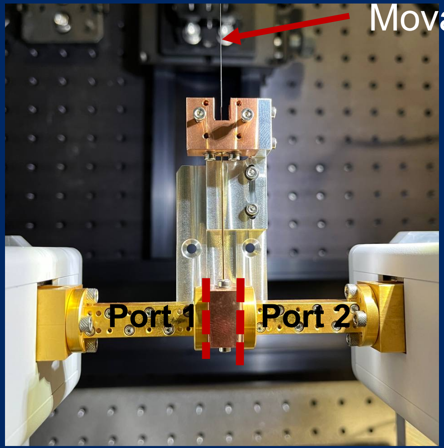


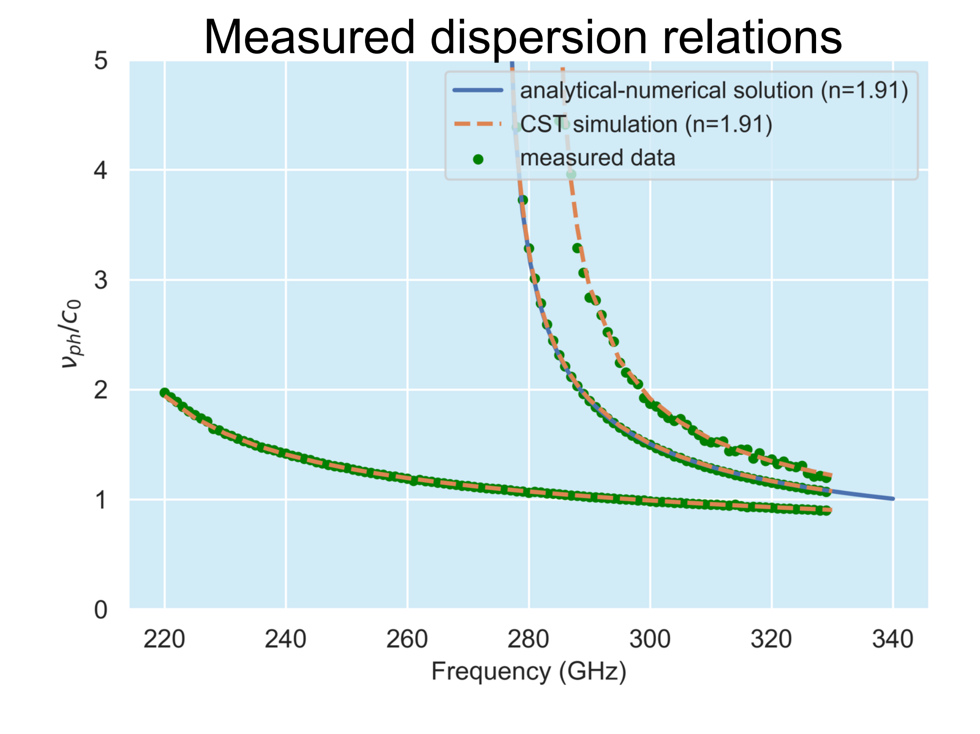
Dielectrically loaded Waveguide Accelerator (DLW-LINAC)

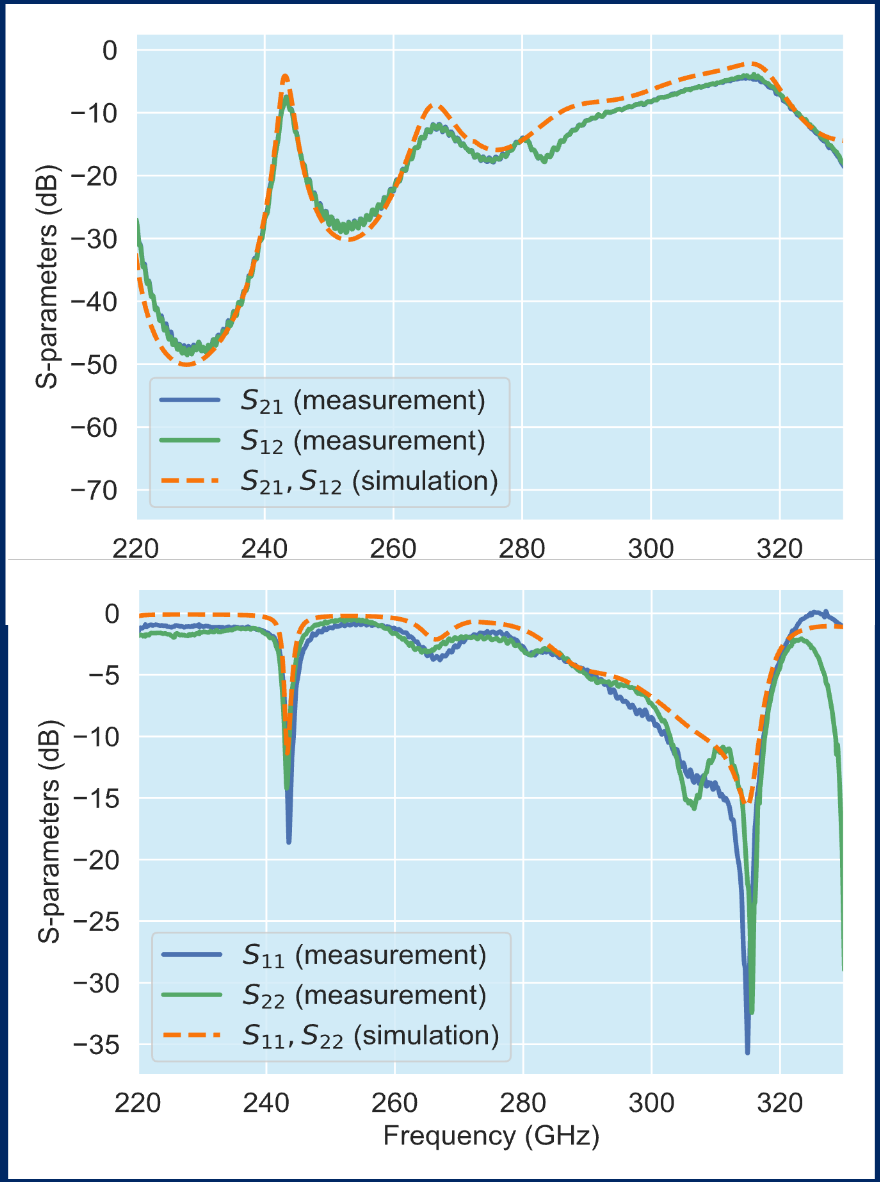




DLW-LINAC Fabrication and Measurements



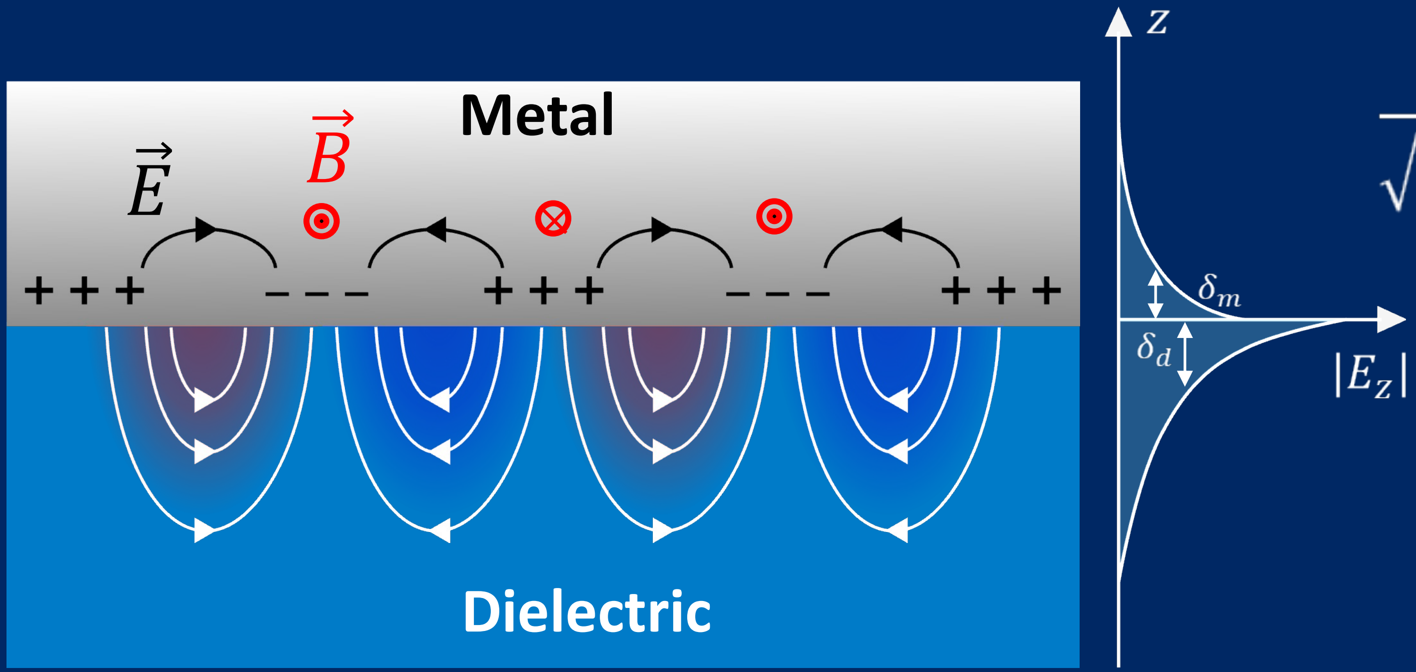




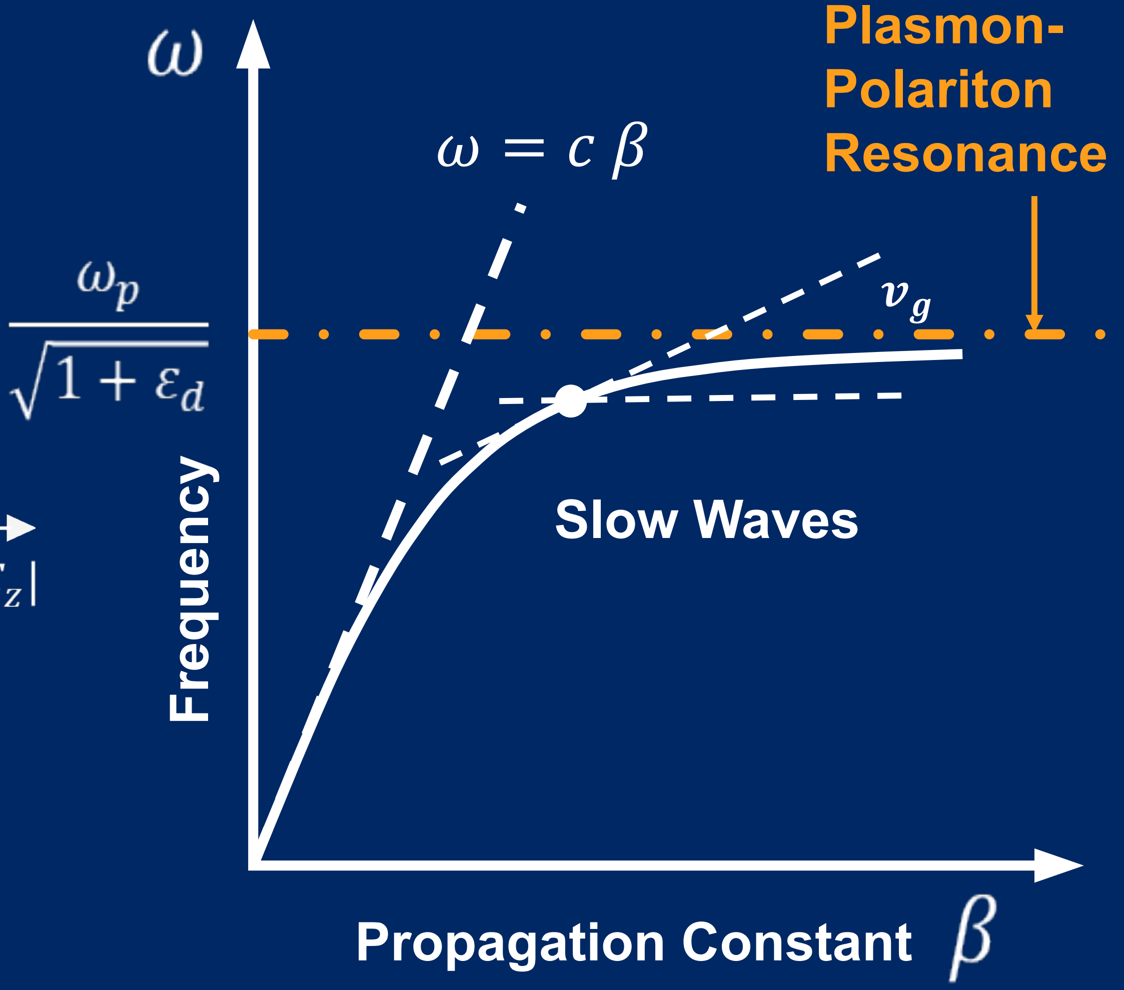
Surface Plasmon Polariton and its Resonance

Plasma frequency

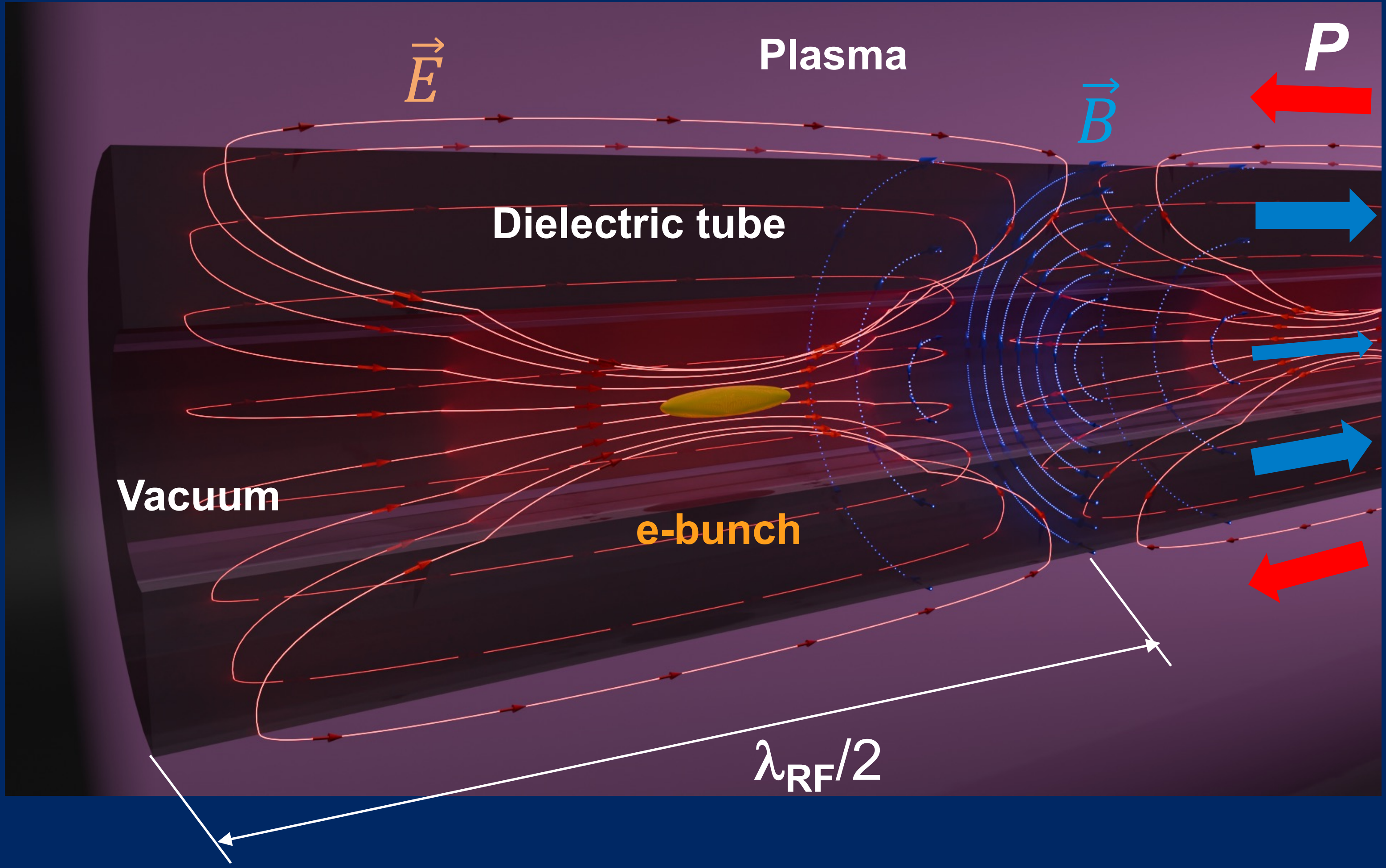
$$\omega_p^2 = \frac{e^2\, n_e}{\varepsilon_0\, m_e};$$



Dispersion Relation

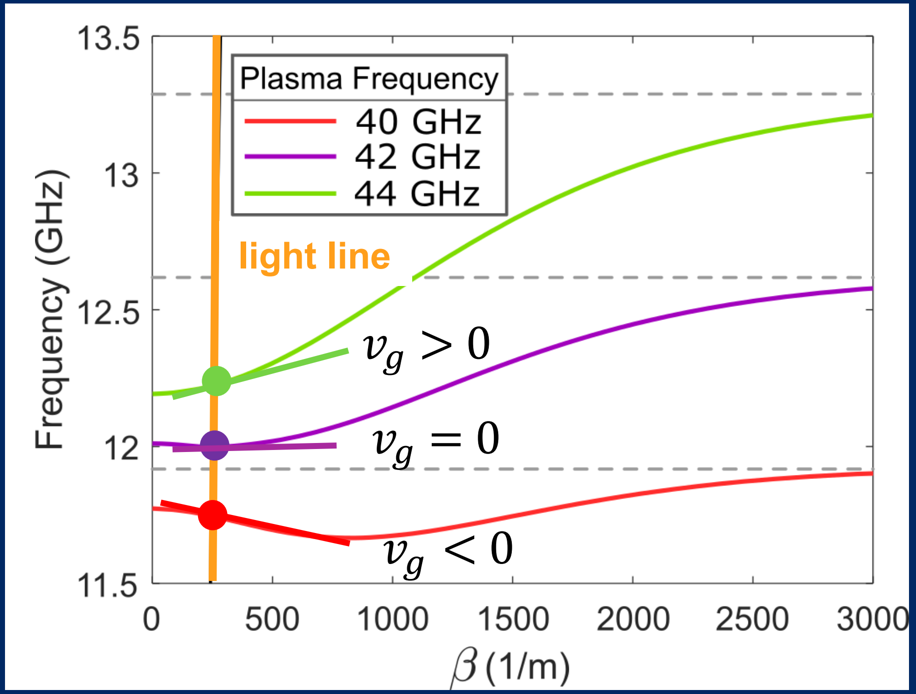


Hollow Surface Plasmon Polariton



$n_e \sim 2 \times 10^{13}\ cm^{-3}$

Dispersion Relation



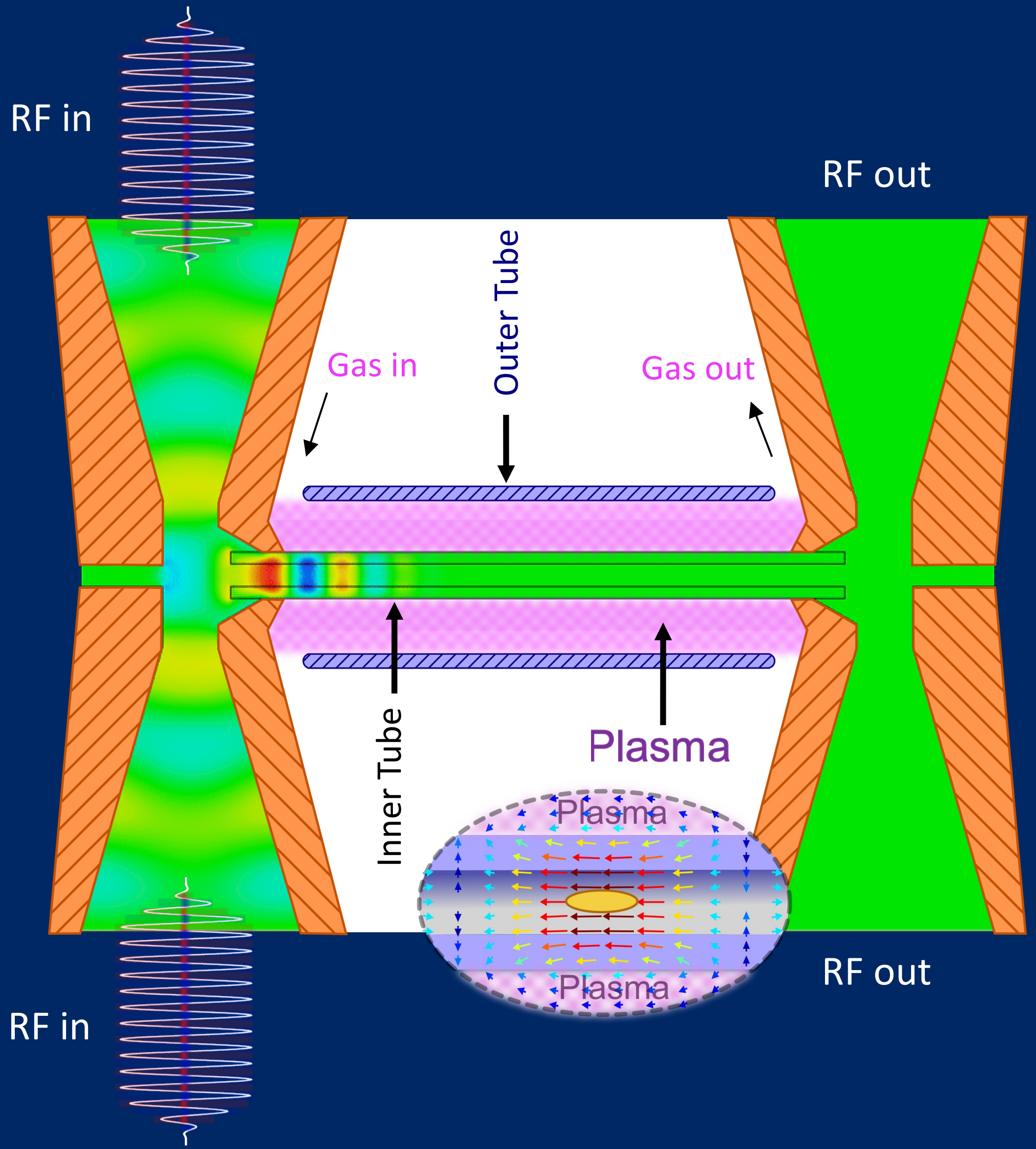
while being phase matched

$v_{ph} = c$

G. Rosenblatt et al., Opt Express 18:25, 25861 (2010)

Hollow Surface Plasmon Polariton Accelerator Module

Plasma – Dielectric RF-Accelerator



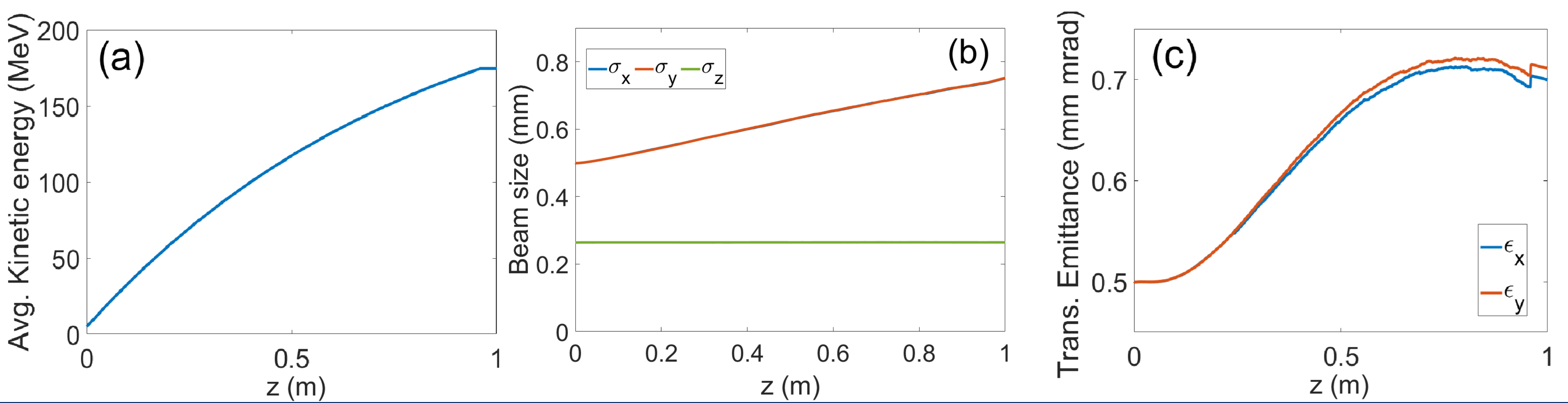
Advantages

- > 1 GV/m guided fields
- plasma density tuning
- low dielectric losses, sapphire, Q = 50.000
- low plasma losses << metal losses, Q = 20.000
- suppression of multipacting and RF - breakdown

Realistic Example

20 J, 150 ns pulses generated by compressing 40 J, 1.5 μs pulses using a BOC, close to INFN Eupraxia Specs

200 pC charge



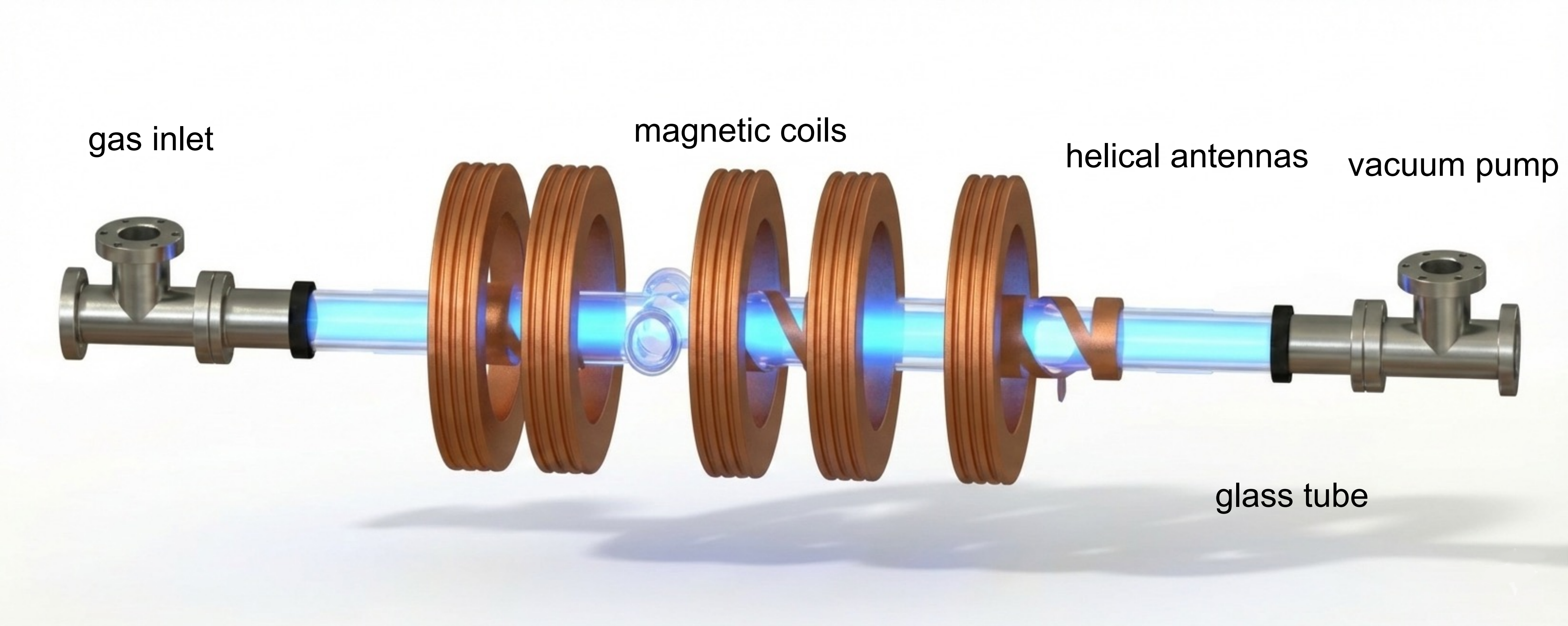
20 J, 30 ns pulses → 1 GV/m, 60 MeV over 10 cm.

Efficient Highly Ionized Plasma Generation

Helicon Plasma

UCLA
Chen, Francis

- Very efficient
- Low electron temperature (1–2 eV) → reduces RF power
- High ionization rate and electron density
- RF frequency = 13.56 MHz
- Argon @ 1 Pa; with 10% ionization $n_e = 2 \times 10^{13}$ cm^{-3}



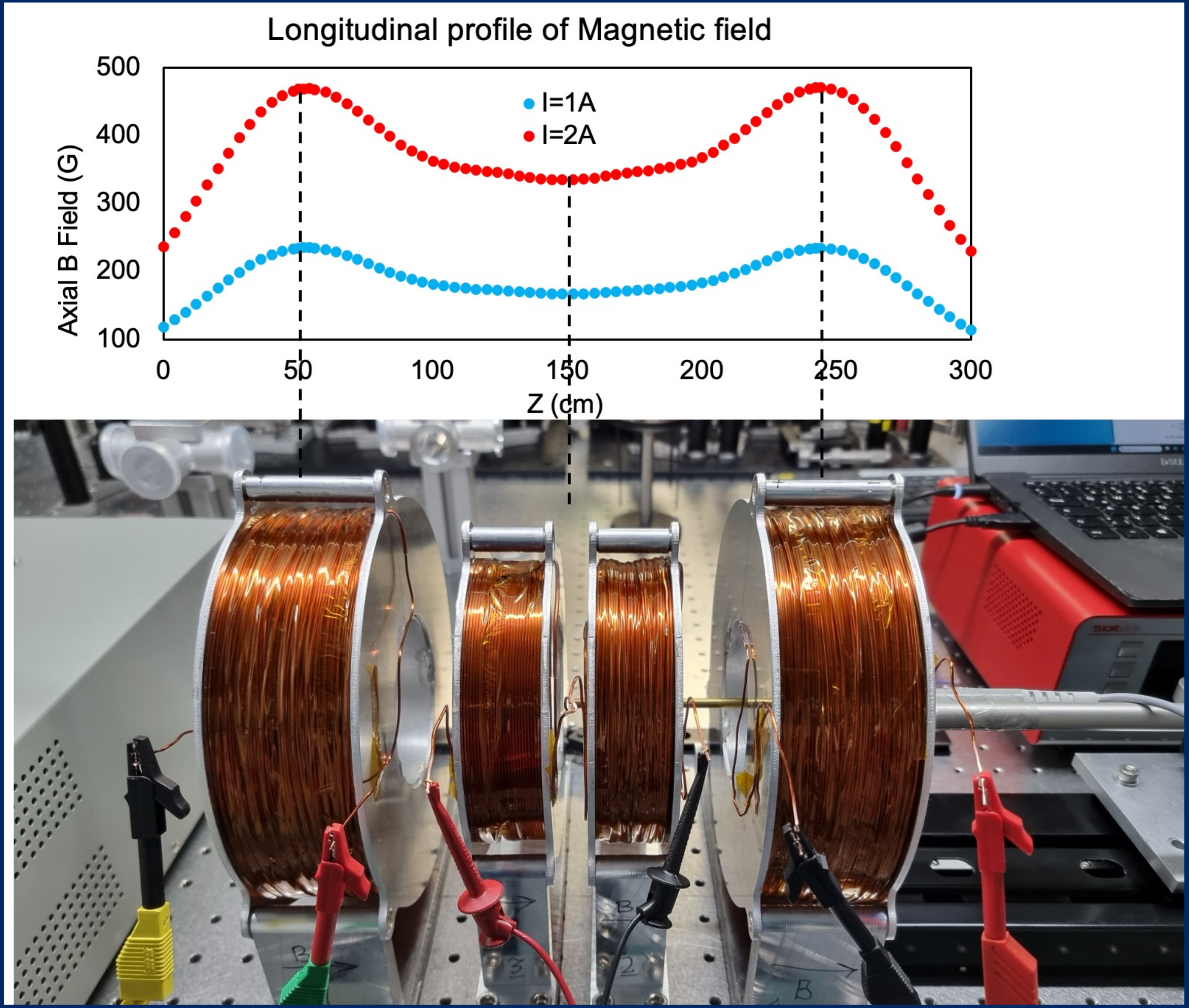
Efficient Highly Ionized Plasma Generation

Helicon Plasma

Following AWAKE but lower density

Phys. Plasmas 32, 093507 (2025)
https://doi.org/10.1063/5.0267516

AWAKE Report: CERN-SPSC-2019-037 / SPSC-SR-258



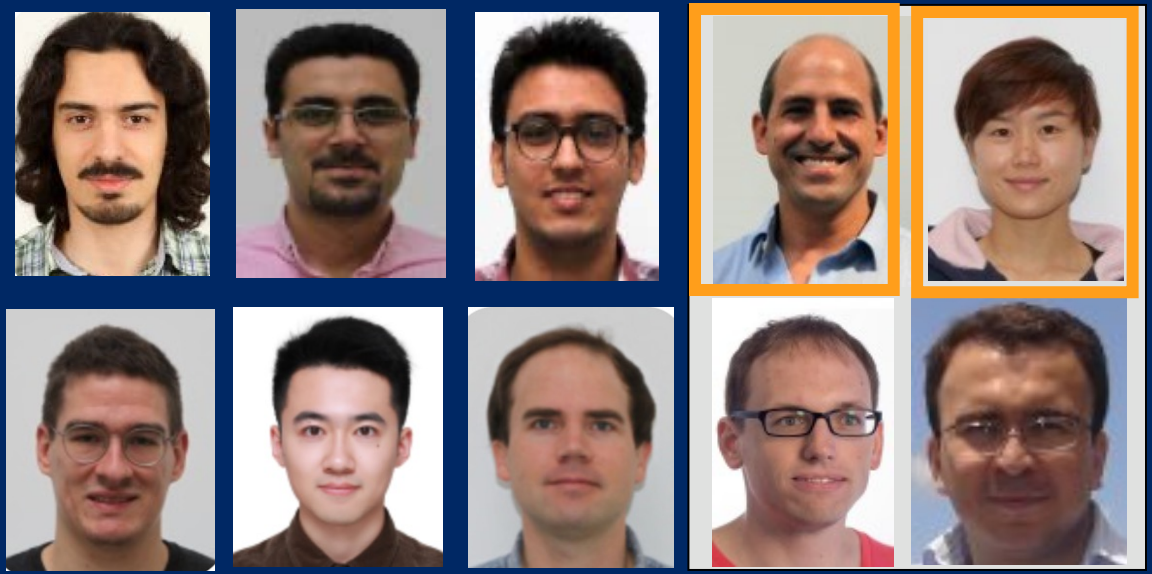
Callenge: Plasma uniformity

AWAKE : 11%

HoSPPA : 0.1%

Team and Collaborators

THz Generation and Acceleration Team

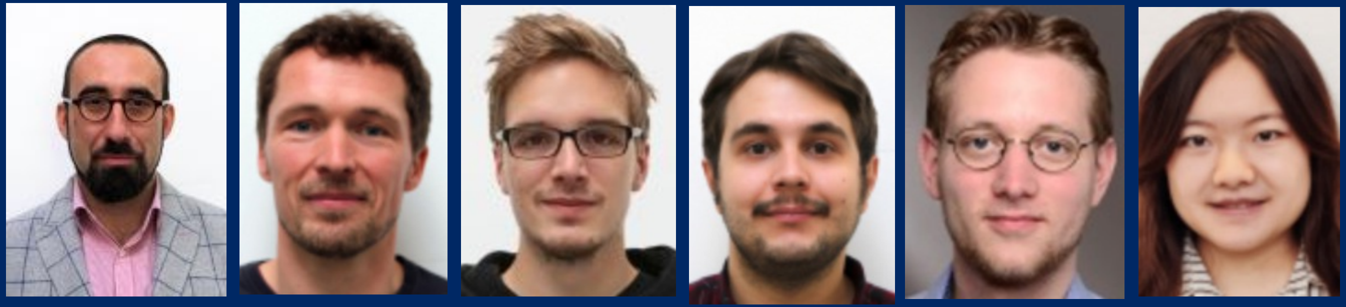


Alumni

Dongfang Zhang and his group at JTUS

Engineering Team

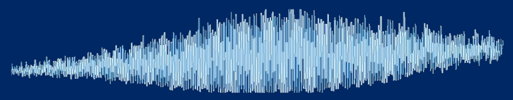
Laser Team



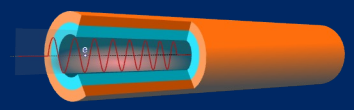
Accelerator Division

Summary

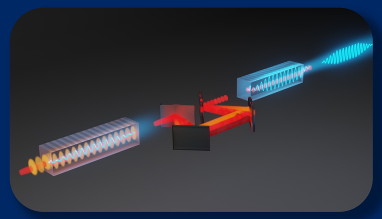
- THz-accelerators need (multi)-mJ-level MC-THz pulses



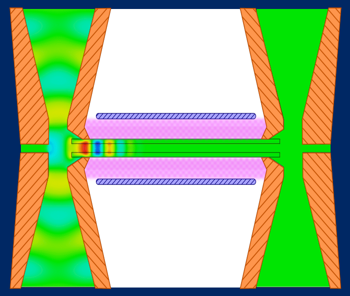
- Two accelerator structures
  - Segemented THz waveguide accelerators (STEAM)
  - Dielectrically loaded waveguides (DLW) - LINACs



- GV/m gradients should be possible
- mJ-level SC-THz pulses from 200 mJ, sub/ps laser pulses and 20-mJ THz pulses from 2 J, ns Lasers possible



- High Energy THz amplifier – Phlystron utilized long pulse lasers
- THz accelerators have a great potential for UED
- HoSPPA has great potential for compact light sources



Acknowledgement

HELMHOLTZ ASSOCIATION

erc European Research Council

DFG Deutsche Forschungsgemeinschaft

cui

Alexander von Humboldt Stiftung/Foundation

MAX PLANCK SCHOOL of photonics

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