Generation of High-Power, Tunable Terahertz Radiation from Laser Interaction with a Relativistic Electron Beam

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Joint DESY and University of Hamburg Accelerator Physics Seminar

6/13/2017

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- ☐ Introduction

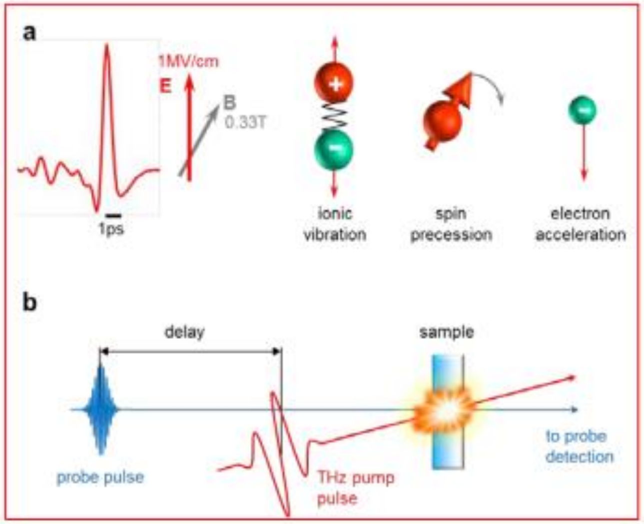
- ☐ Proposed THz source
  - Theory
  - Simulation
  - Radiation generation

- ☐ Recent experimental studies

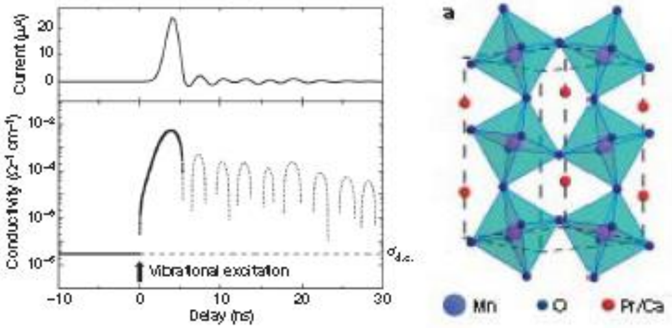
- ☐ Discussions and summary

Introduction

nonlinear (High-field) THz experiments

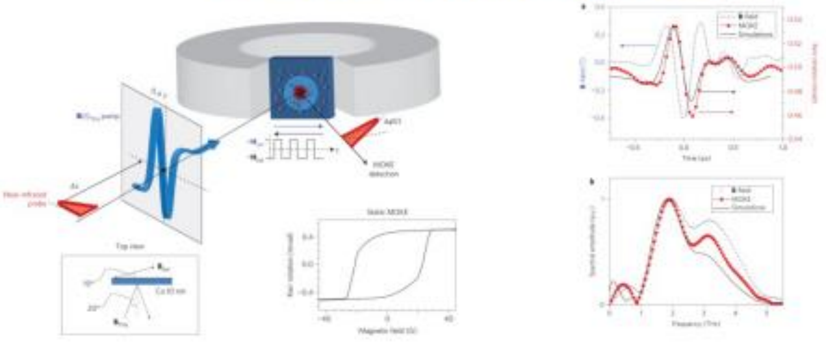


THz control of conductivity



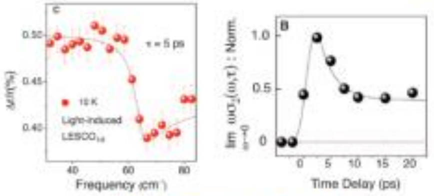
M. Rini et. al. , Nature 2007
+ M. Liu et. al., Nature 2012.

THz control of magnetism

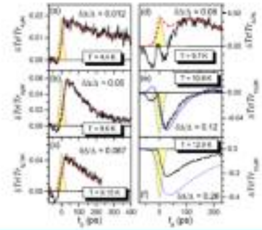


C. Vicario et. al. , Nature Photon. 2013
+ T. Kampfrath et. al., Nature Photon. 2011.

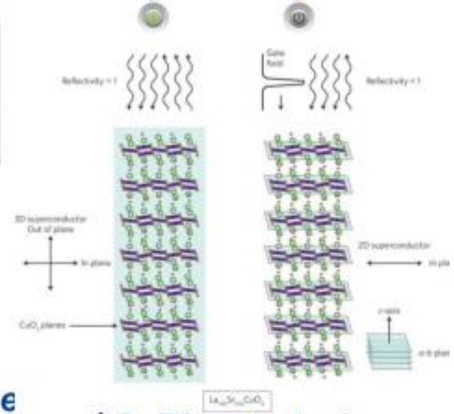
THz control of superconductivity



M. Fausti et. al. ,
Science 2011

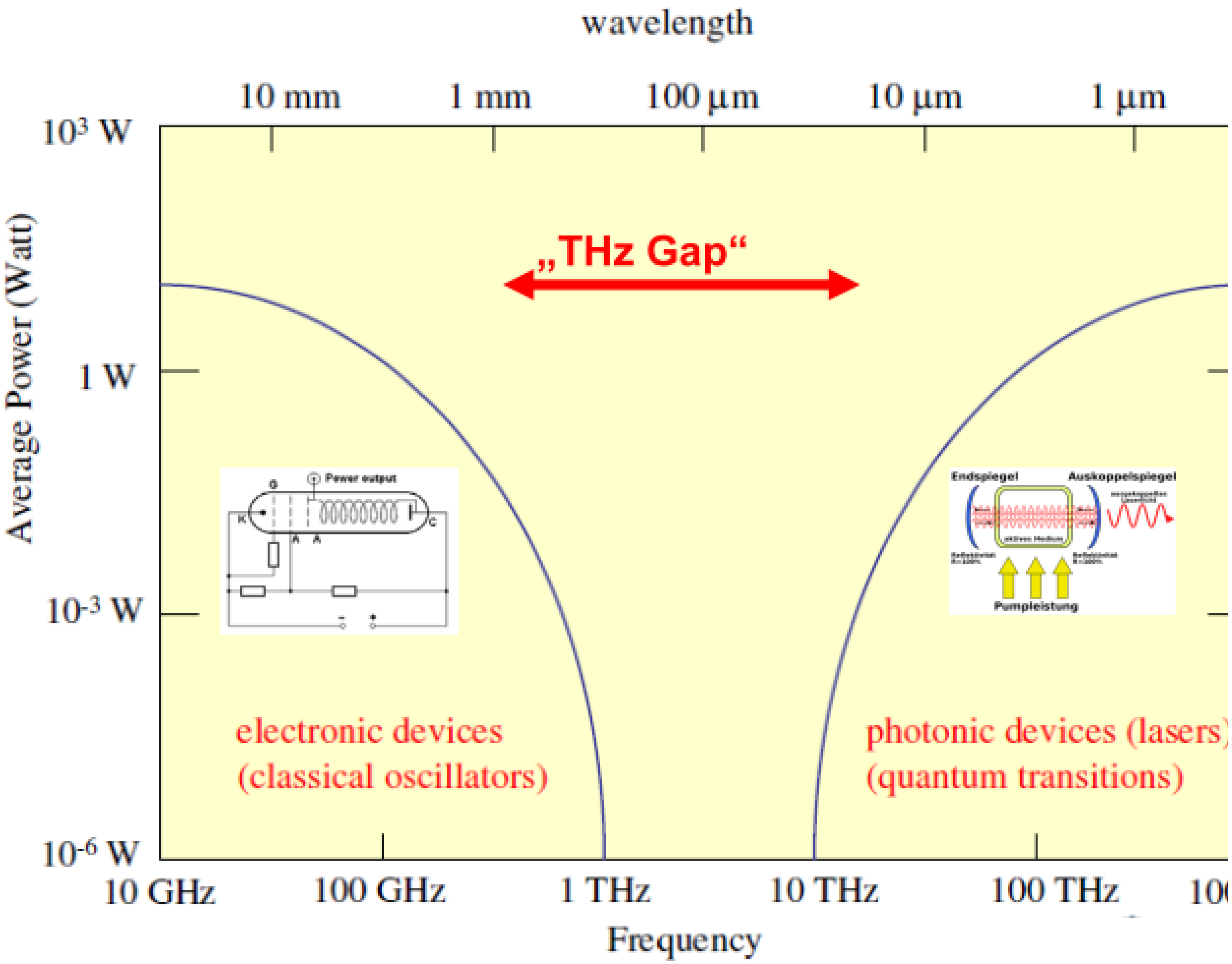


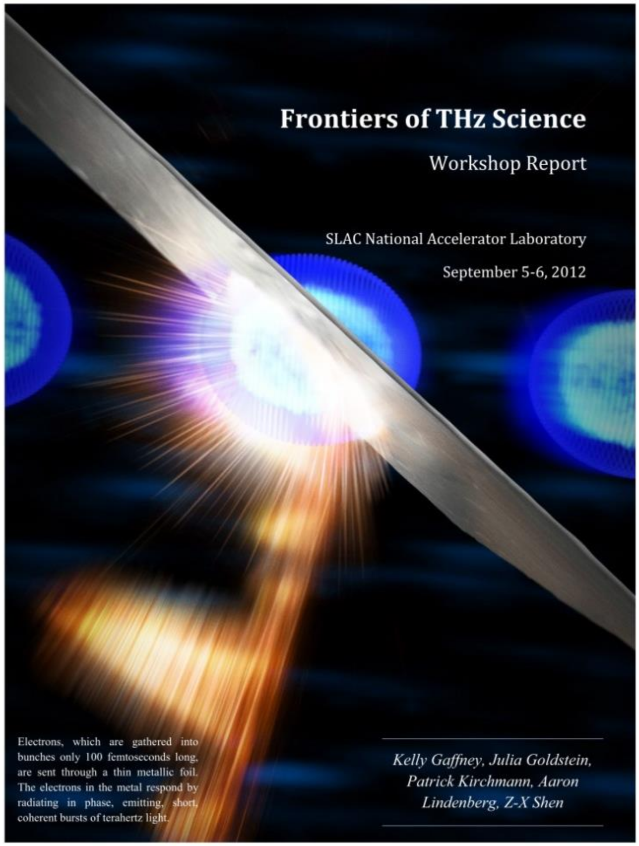
M. Beck e
PRL2011



A. Dienst et. al. ,
Nature Photn. 2011 +
Nature Mat. 2013

THz gap (1 to 20 THz)




Frontiers of THz Science

Workshop Report

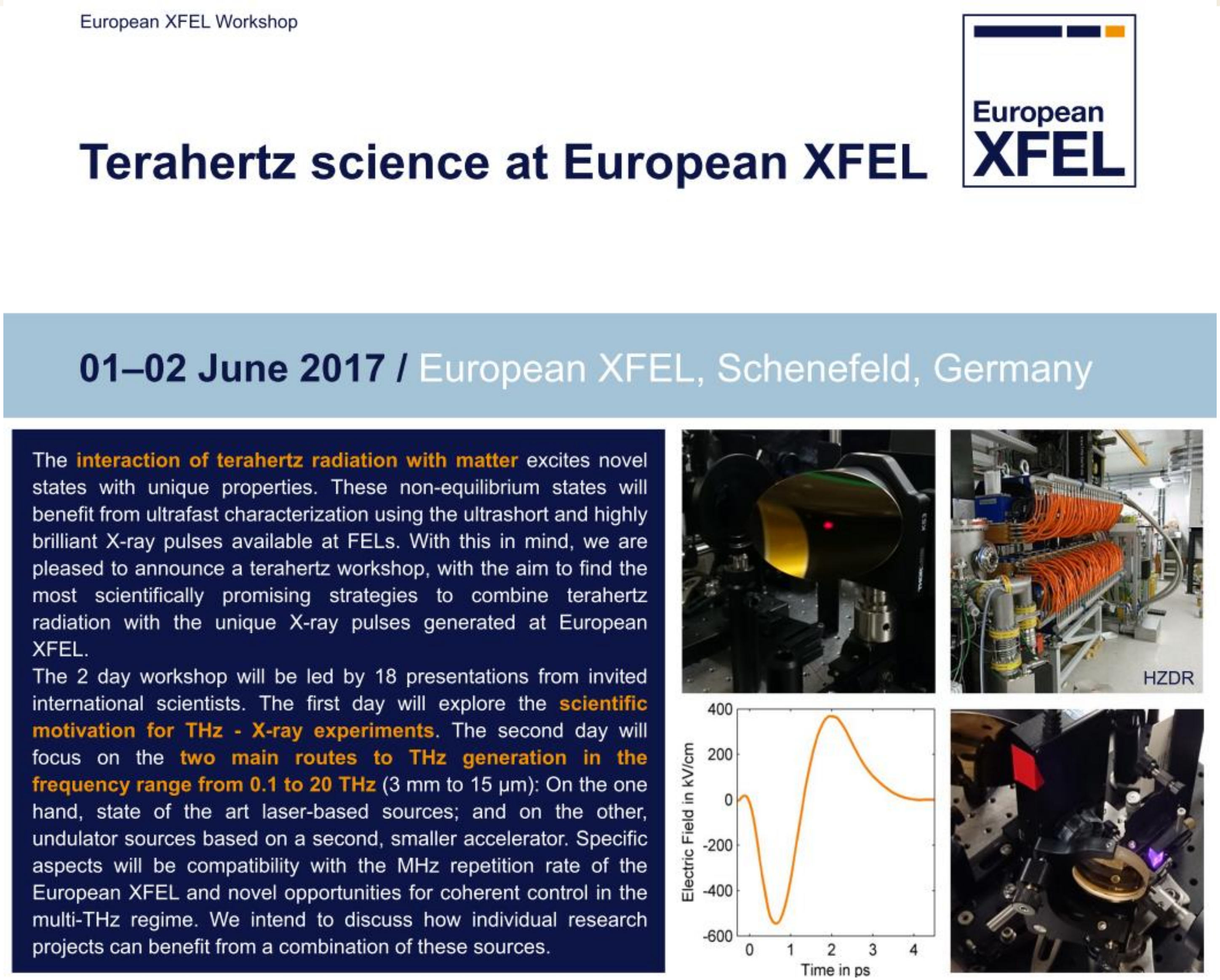
SLAC National Accelerator Laboratory

September 5-6, 2012

Electrons, which are gathered into bunches only 100 femtoseconds long, are sent through a thin metallic foil. The electrons in the metal respond by radiating in phase, emitting short, coherent bursts of terahertz light.

Kelly Gaffney, Julia Goldstein, Patrick Kirchmann, Aaron Lindenberg, Z-X Shen

Eu-XFEL’s interests



European XFEL Workshop

Terahertz science at European XFEL

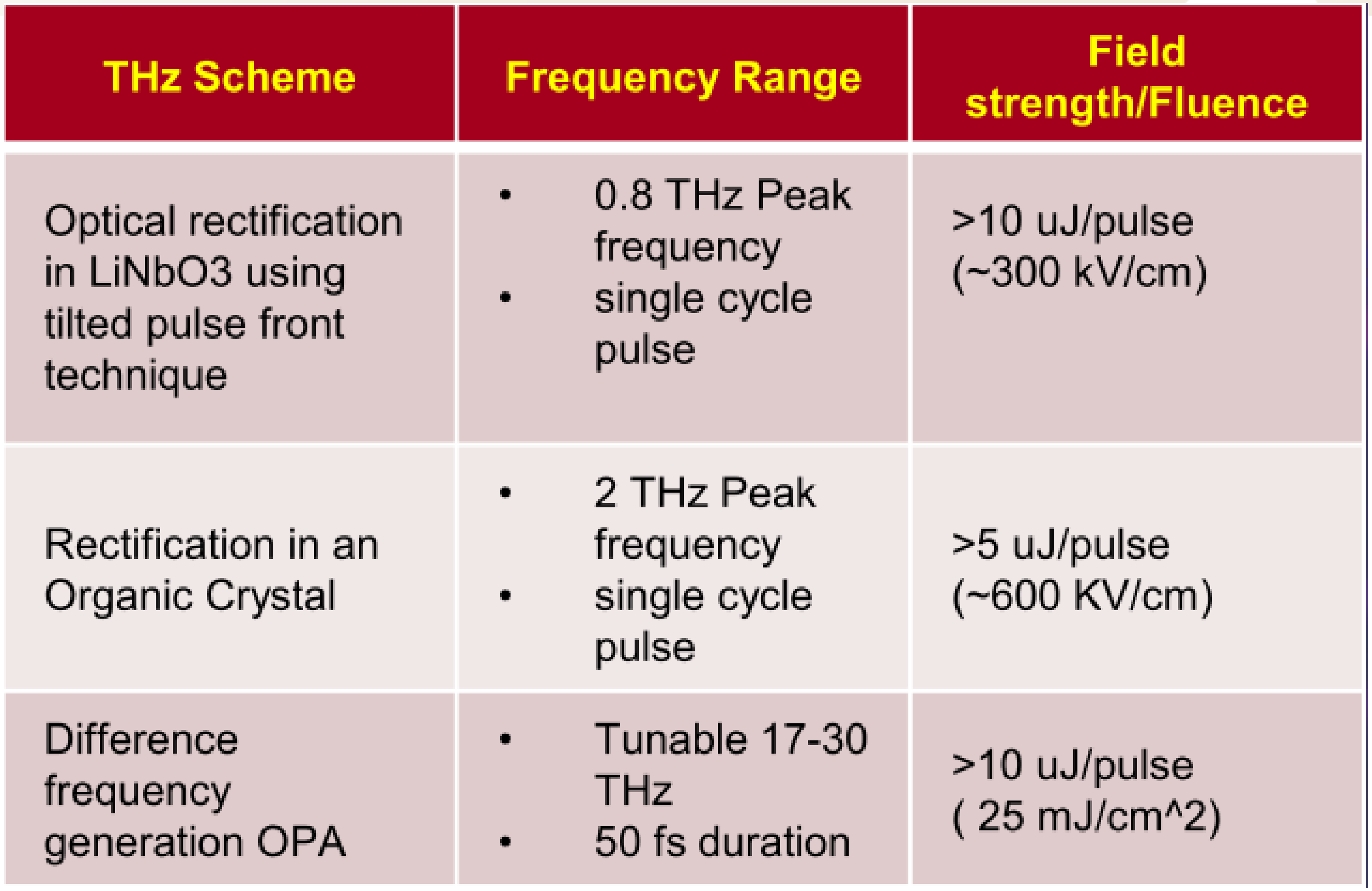
01–02 June 2017 / European XFEL, Schenefeld, Germany

The **interaction of terahertz radiation with matter** excites novel states with unique properties. These non-equilibrium states will benefit from ultrafast characterization using the ultrashort and highly brilliant X-ray pulses available at FELs. With this in mind, we are pleased to announce a terahertz workshop, with the aim to find the most scientifically promising strategies to combine terahertz radiation with the unique X-ray pulses generated at European XFEL.

The 2 day workshop will be led by 18 presentations from invited international scientists. The first day will explore the **scientific motivation for THz - X-ray experiments**. The second day will focus on the **two main routes to THz generation in the frequency range from 0.1 to 20 THz** (3 mm to 15 µm): On the one hand, state of the art laser-based sources; and on the other, undulator sources based on a second, smaller accelerator. Specific aspects will be compatibility with the MHz repetition rate of the European XFEL and novel opportunities for coherent control in the multi-THz regime. We intend to discuss how individual research projects can benefit from a combination of these sources.

HZDR

Laser based sources (Matthias Hoffmann)



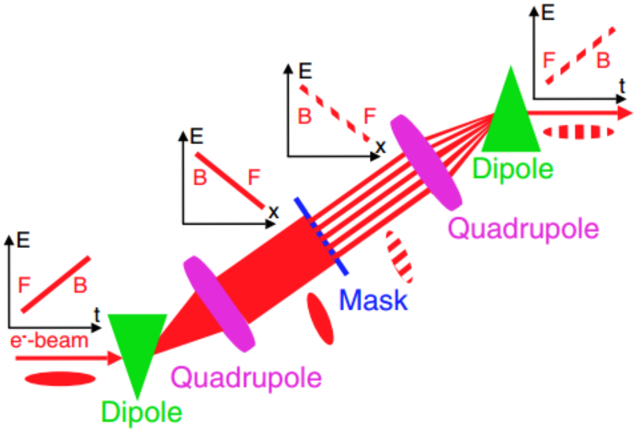
THz Scheme	Frequency Range	Field strength/Fluence
Optical rectification in LiNbO3 using tilted pulse front technique	• 0.8 THz Peak frequency • single cycle pulse	>10 uJ/pulse (~300 kV/cm)
Rectification in an Organic Crystal	• 2 THz Peak frequency • single cycle pulse	>5 uJ/pulse (~600 KV/cm)
Difference frequency generation OPA	• Tunable 17-30 THz • 50 fs duration	>10 uJ/pulse (25 mJ/cm^2)

My take-away points

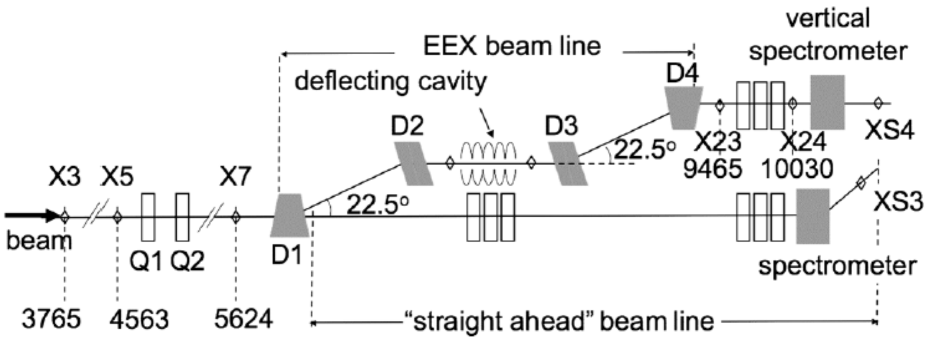
- 5-20 THz narrowband + High-rep. rate is really really hard

Accelerator based narrow-band THz schemes

- Exchange transverse modulation to longitudinal distribution

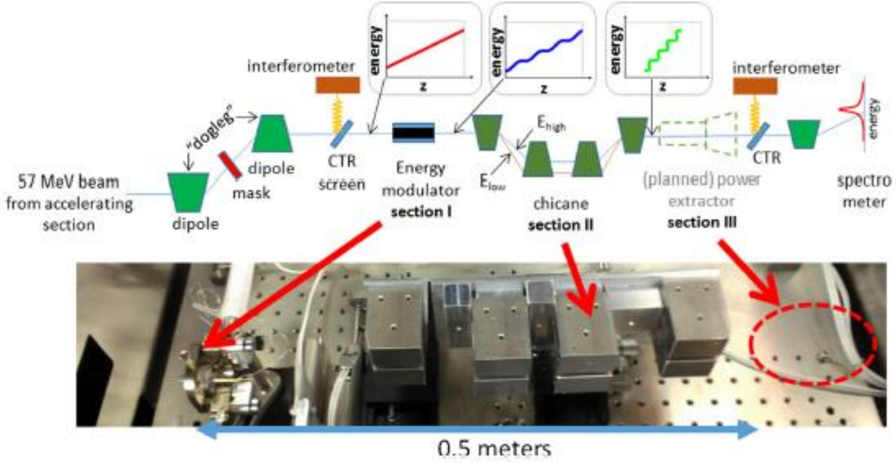


P. Muggli et al., PRL 101, 054801 (2008)



Y. E. Sun et al., PRL 105, 234801 (2010)

- Exchange wake-induced energy modulation to density bunching



K. Bane and G. Stupakov, NIM-A 677, 67 (2012)

S. Antipov et al., PRL 108, 144801 (2012)

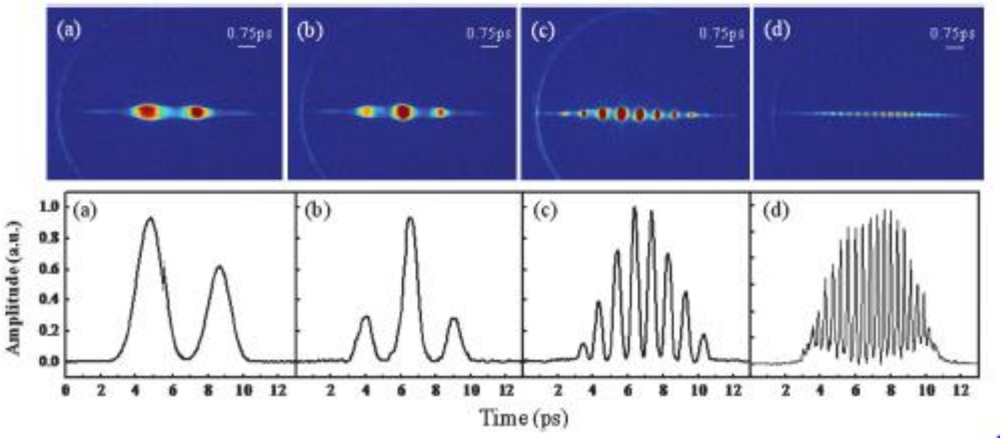
S. Antipov et al., PRL 111, 134802 (2013)

G. Stupakov, PRST-AB 18, 030709 (2015)

K. Bane et al., NIMA 844, 121 (2017)

Accelerator based narrow-band THz schemes

- Direct modulate the drive laser of the gun



Y. Li et al., APL 92, 014101 (2008)

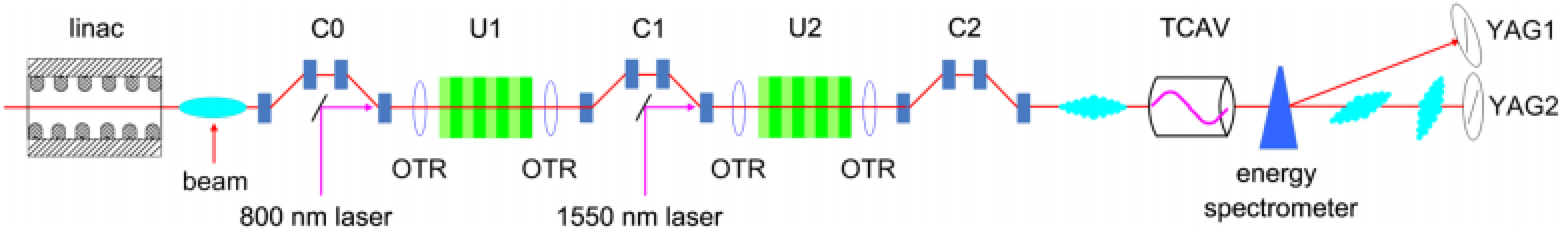
P. Musumeci et al., PRL 106, 184801 (2011)

Y. Shen et al., PRL 107, 204801 (2011)

P. Musumeci et al., PRST-AB 16, 100701 (2013)

Z. Zhang et al., PRL 116, 184801 (2016)

- Frequency beating of laser-induced density bunching



D. Xiang et al., PRST-AB 12, 080701 (2009)

M. Dunning et al., PRL 109, 074801 (2009)

Outline

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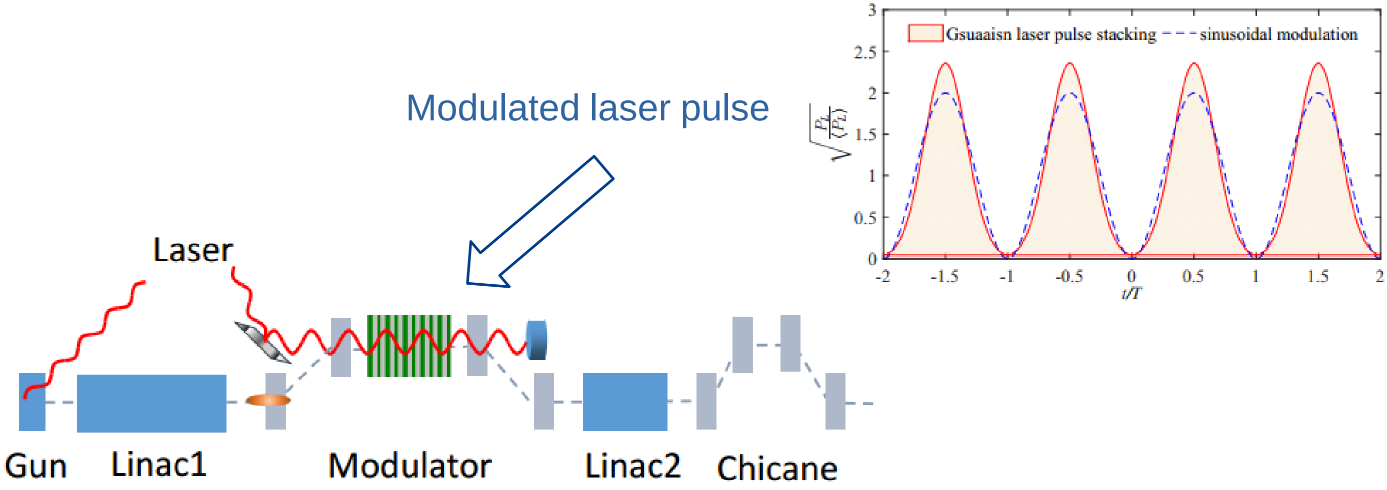
- Theory
- Simulation
- Radiation generation

☐ Recent experimental studies

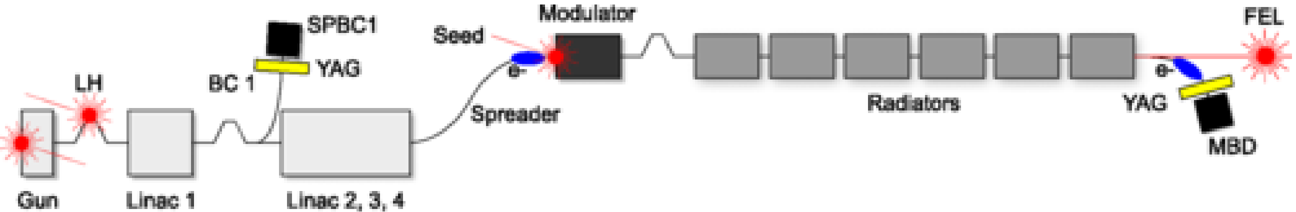
☐ Discussions and summary

Our method (Z. Zhang et al., Phys. Rev. AB 20, 050701, 2017)

- We propose a method based on the slice energy spread modulation to generate density bunching in a relativistic electron beam (a la **laser heater setup**)



- Similar method has been used in storage ring and FERMI FEL (for two-color FEL).



S. Bielawski et al. Nature Physics, 4(5), 390-393 (2008)
E. Roussel et al. Phys. Rev. Lett. 115, 214801(2015).

Theory

- The density modulation appears after the chicane with the bunching factor as follows

$$b(k) = \frac{1}{I_0}\int d\delta dz e^{-ikz} f(\delta, z)$$

- Using the Liouville theorem $f(\delta, z) = f_0(\delta_0, z_0), d\delta dz = d\delta_0 dz_0$, and making a change of variable from δ_0 to

$$\eta = \frac{\delta_0}{1 + A\sin(k_0 z_0)}$$

we can obtain

$$\begin{aligned} b(k) &= \int d\delta_0 dz_0 e^{-ik(1+hR_{56})z_0 - ikR_{56}\delta_0} \frac{1}{\sqrt{2\pi}\sigma_\delta(z_0)} \exp\left[-\frac{\delta^2}{2\sigma_\delta(z)^2}\right] \\ &= \int d\eta dz_0 e^{-ik(1+hR_{56})z_0 - ikR_{56}\eta[1+A\sin(k_0 z_0)]} \frac{1}{\sqrt{2\pi}\bar{\sigma}} \exp\left[-\frac{\eta^2}{2\bar{\sigma}^2}\right] \\ &= \frac{1}{\sqrt{2\pi}\bar{\sigma}} \int d\eta \exp\left[-ikR_{56}\eta - \frac{\eta^2}{2\bar{\sigma}^2}\right] \int dz_0 e^{-ik(1+hR_{56})z_0} \sum_n J_n(kR_{56}\eta A) e^{-ink_0 z_0} . \end{aligned}$$

Theory

- Integration over z_0 yields nonvanishing bunching at the wavenumber

$$\bar{k}_n = nk_0/(1+h\bar{R}_{56})$$

with the bunching factor

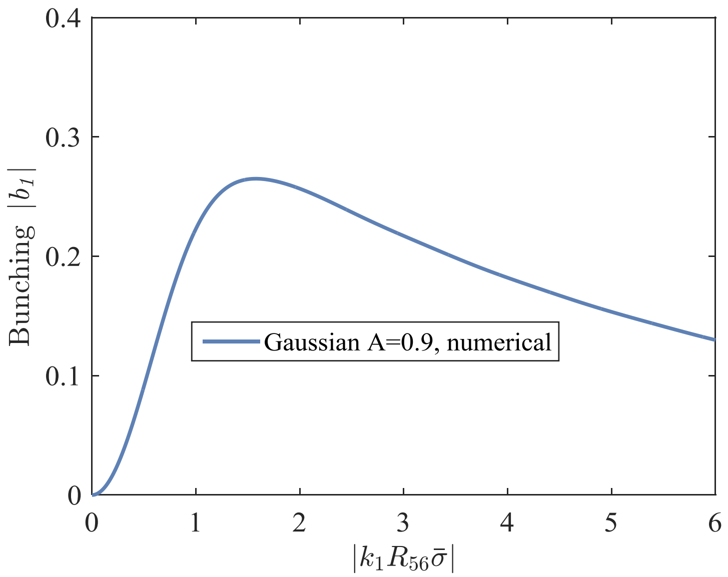
$$b_n = \frac{(-1)^n}{\sqrt{2\pi}\bar{\sigma}} \int d\eta J_n(k_n R_{56} A\eta) e^{-ik_n R_{56}\eta - \frac{\eta^2}{2\bar{\sigma}^2}}$$

- Numerical calculation can be used to find the exact bunching factor and current distribution.
- The maximum bunching factor available is ~0.27
- For $|x| < 3$ $J_1(x) \approx a\sin(bx)$ with $a = 0.58, b = 0.85$

$$b_1 = \frac{a}{2}[e^{-\frac{k_1^2 R_{56}^2 \bar{\sigma}^2 (1-bA)^2}{2}} - e^{-\frac{k_1^2 R_{56}^2 \bar{\sigma}^2 (1+bA)^2}{2}}]$$

- The optimal chicane setting is to satisfy

$$|k_1 R_{56} \bar{\sigma}| \approx 1.75$$



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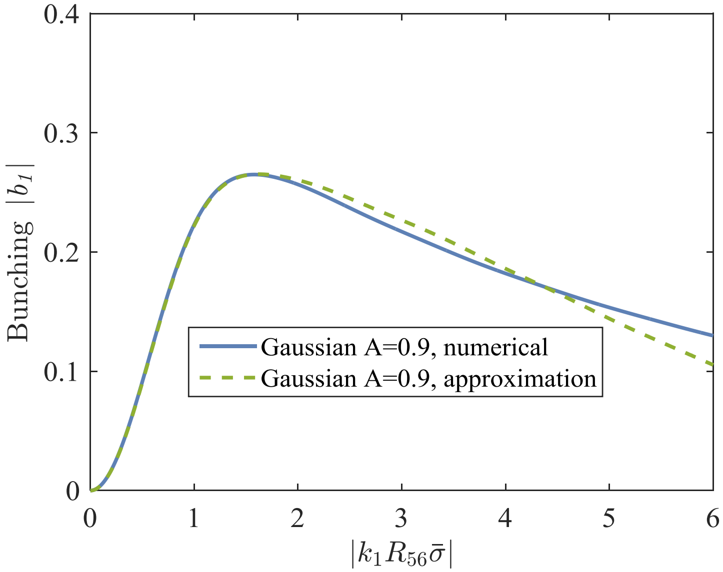
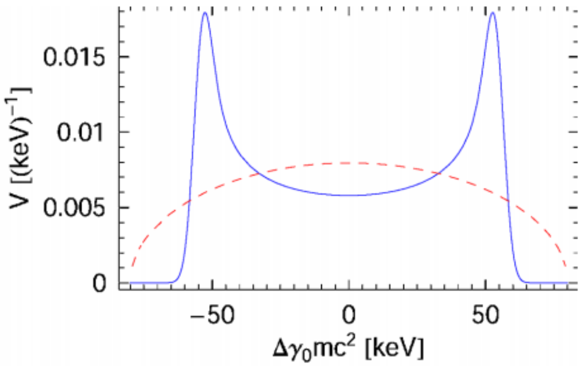
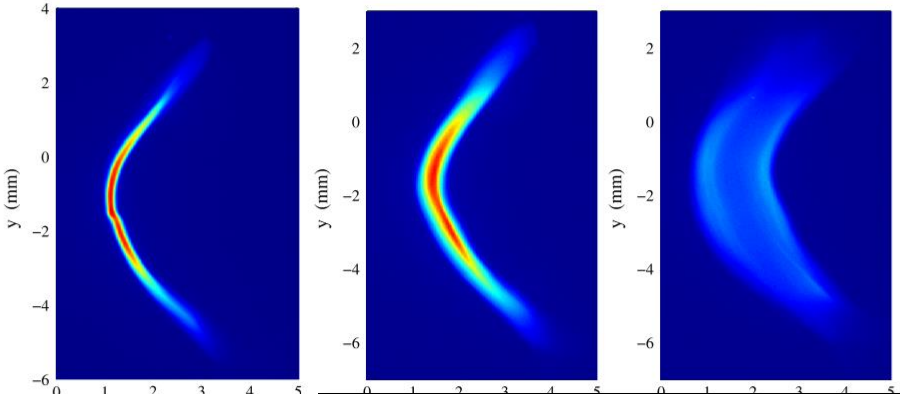


Theory

- The derivations above assume the beam has a Gaussian slice energy distribution, which is not always true in the laser heater.

- When the laser waist size in the undulator is much larger than the beam size, the resulting energy profile is a double-horn distribution



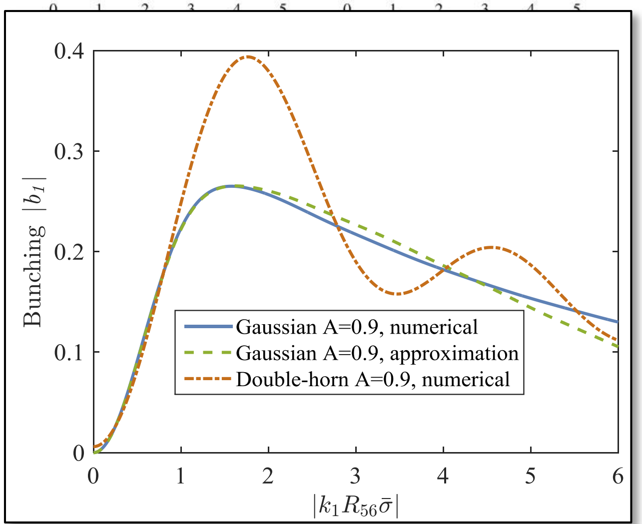


(a) no heating

Z. Huang et al., PRST-AB 7, 074401 (2004)
Z. Huang et al., PRST-AB 13, 020703 (2010)

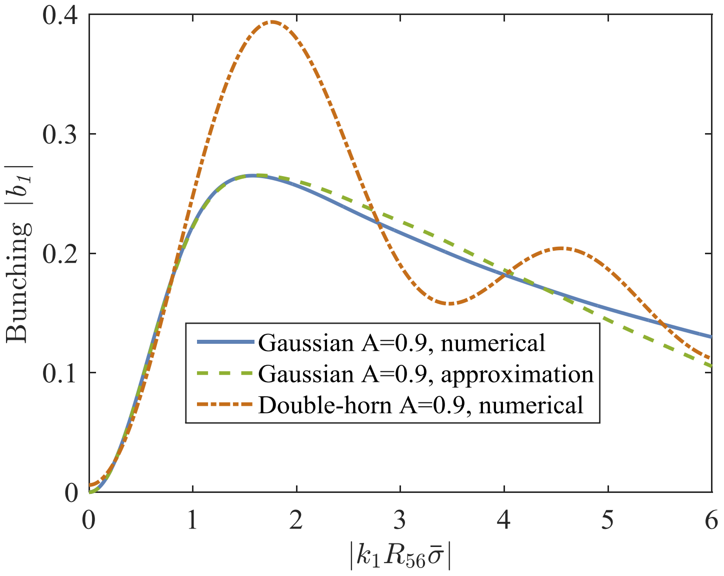
- We find that the double-horn energy distribution is more effective to increase the bunching factor in our study.

- The maximum bunching factor is up to ~0.4!!



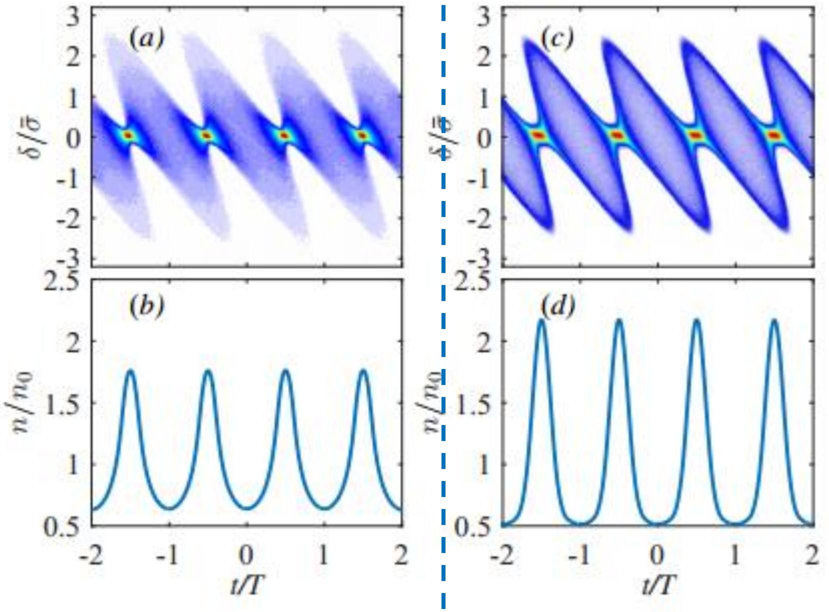
Theory

- Phase spaces of Gaussian and double-horn distributions when yielding maximum bunching factor



Gaussian

Double-horn

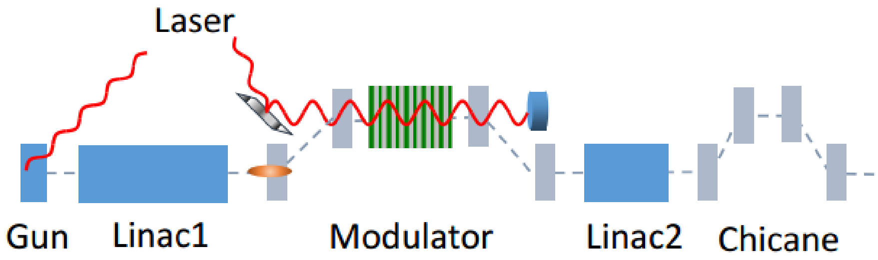


$b_1 \approx 0.27$

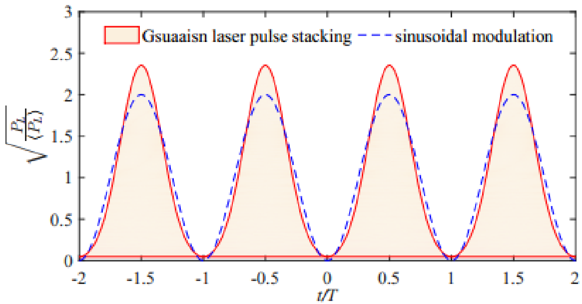
$b_1 \approx 0.4$

Simulation setup

- We use the code ELEGANT to simulate the laser modulation and beam dynamics



- The laser pulse train can be generated by the chirped pulse beating or pulse stacking

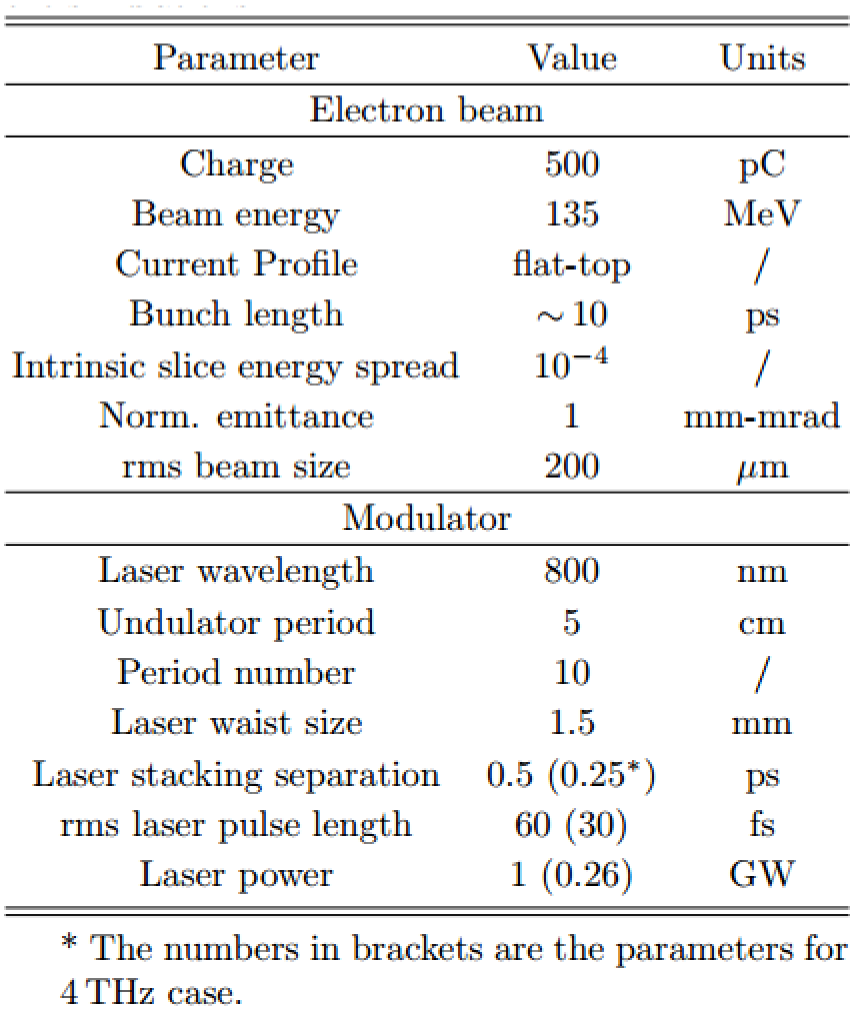


$$\text{period } T = 0.5\text{ps}$$
$$\text{frequency } f_0 = 2\text{ THz}$$
$$\sigma_t = 60\text{fs}$$

- The simulation starts from the exit of Linac1 to the end. The acceleration phase of Linac2 is -/+90 degrees to only add energy chirp, but does not change the beam energy.

Simulation parameters

- Simulation parameters (LCLS injector)

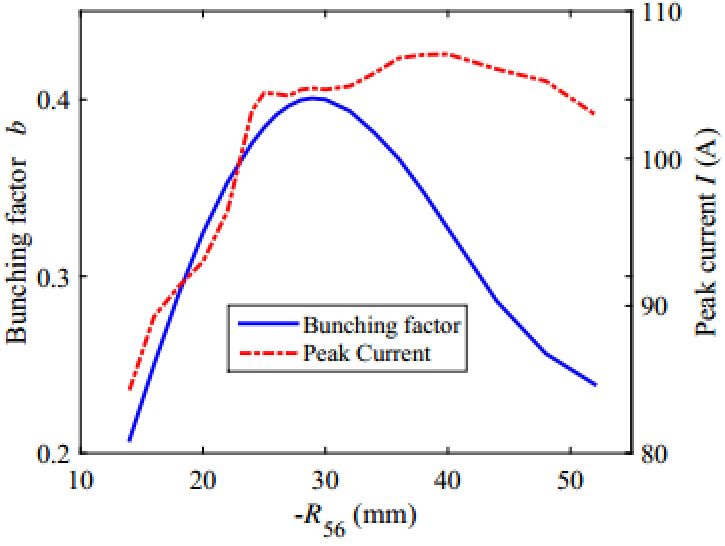


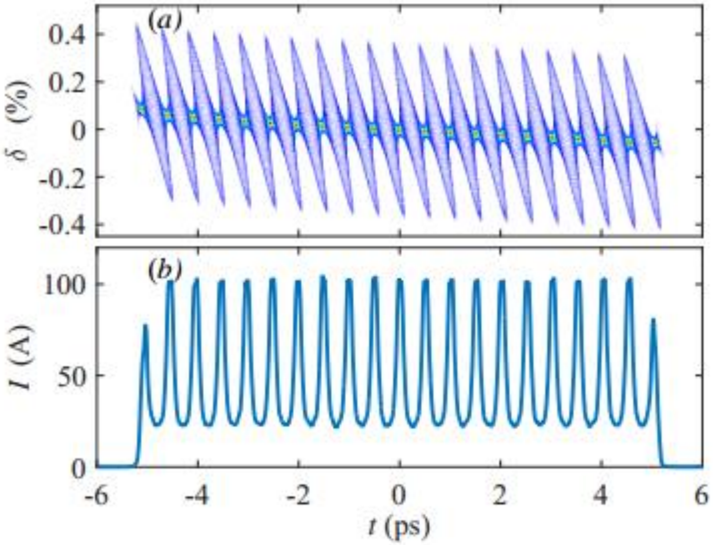
Parameter	Value	Units
Electron beam		
Charge	500	pC
Beam energy	135	MeV
Current Profile	flat-top	/
Bunch length	~ 10	ps
Intrinsic slice energy spread	10^{-4}	/
Norm. emittance	1	mm-mrad
rms beam size	200	μm
Modulator		
Laser wavelength	800	nm
Undulator period	5	cm
Period number	10	/
Laser waist size	1.5	mm
Laser stacking separation	0.5 (0.25*)	ps
rms laser pulse length	60 (30)	fs
Laser power	1 (0.26)	GW

* The numbers in brackets are the parameters for 4 THz case.

Simulation results

- 2THz, scan R_{56}, parameters: $P = 1GW,\ \bar{\sigma} = 190\text{keV}\ (1.4 \times 10^{-3})$
- Laser peak power P = 100 MW with a smaller transverse cross section works just fine.



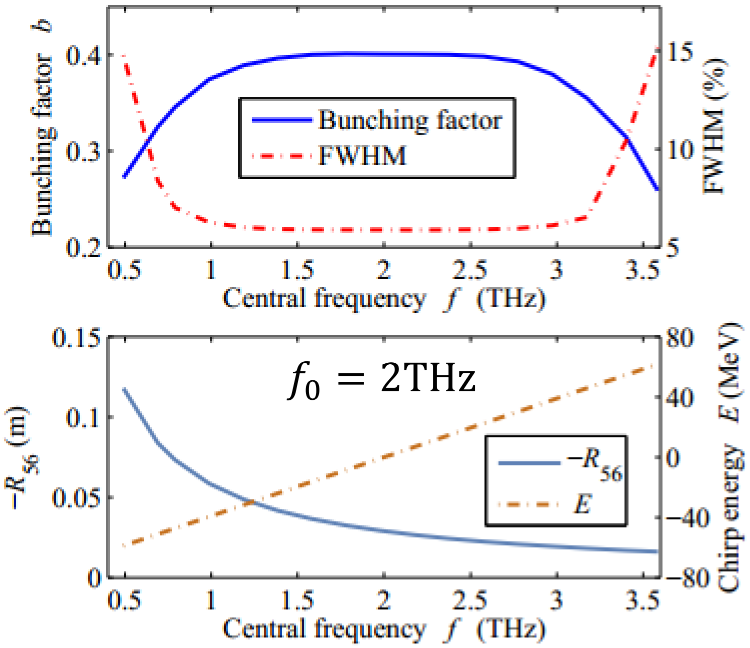


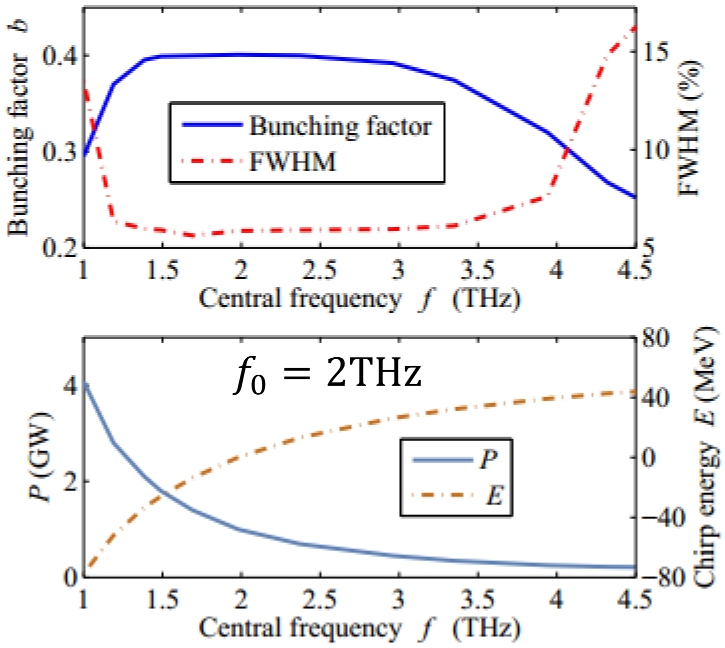
- The optimal condition $|k_1\bar{\sigma}R_{56}| \approx 1.75$ predicts the optimal chicane is -29.4mm, consisting with the simulations (-29mm).
- The peak current stays constant with larger R_{56}.

- The longitudinal phase space and current profile when the $R_{56} = -29\text{mm}$ (optimal bunching)

Tunability

- We can vary the frequency by compressing the beam or changing the laser power envelope modulation period.
- We need to keep the optimal condition $|k_1\bar{\sigma}R_{56}| \approx 1.75$ while changing k_1



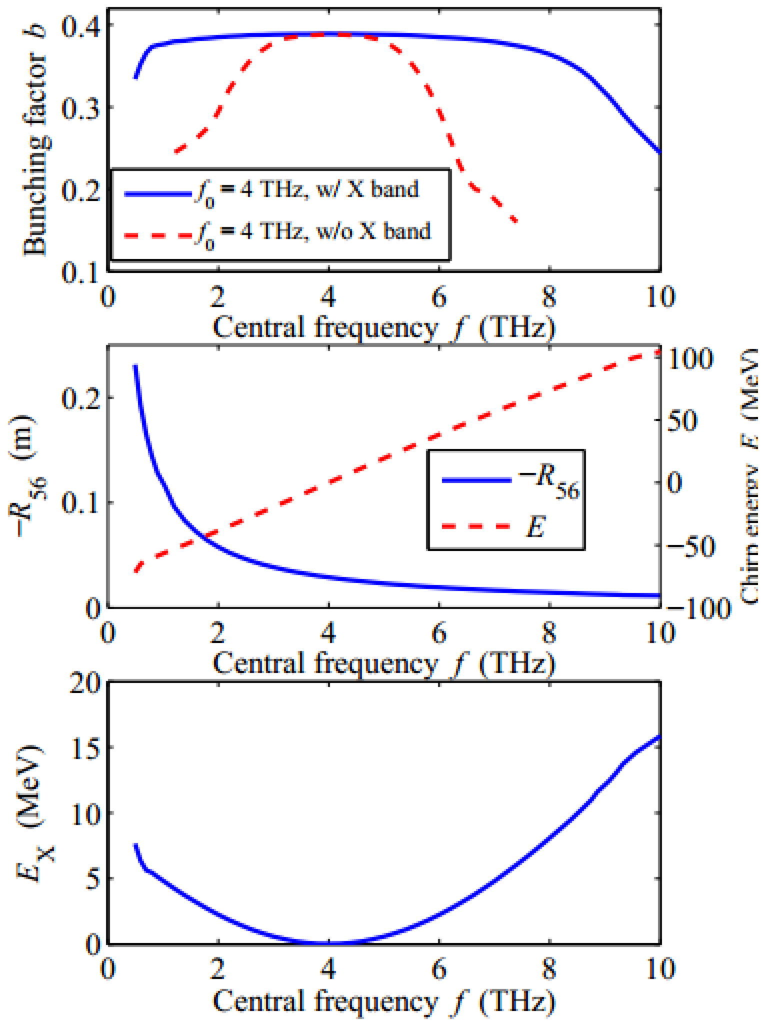


- Keep $P = 1GW$
- For k_1, calculate the required R_{56}
- Vary the energy chirp of L2 to achieve k_1

- Keep $R_{56} = -29\text{mm}$
- For k_1, calculate the required P
- Vary the energy chirp of L2 to achieve k_1

Higher THz frequencies

- In the range of 1THz to 3THz, the bunching factor are all around 0.4.
- The frequency range is limited by the nonlinear effects in beam compression.
- If we use an X-band cavity (to linearize LPS) before the chicane, the frequency range with large bunching factor can be extended significantly.
- For 4THz initial modulation case:
  with X-band: 1~10 THz
  without X-band: 3~5 THz
- We also give the required parameters for different frequencies, including the X-band cavity energy.
- **More bunch compression can yield >10 THz.**



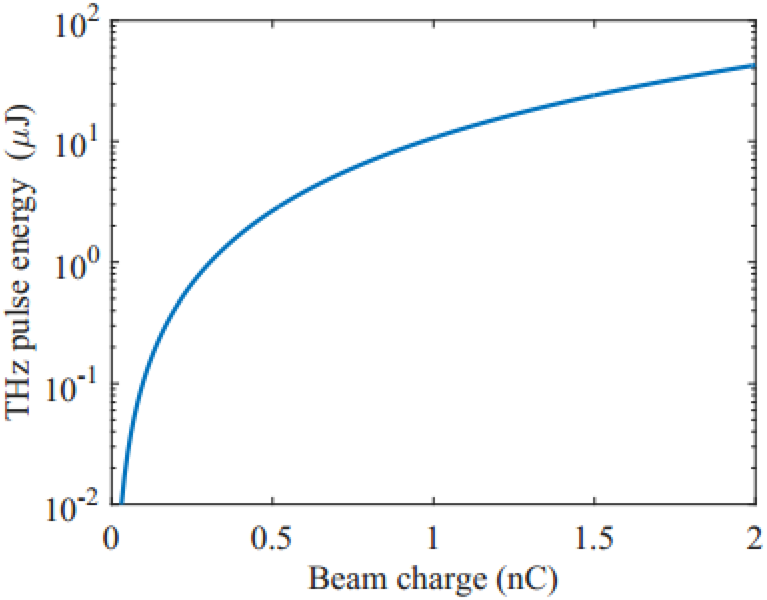
THz transition radiation

- For CTR, the THz pulse energy can be estimated by

$$E_{\mathrm{THz}} = N_e^2 b^2 \frac{dW_1}{d\omega} \Delta\omega$$

N_e is the number of electron, b is the bunching factor,
$\frac{dW_1}{d\omega}$ is the single electron radiation spectra, $\Delta\omega$ is the linewidth of the spectra $\approx \frac{1}{N_b}$

For 2THz radiation



- At 2nC charge and 2THz radiation, the pulse energy can be 40μJ within 5% bandwidth

THz undulator radiation

- For undulator radiation, take λ_w =10 cm, K_{rms} = 11.77, radiation wavelength λ_r = 100 um (3 THz) for 135 MeV beam with 1 nC charge
- For N_w = 100 period, undulator length is 10 m, radiation bandwidth 1%
- Undulator radiation energy for a thin beam (large diffraction regime)

$$W_0 = W_\mathrm{b}\left[\frac{\pi^2 a_\mathrm{in}^2}{2}\right]\left[\frac{I}{\gamma I_\mathrm{A}}\right]\left[\frac{K^2}{1+K^2}\right]N_\mathrm{w}$$

Saldin, Schneidmiller, Yurkov, NIMA539, 499 (2005)

W_b is the beam power (135 mJ), $a_{in} = 2b = 0.8$, $I = 100$ A

- THz pulse energy $W_0 = 300\ \mu$J, can approach mJ with further optimization!!

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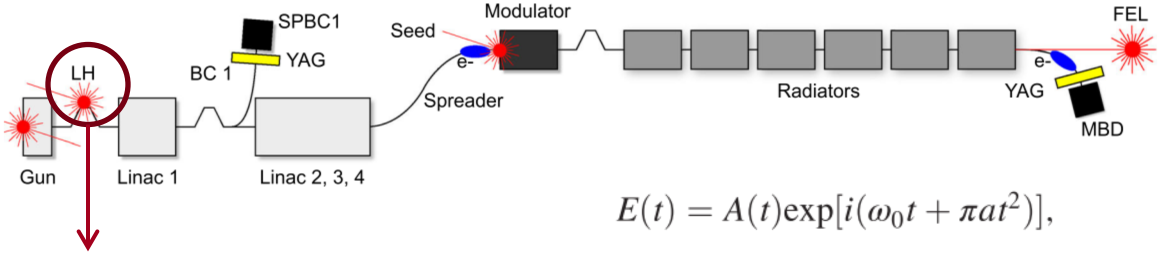
FERMI experiments

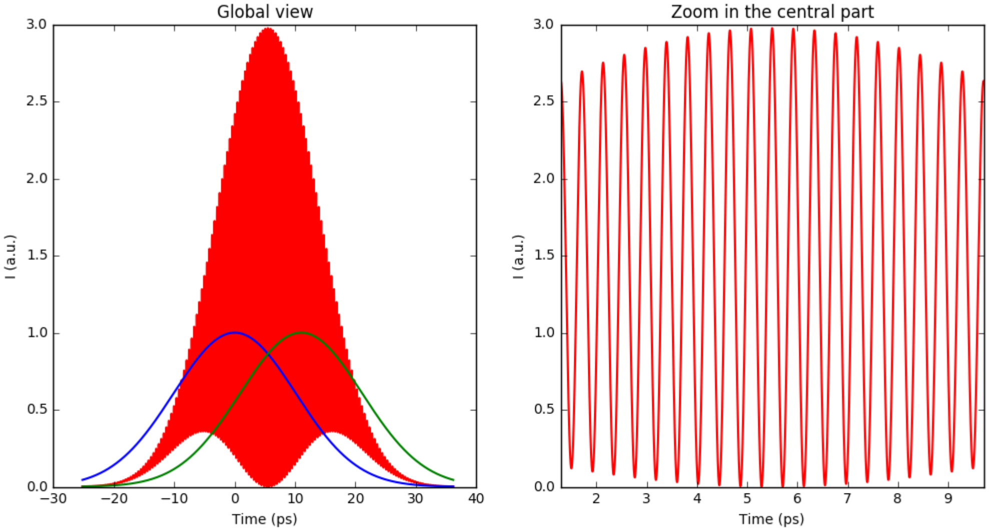


Interference of two chirped pulses

$$E(t) = A(t)\exp[i(\omega_0 t + \pi a t^2)],$$

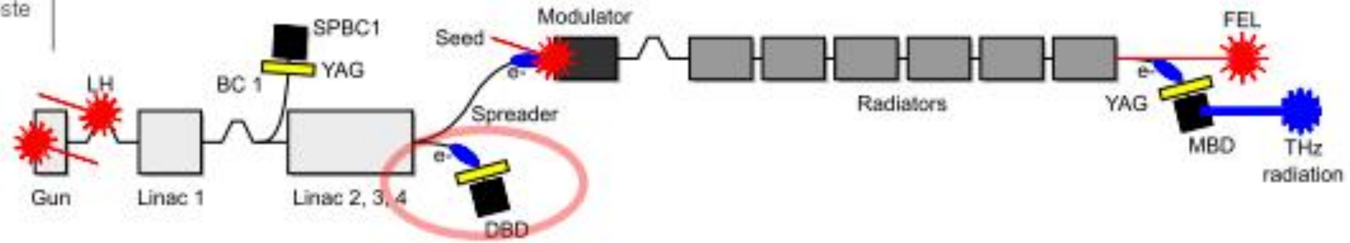
$$\begin{aligned} I(t,\tau) &= |E_1(t) + E_2(t+\tau)|^2 \\ &= A_1(t)^2 + A_2(t+\tau)^2 \\ &\quad + 2A_1(t)A_2(t+\tau)\cos\left(\omega_0\tau + 2\pi \underline{a\tau} t + \pi a\tau^2\right), \end{aligned}$$

Beating frequency/wavelength = 2.37737 THz/126.103 um

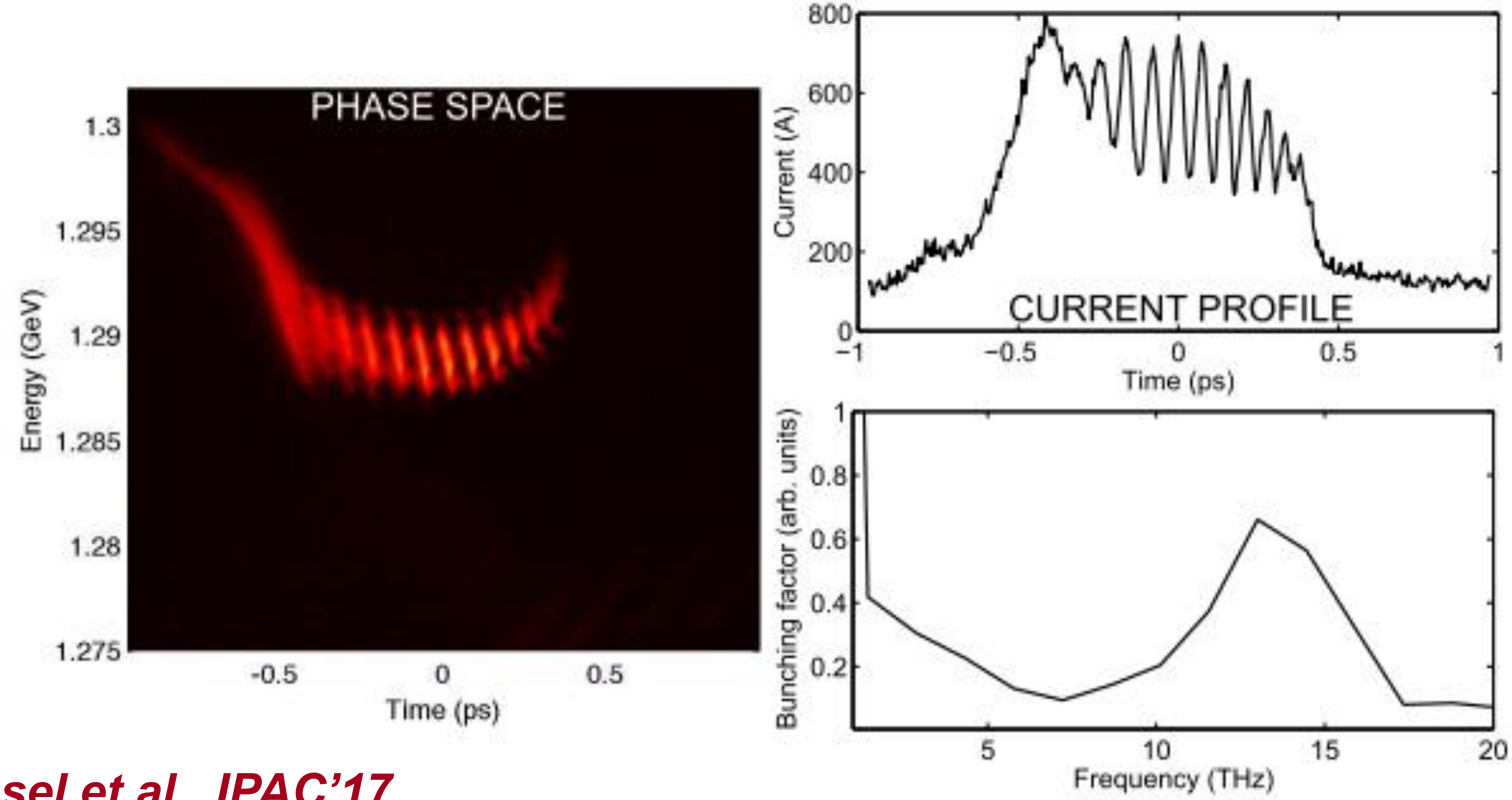


E. Roussel et al., PRL 115, 214801 (2015))

Experimental THz-modulated ebeam



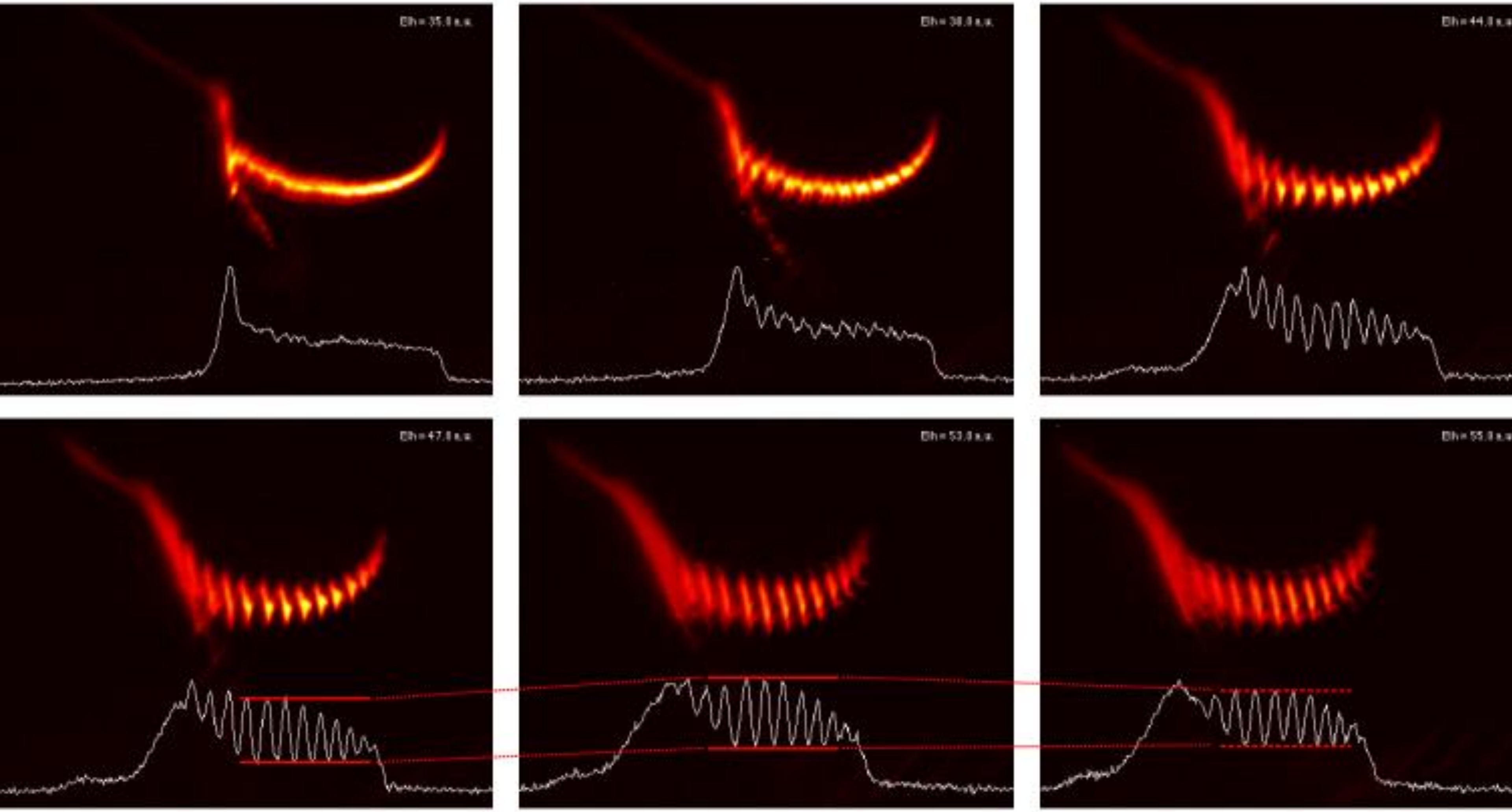
- Observation of a modulated beam in the tens of THz range at the end of the linac starting from an initial modulation in LH around 2 THz.



E. Roussel et al., IPAC’17

Optimization of modulation amplitude (bis)

By changing laser power (or by dispersion strength)

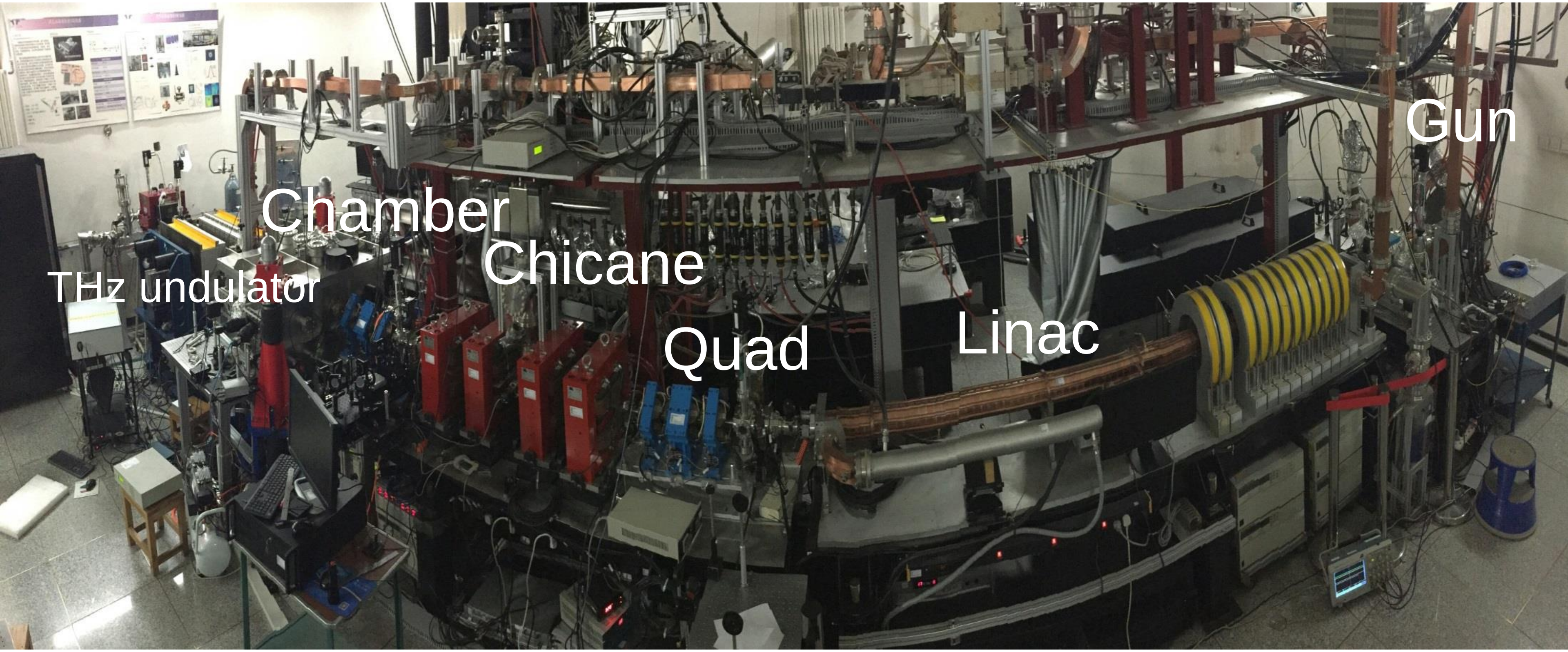


E. Roussel et al., IPAC'17

Proposed Tsinghua University experiment

Experimental configuration and goal (demonstrate this concept at 50 MeV)

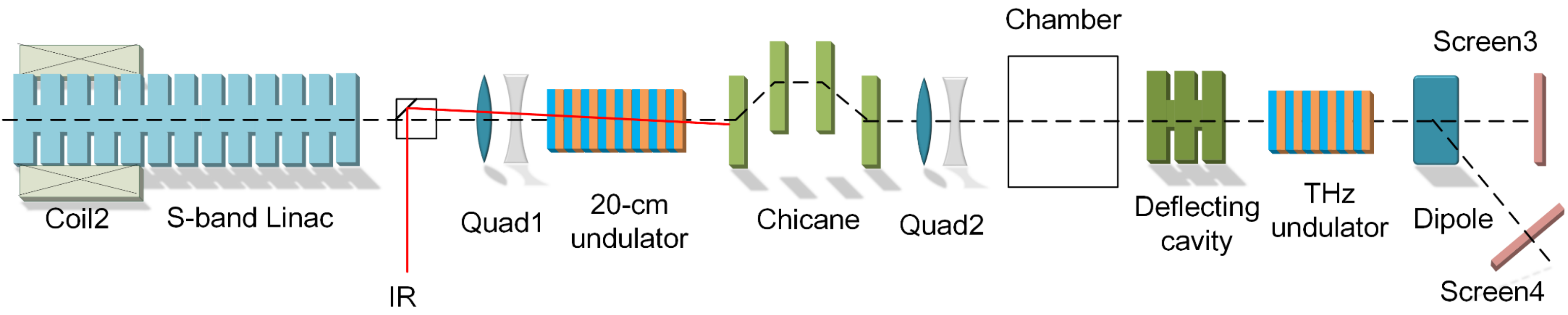
Undulator period 2.5 cm, K=1.3. Third harmonic resonant wavelength is 800 nm

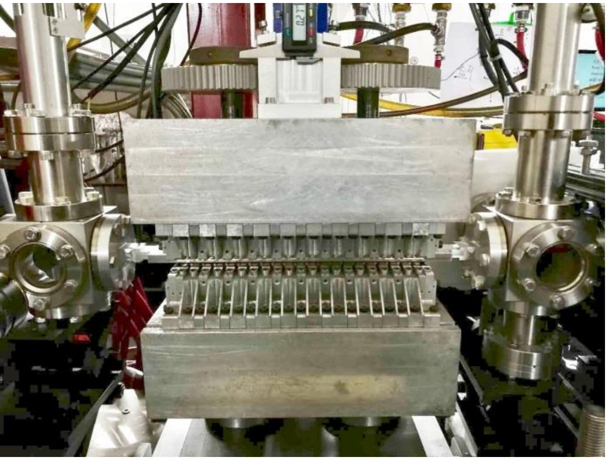


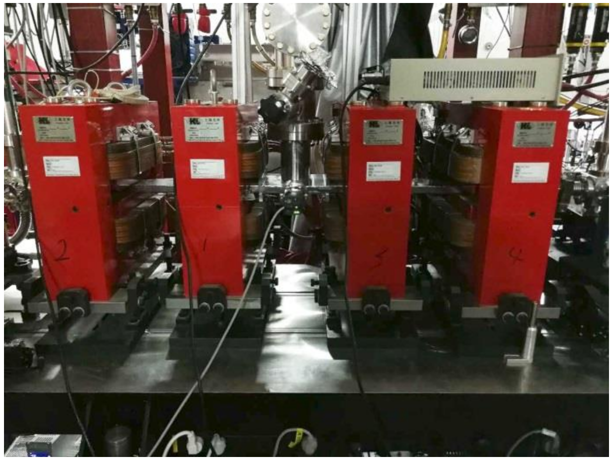
Total beamline length ~10 m, a very compact setup!

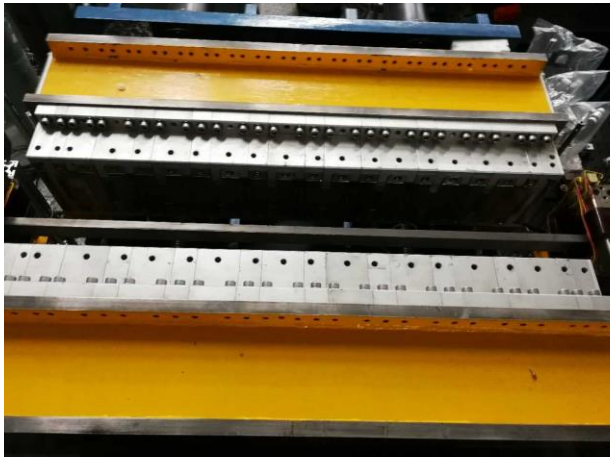
Z. Zhang et al.,

Tsinghua University experimental status









Modulator (works at 3rd harmonic)

chicane

THz undulator

Z. Zhang et al.,

Outline

☐ Introduction

☐ Proposed THz source

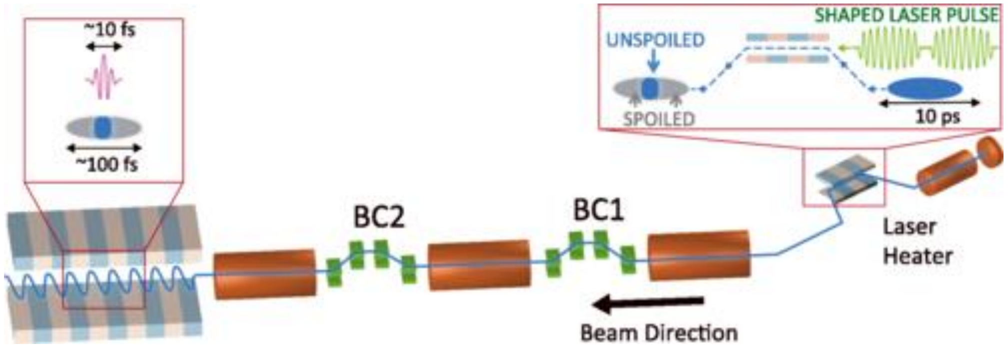
- Theory
- Simulation
- Radiation generation

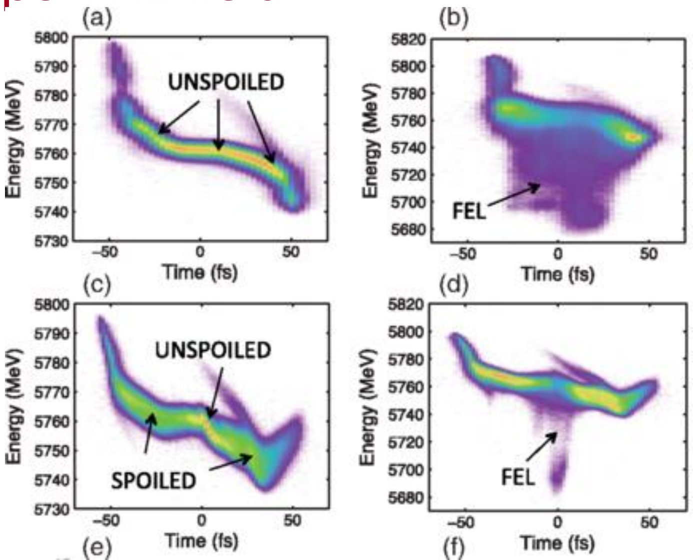
☐ Recent experimental studies

☐ Discussions and summary

Discussions

- Based on the slice energy spread modulation method, the bunching factor can be kept around 0.4 for a wide frequency range (1-10 THz) and can be extended to 20 Thz by compression or by taking advantage of the second harmonic bunching.
- THz pulse energy is estimated to be tens of uJ to hundreds of uJ.
- The method is also applicable for the electron beams from storage rings, ERL, or even thermal-cathode injectors with higher repetition rate.
- Laser envelope shaping can be applied to shape THz field





A. Marinelli et al., PRL 116 25480 (2016)

High-rep. Rate Stand-alone THz source

- Stand-alone THz source at the experimental area (XFEL, LCLS-II)
- Use LCLS-II spare gun + accel. cryomodule (50 MeV) for a high-rep. rate compact accelerator
- E-beam power is similar to LCLS-I (5-10 kW) and requires LCLS-I type of shielding
- Leverage OPCPA laser at LCLS-II R&D (800 nm, 0.1 -1 MHz, 100 W)
- Expect good synchronization with hutch lasers (both through OPCPA)
- Strong THz field may be used in the LCLS(-II) TimeTool to cross-correlate with optical signals (and X-rays) for jitter corrections

- THz pulse form can be controlled by both laser and e-beam techniques (narrowband, chirped, a few cycle pulses, all possible)
- Flexible, powerful, high-rep. rate THz, well-synchronized with X-rays.

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