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

Zhirong Huang (SLAC, Stanford University)
September 20, 2017

Outline

- ☐ Introduction

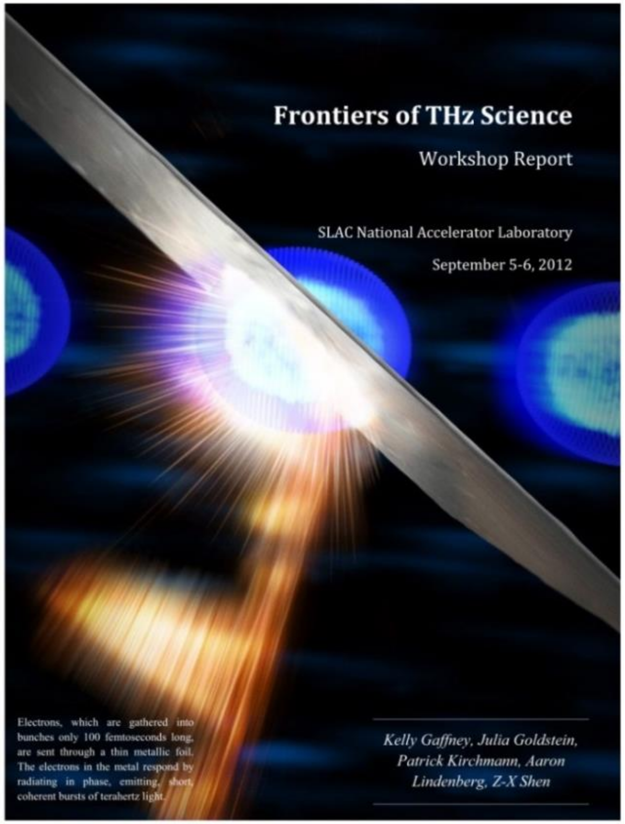
- ☐ Proposed THz source
  - Theory
  - Simulation
  - Radiation generation

- ☐ Recent experimental studies

- ☐ Discussions and summary

Introduction

- THz science is a rich field with the potential to advance research in many scientific areas.
- Very strong interests exist in combining THz radiation with X-ray FELs for pump-probe experiments



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

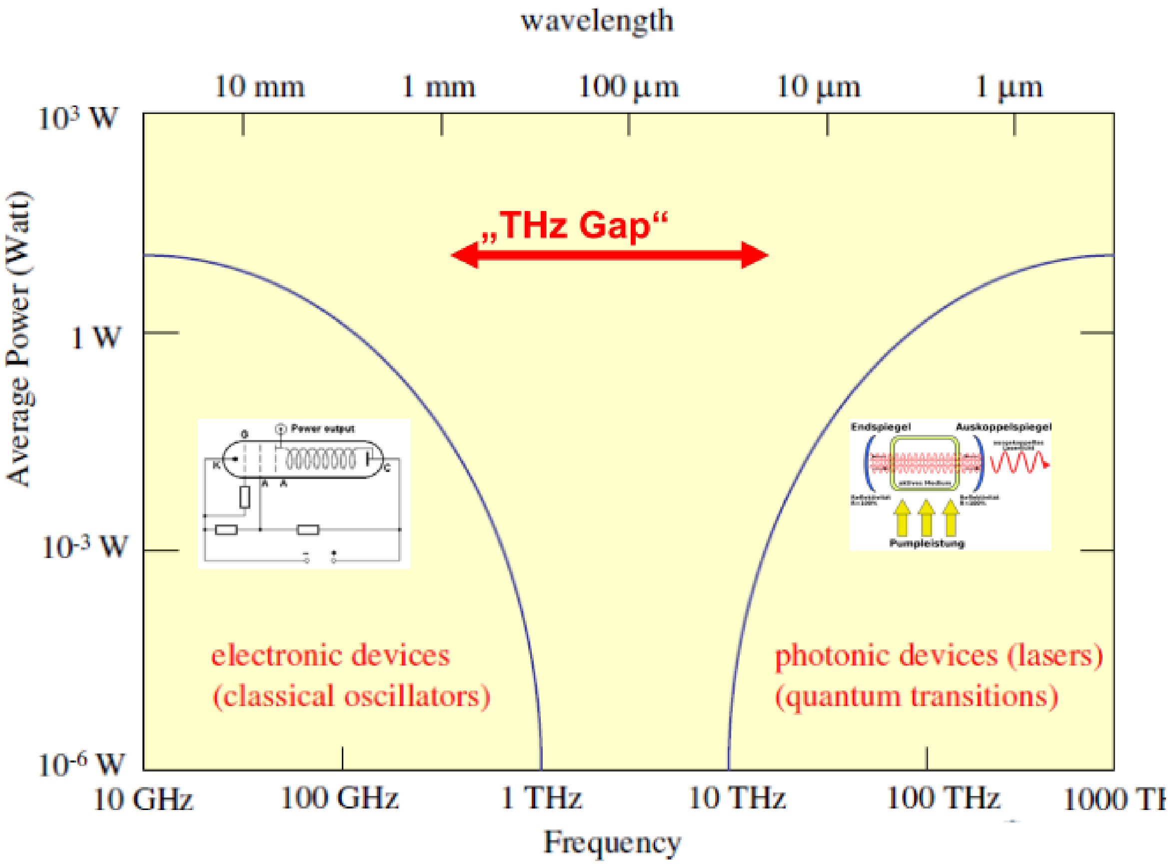
European XFEL Workshop

Terahertz science at European XFEL

European XFEL

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

THz gap (1 to 20 THz)



- Laser-based sources have made significant progress, but very challenging to reach above a few THz.
- Accelerator based sources are well suited for high-field, high-frequency, high-rep. rate THz applications

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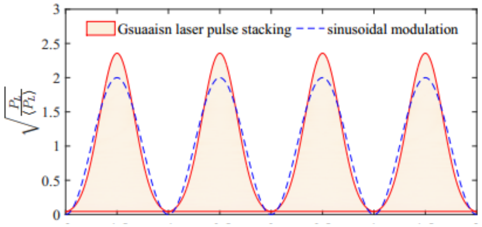
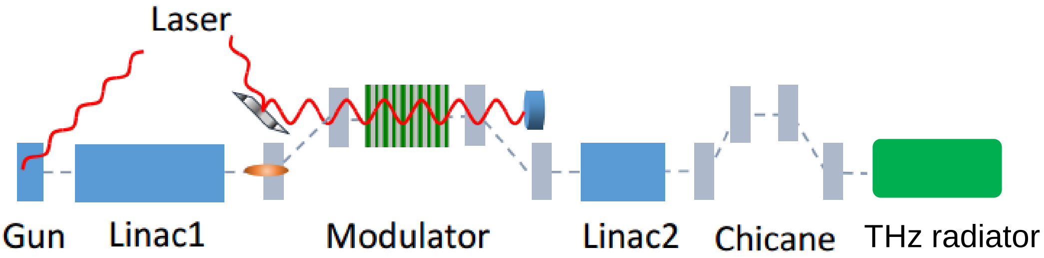
Our method (Z. Zhang et al., Phys. Rev. AB 20, 050701, 2017)

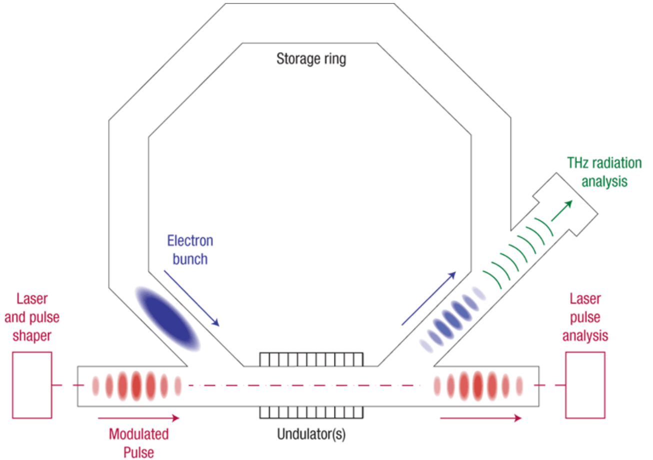
- We propose a method based on the slice energy spread modulation to generate density bunching in a relativistic electron beam (a la **laser heater setup**)

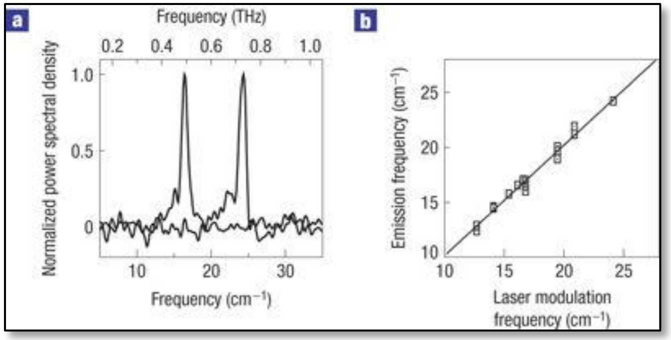
Amplitude-Modulated laser pulse




Laser
Gun
Linac1
Modulator
Linac2
Chicane
THz radiator

- Similar method has been used in storage ring THz generation





S. Bielawski et al. Nature Physics, 4(5), 390-393 (2008).
C. Evain et al., PRSTAB 13, 090703 (2010).

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

$$k_n = nk_0/(1+hR_{56})$$

with the bunching factor

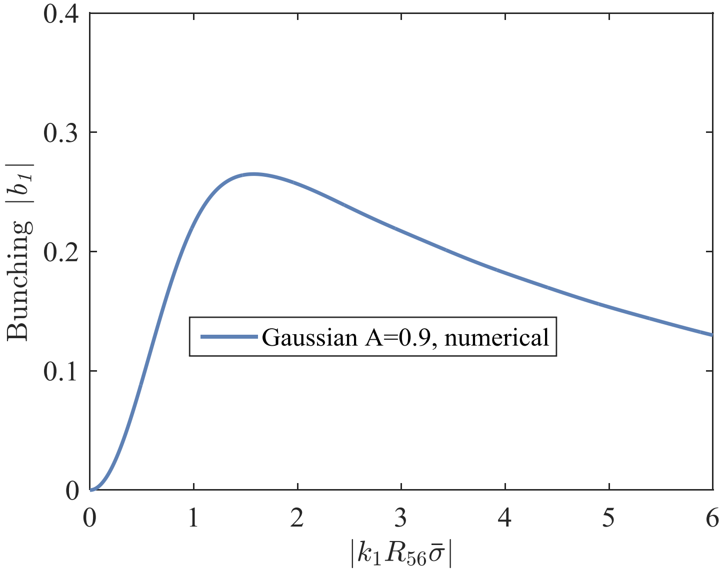
$$b_n = \frac{(-1)^n}{\sqrt{2\pi}\bar{\sigma}} \int d\eta J_n(k_n R_{56} A\eta) e^{-ik_n R_{56}\eta - \frac{\eta^2}{2\bar{\sigma}^2}}$$

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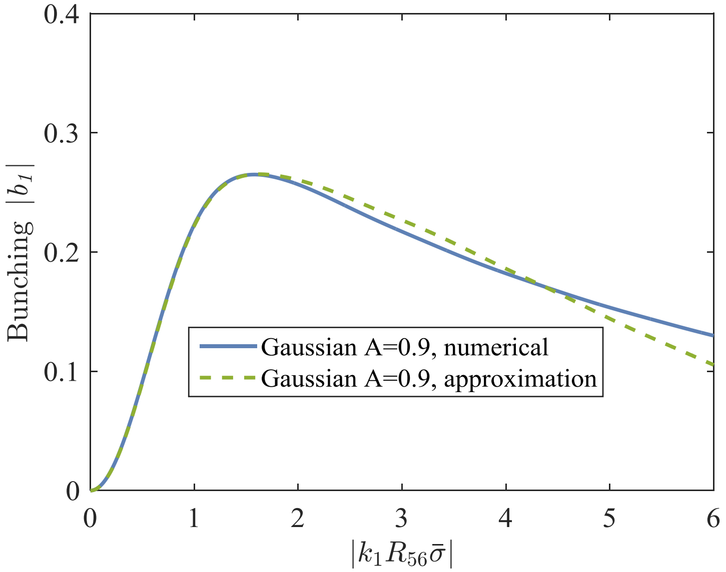
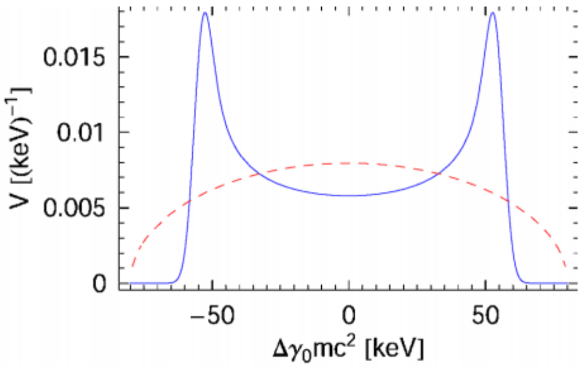
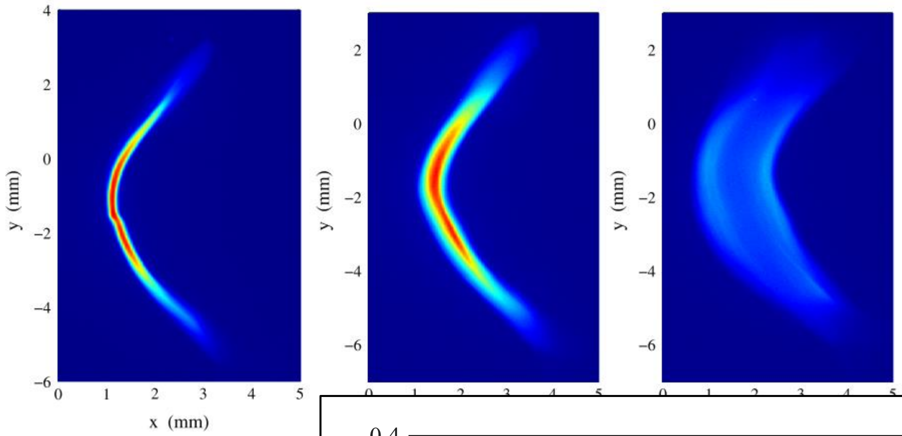


Theory

- 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



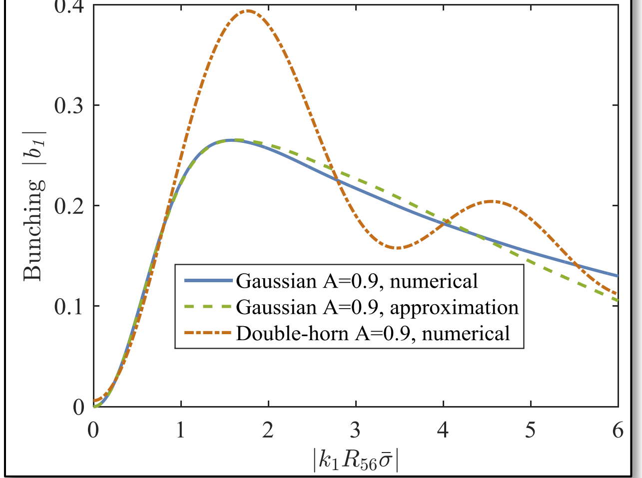


(a) no heating

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

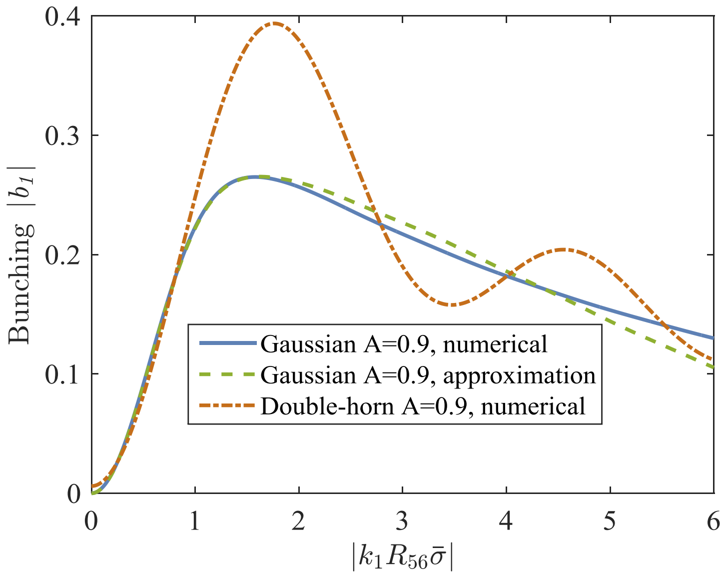
- We find that the double-horn energy distribution is more effective to increase the bunching factor in our study.

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



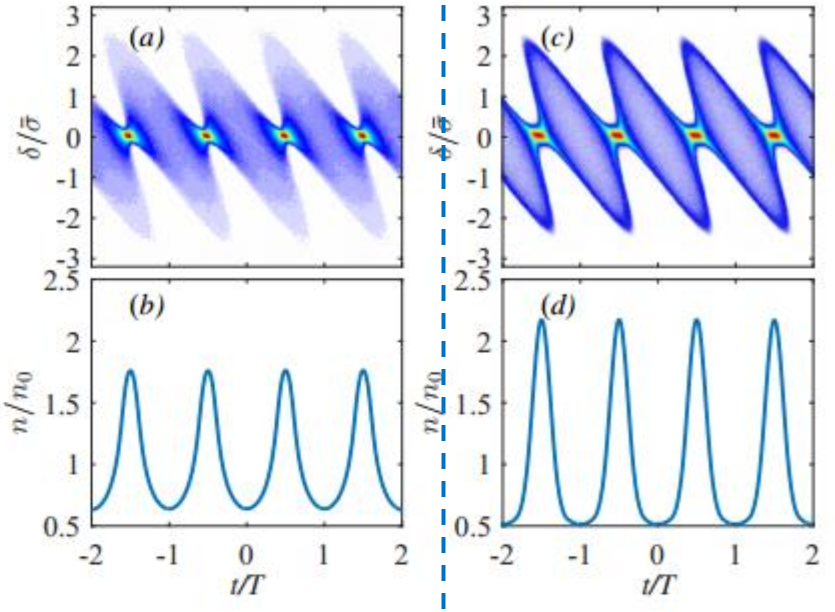
Theory

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



Gaussian

Double-horn



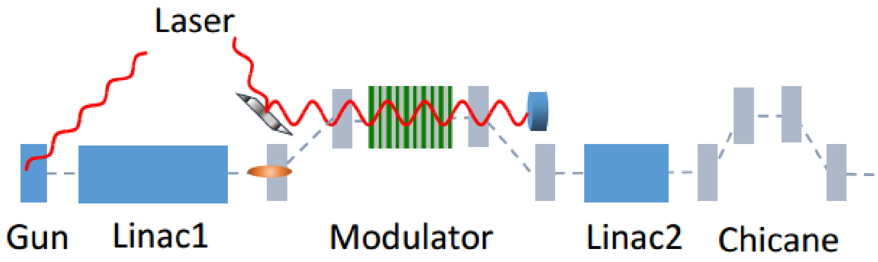
$b_1 \approx 0.27$

$b_1 \approx 0.4$

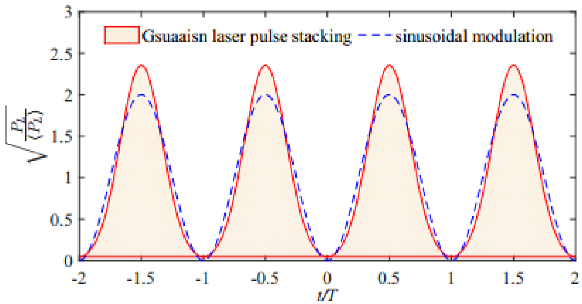
- Significant second harmonic bunching (~0.25) can be used to reach higher THz frequencies

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

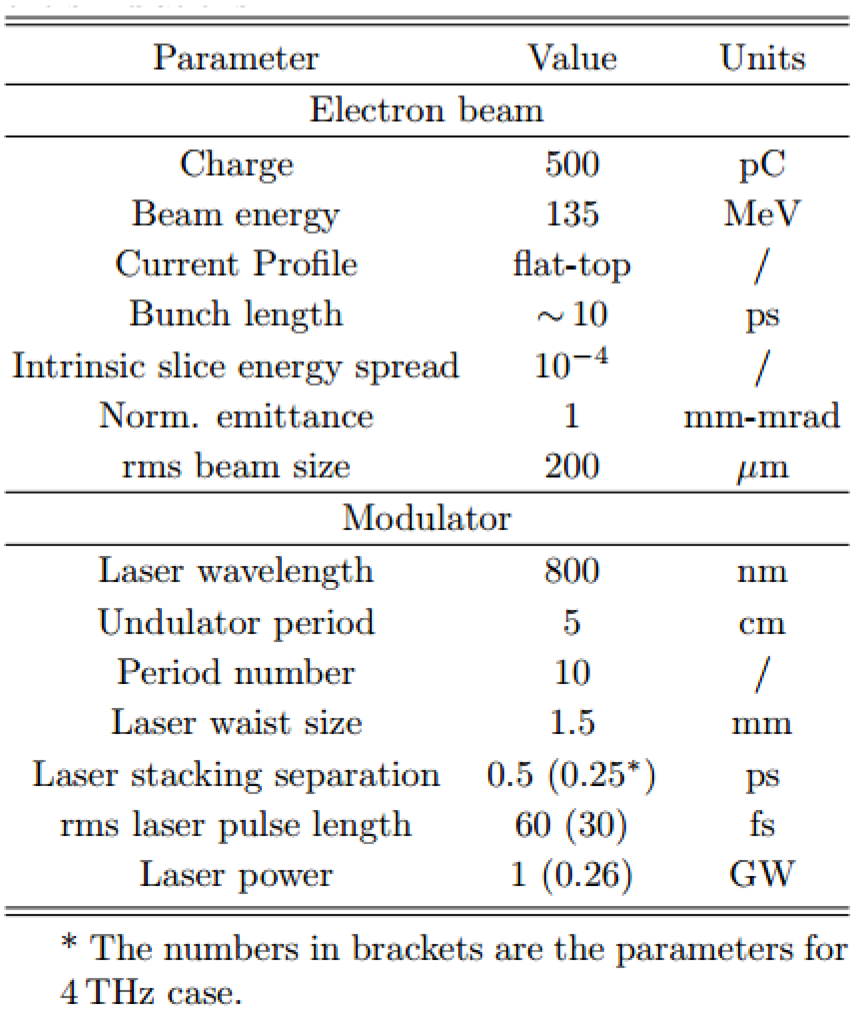


$$\text{period } T = 0.5\text{ps}$$
$$\text{frequency } f_0 = 2\text{ THz}$$
$$\sigma_t = 60\text{fs}$$

- 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)

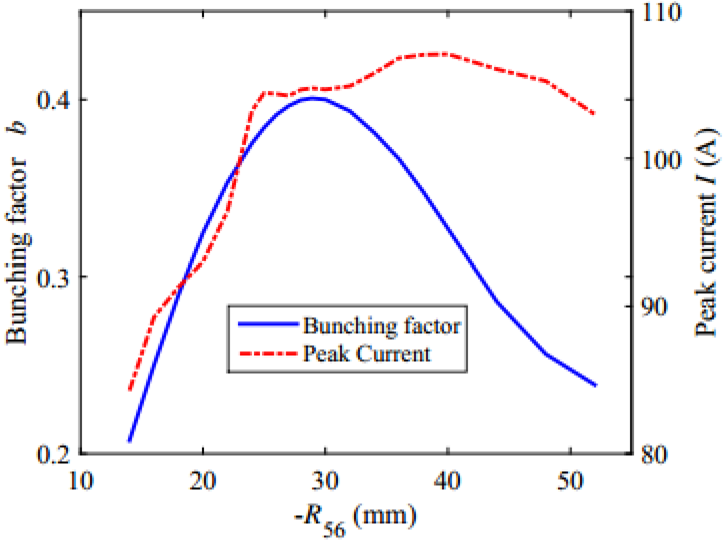


Parameter	Value	Units
Electron beam		
Charge	500	pC
Beam energy	135	MeV
Current Profile	flat-top	/
Bunch length	~ 10	ps
Intrinsic slice energy spread	10^{-4}	/
Norm. emittance	1	mm-mrad
rms beam size	200	μm
Modulator		
Laser wavelength	800	nm
Undulator period	5	cm
Period number	10	/
Laser waist size	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.

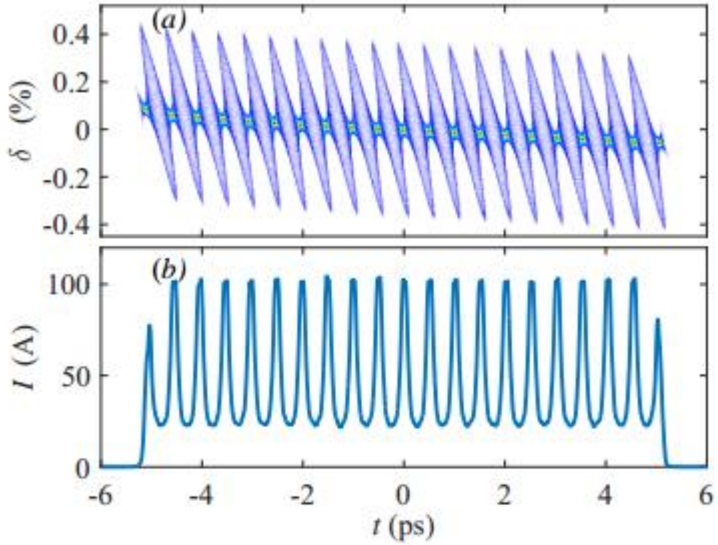
Simulation results

- 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).

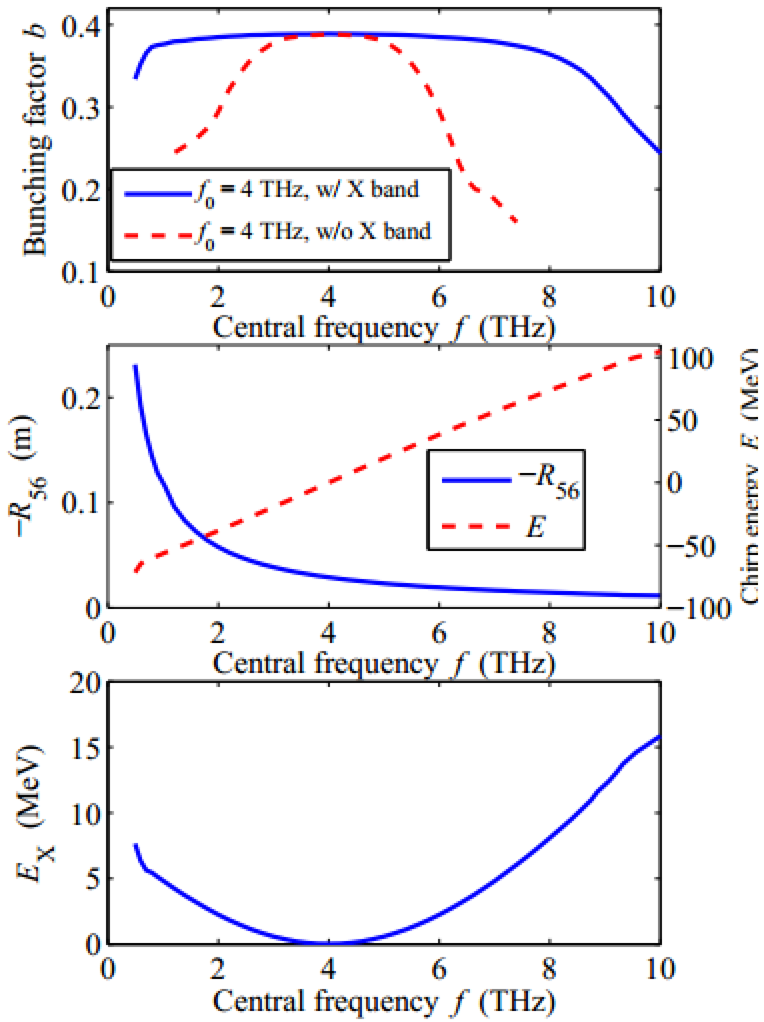
- The peak current stays constant with larger R_{56}.



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

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.**



Stand-alone compact accelerator-based Thz source

- Compact accelerator of ~50 MeV interacts with a 800-nm laser in the undulator
- Laser-electron interaction through 3rd harmonic (for a planar undulator with fundamental resonant wavelength 2.4 μm.)

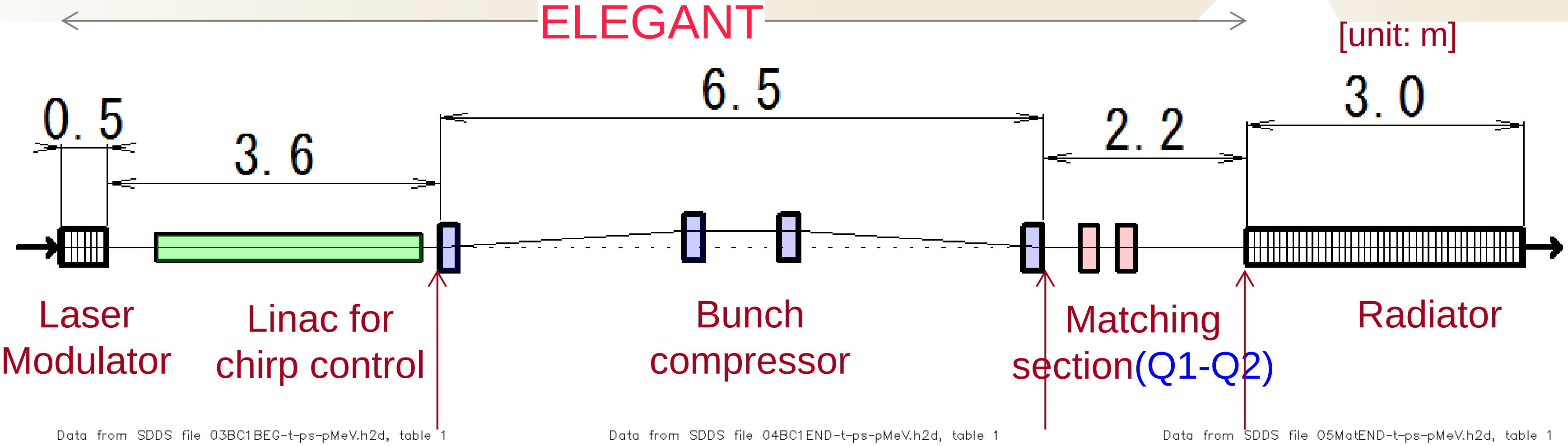
Parameter	Value
E-beam charge	1 nC
Beam energy	50 MeV
RMS beam size	0.2 mm
Bunch length (flattop)	10 ps
Modulator	
Undulator period	2.5 cm
Peak field/ K value	0.56 T /1.29
Undulator length/period	0.5 m / 20
Laser wavelength	800 nm
Laser RMS spot size	0.5 mm
Laser stacking separation	0.5 ps (2 THz)
Laser peak power	100 MW

Relative energy modulation

$$\delta = \sqrt{\frac{P_L}{P_0}}\,\frac{K L_u}{\gamma^2 \sigma_r}\left[\mathrm{JJ}\right]_3$$

OPCPA laser at high-rep. rate (100 kHz, 100 W average power)

50 MeV simulation results



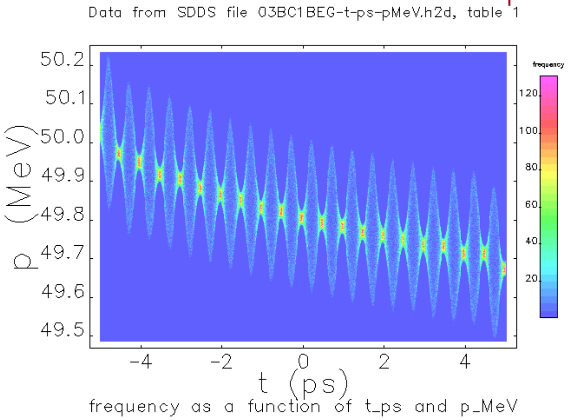
Laser Modulator

Linac for chirp control

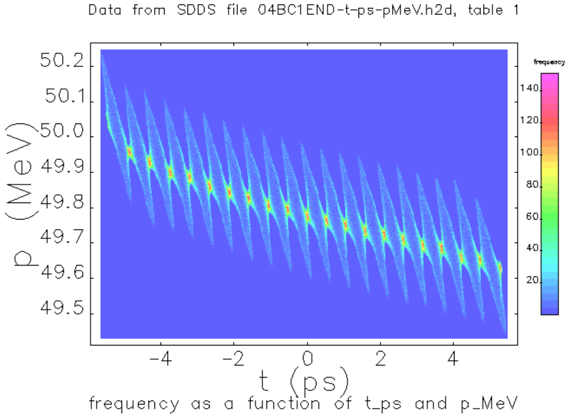
Bunch compressor

Matching section(Q1-Q2)

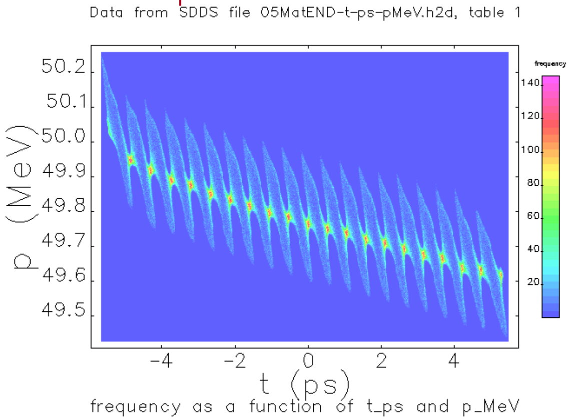
Radiator



Before bunch compressor (2 THz modulation rms Espread=0.15%)



After bunch compressor (bunching=0.37)



After matching section (bunching=0.34)

Courtesy Koichi Kan

THz radiation

- Transition radiation foil is the simplest radiator. CTR energy ~10 uJ (5% bandwidth) with 1 nC charge.

- For a helical wiggler (λ_w =15 cm, K_w = 4.3), resonant wavelength at 50 MeV is λ_r = 150μm (2 THz).
  - Radiation pulse energy for a thin beam (large diffraction regime)

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

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

W_b is the beam power (50 mJ at 1 nC), a_{in} = 2b = 0.68, I = 100 A,

N_w=20 (3 m wiggler) ➔ THz pulse energy W_0 = 140μJ

- Undulator in a waveguide or a dielectric tube may be more efficient radiators

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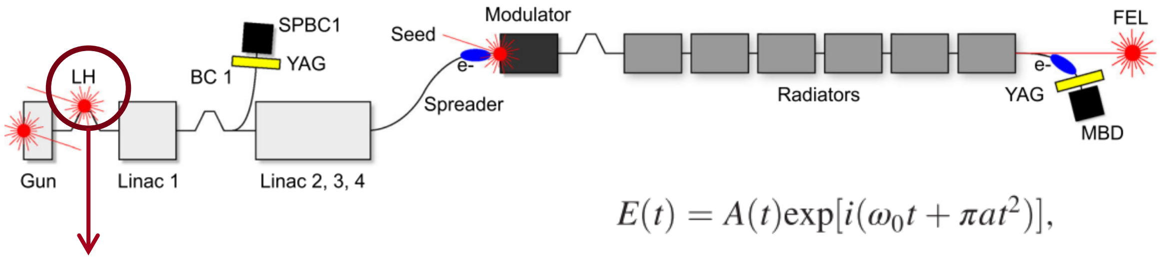
FERMI experiments

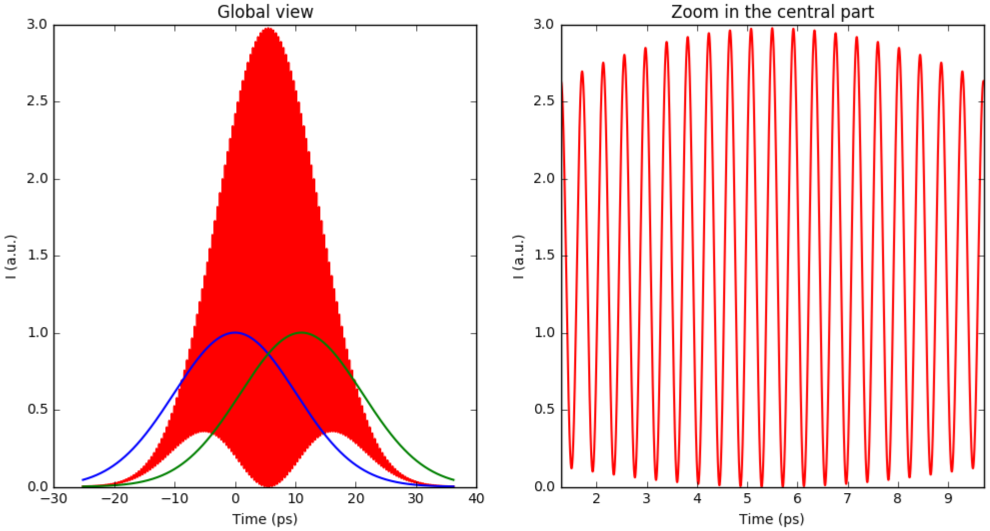


Interference of two chirped pulses

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

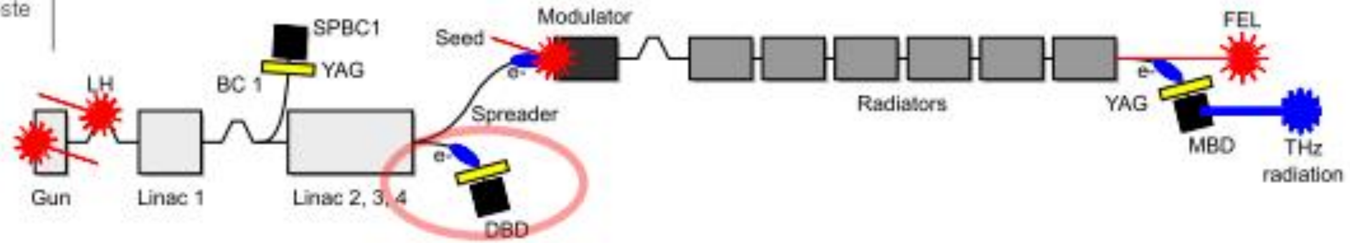
$$\begin{aligned} I(t,\tau) &= |E_1(t) + E_2(t+\tau)|^2 \\ &= A_1(t)^2 + A_2(t+\tau)^2 \\ &\quad + 2A_1(t)A_2(t+\tau)\cos\left(\omega_0\tau + 2\pi\underline{a\tau} t + \pi a \tau^2\right), \end{aligned}$$

Beating frequency/wavelength = 2.37737 THz/126.103 um

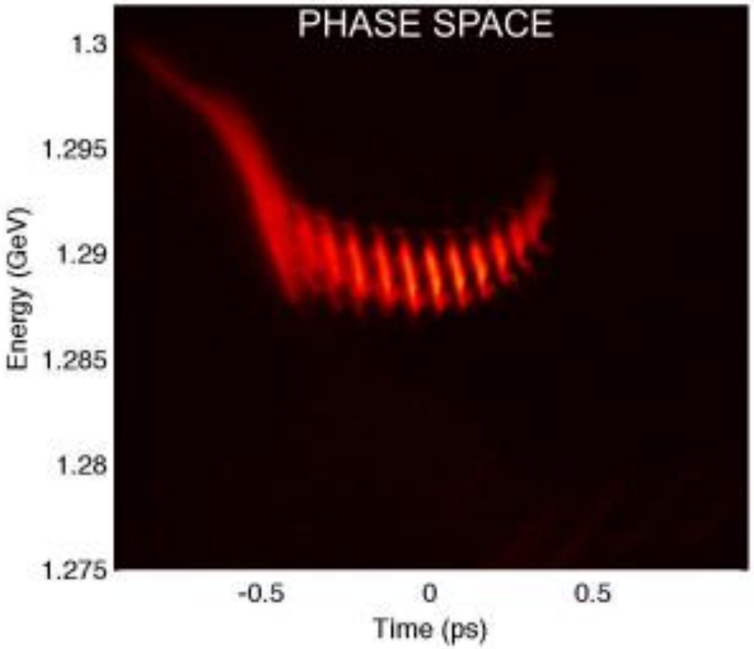


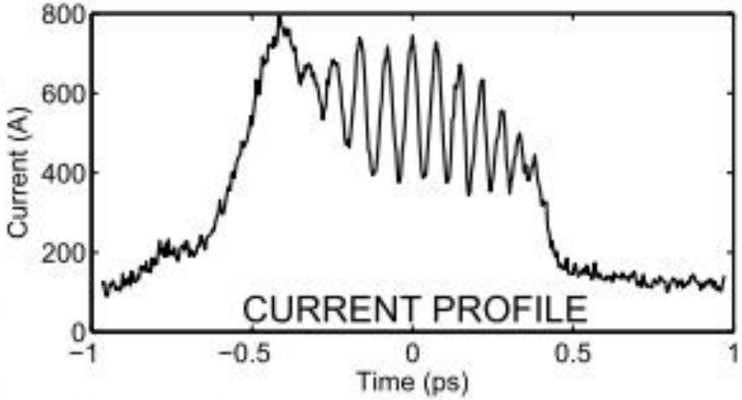
E. Roussel et al., PRL 115, 214801 (2015))

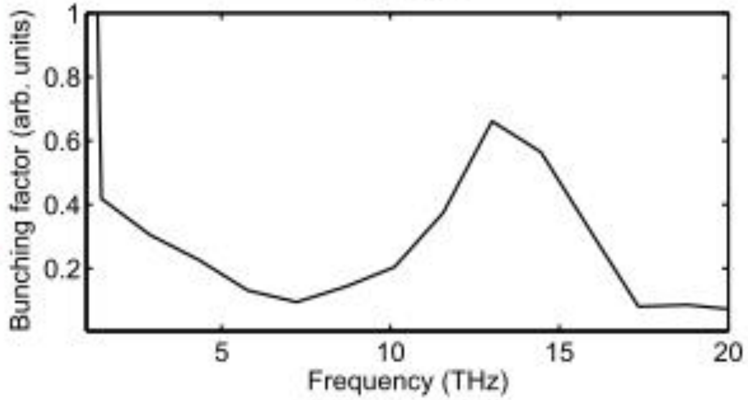
Experimental THz-modulated ebeam



- 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.



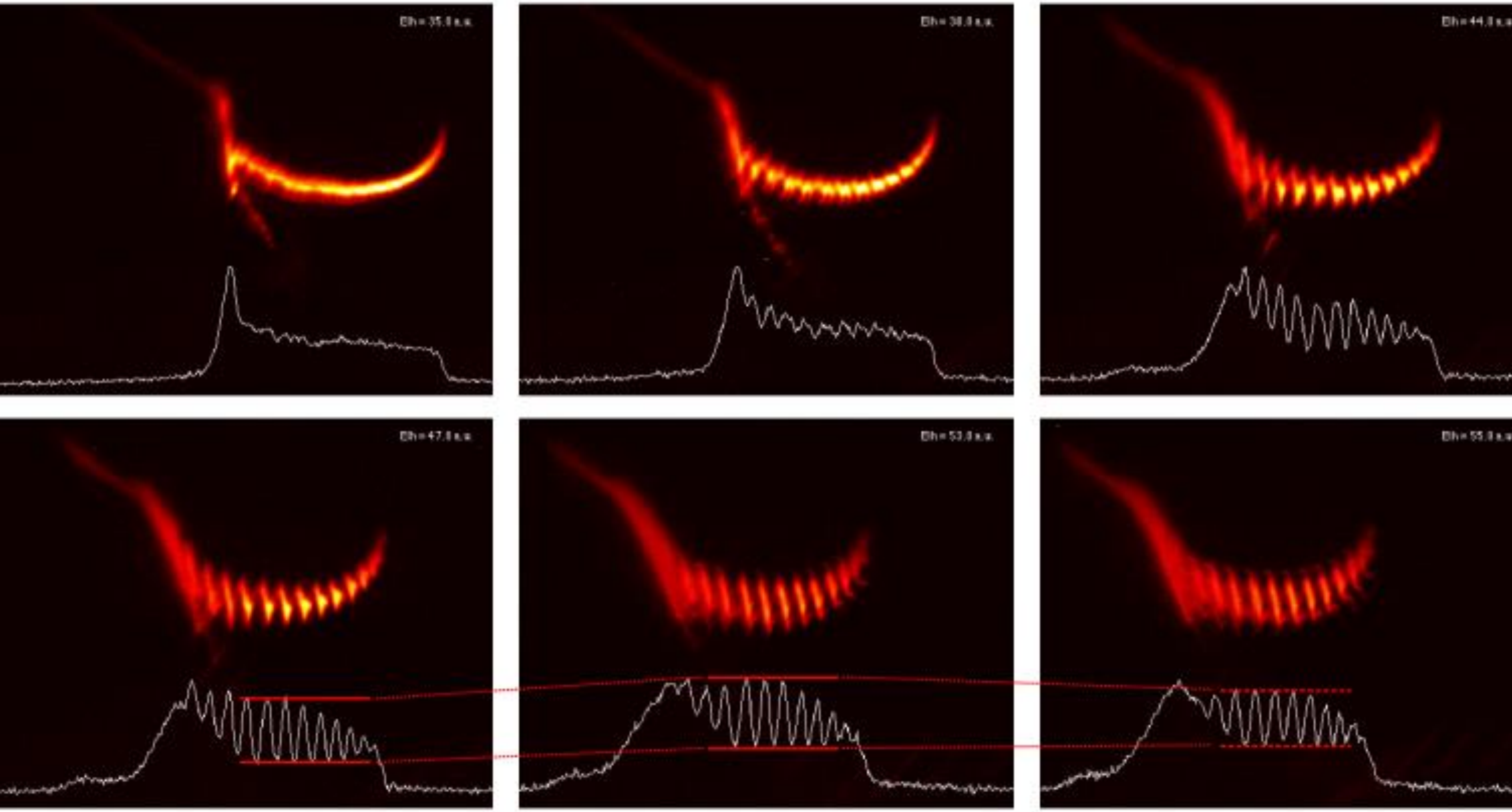




E. Roussel et al., IPAC'17

Optimization of modulation amplitude (bis)

By changing laser power (or by dispersion strength)

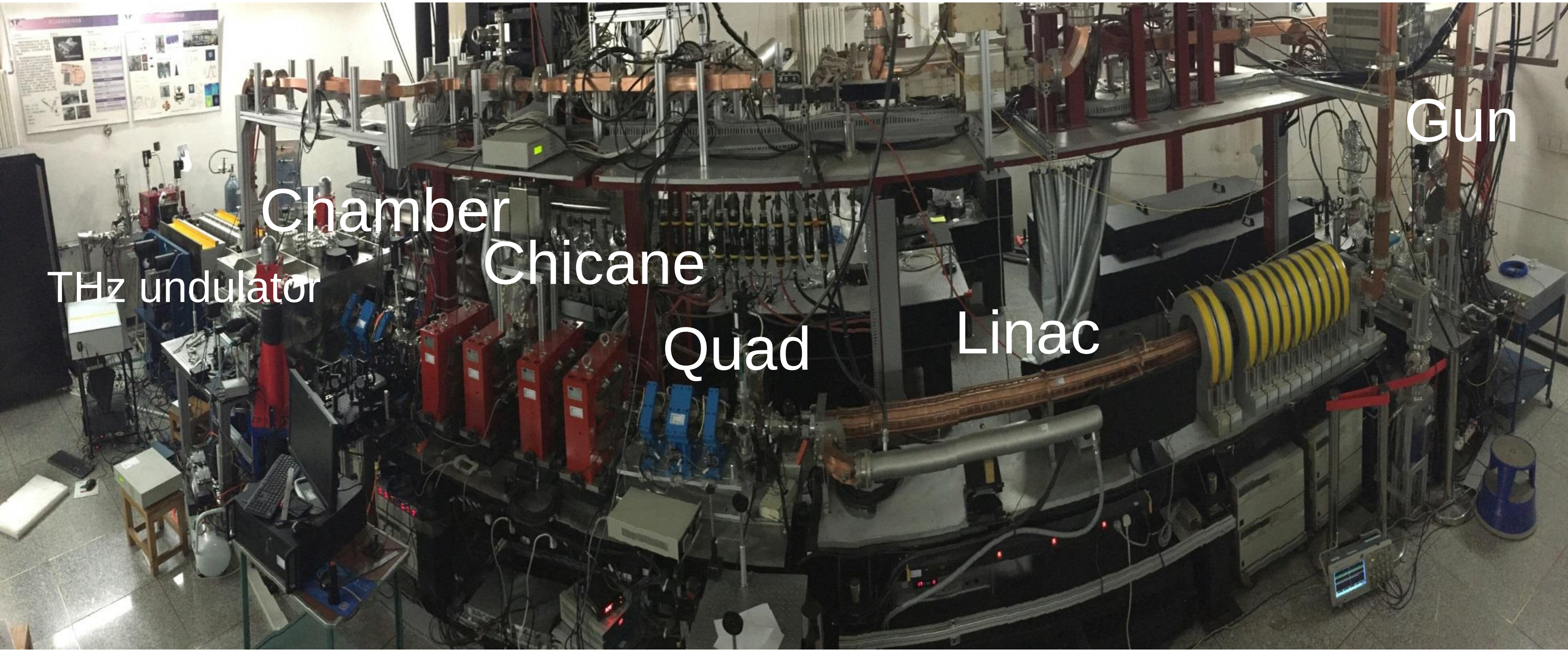


E. Roussel et al., IPAC’17

Proposed Tsinghua University experiment

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

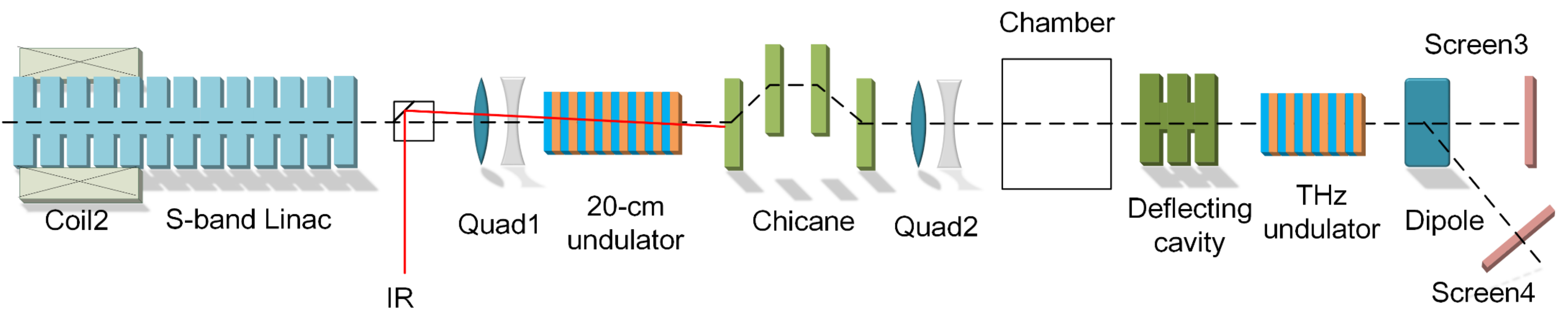
Undulator period 2.5 cm, K=1.3. Third harmonic resonant wavelength is 800 nm

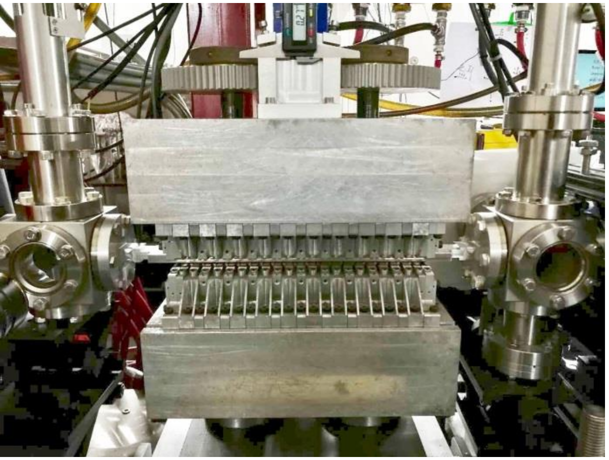


Total beamline length ~10 m, a very compact setup!

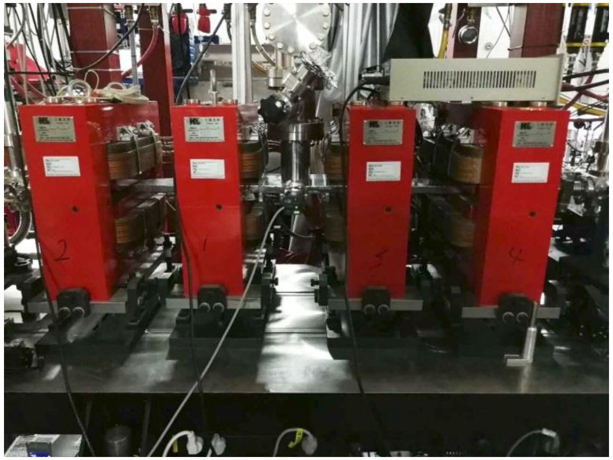
Z. Zhang et al.,

Tsinghua University experimental status

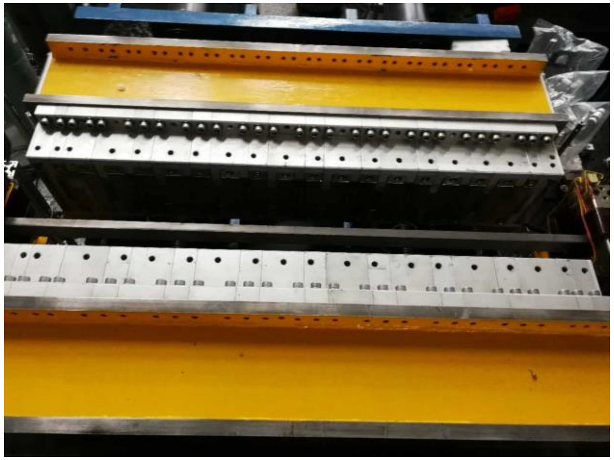




Modulator (works at 3rd harmonic)



chicane



THz undulator

Z. Zhang et al.,

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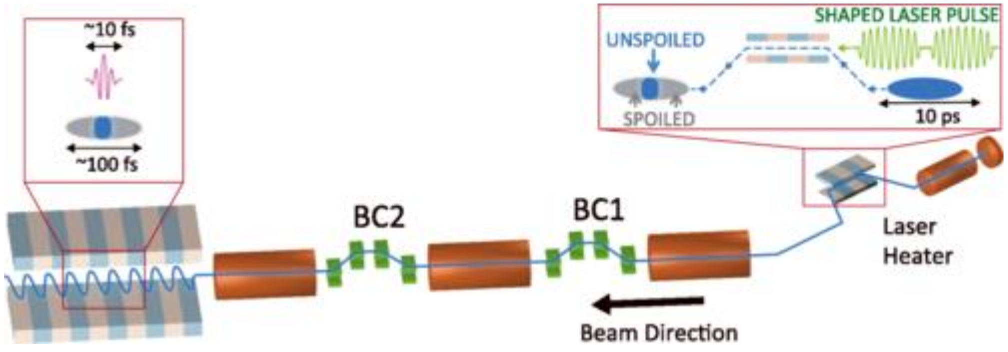
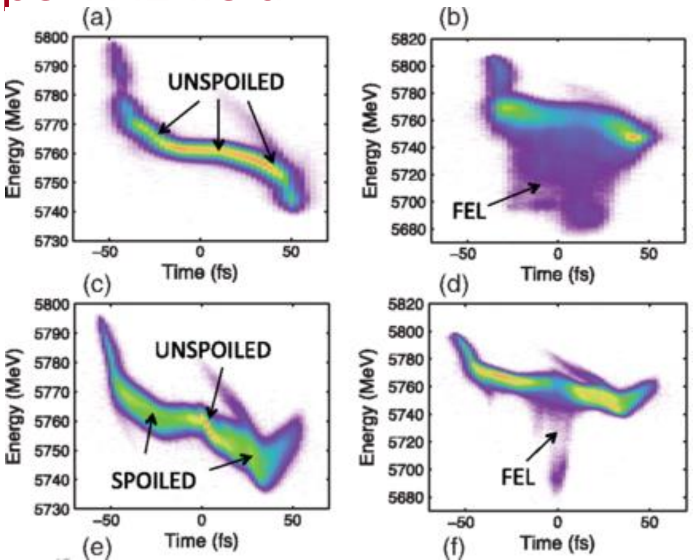
Discussions

- 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.

Acknowledgement

- Thanks Simone and Max for this exciting workshop.

- My Tsinghua University collaborators Zhen Zhang, Lixin Yan, Yingchao Du, Wenhui Huang, and Chuanxiang Tang.

- Many useful discussions with E. Allaria, R. Coffee, B. Garcia, M. Hoffmann, A. Lindenberg, G. Marcus, A. Marinelli, K. Kan, E. Roussel, R. Schoenlein, F. Tavella,…