High-power, narrow-bandwidth Thz generation using laser-electron interaction in a compact accelerator

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Office of Science

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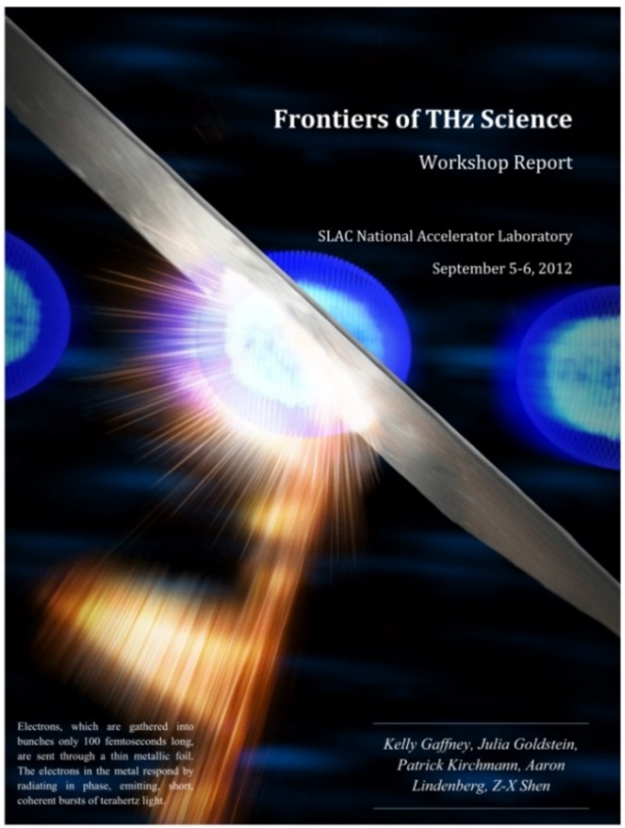
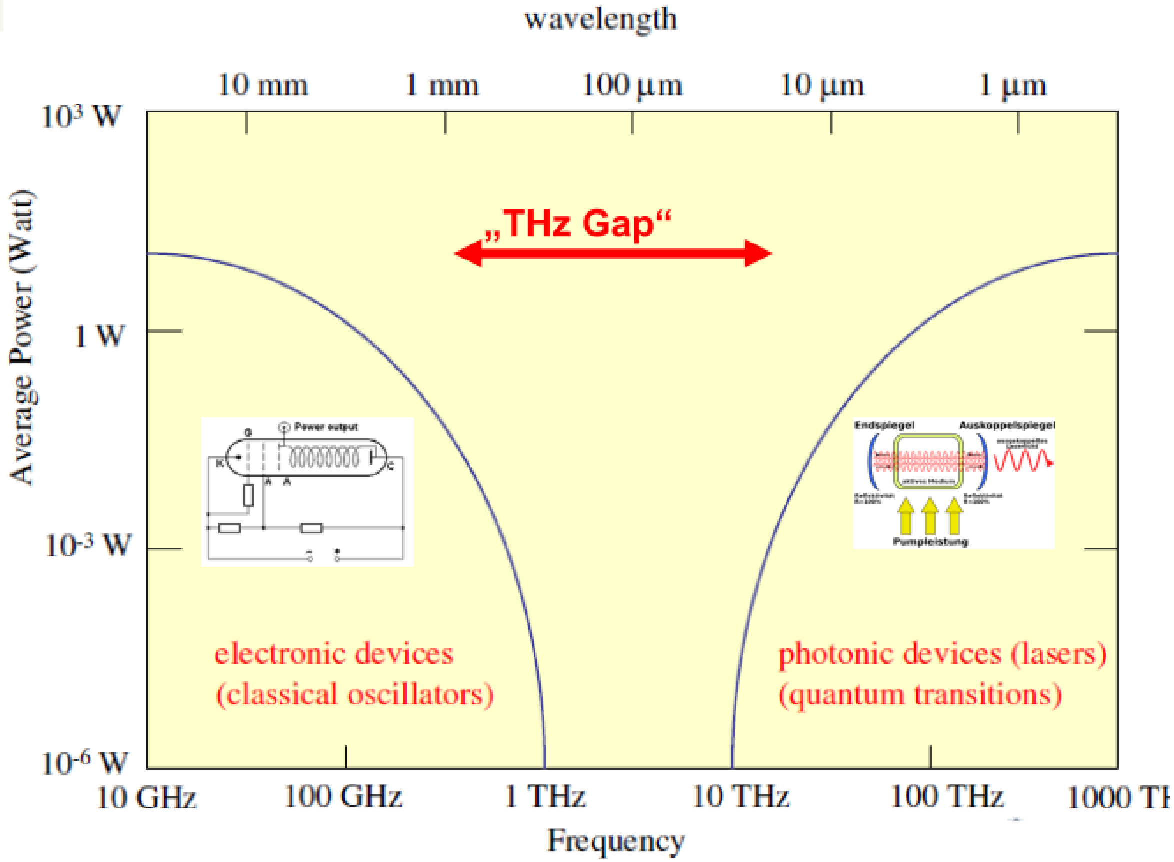
Introduction

- 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



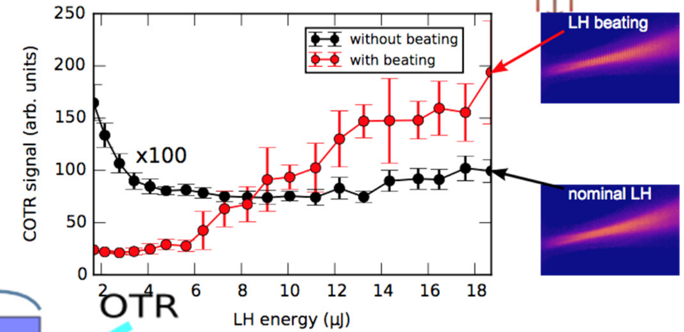
THz gap (1 to 20 THz)

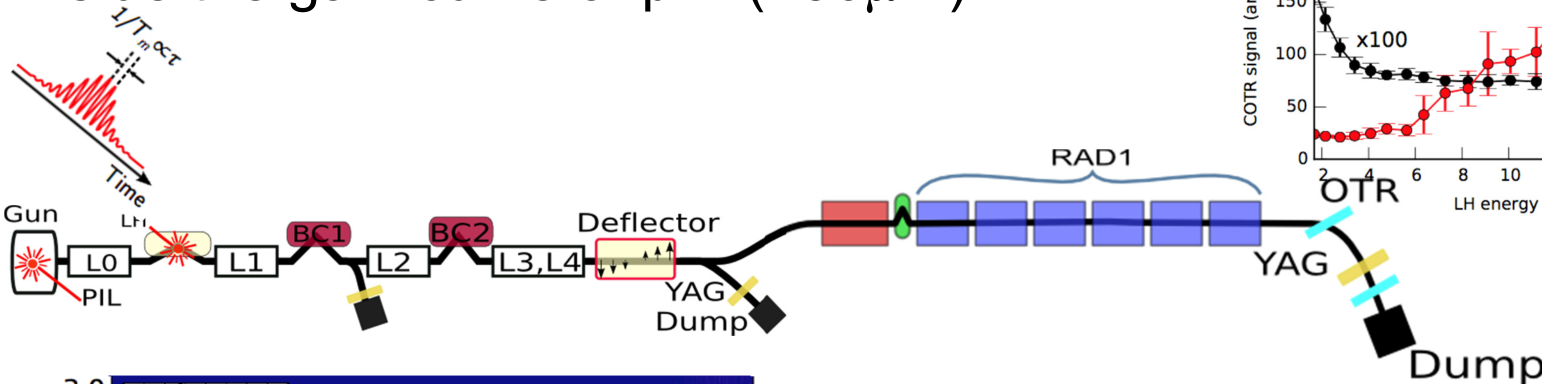


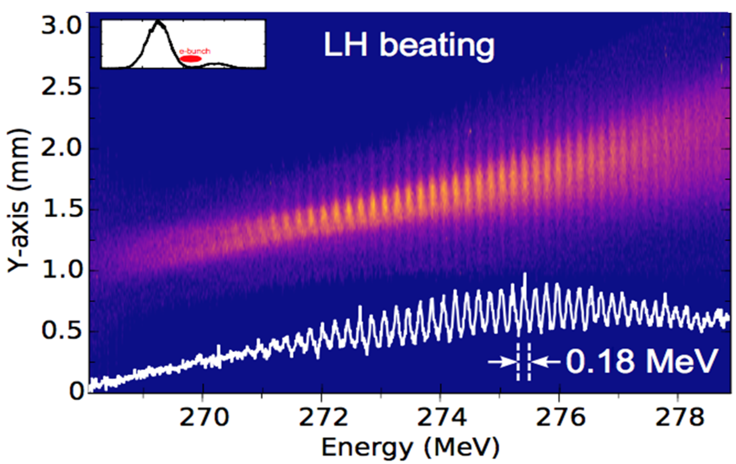
- Laser-based sources have made significant progress, but very challenging to reach above a few THz.
- Accelerator based sources are well suited for high-field, high-frequency, high-rep. rate THz applications

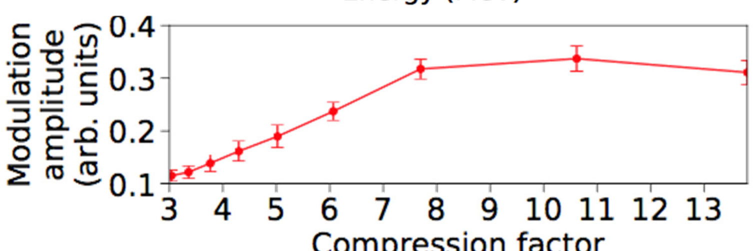
LH beating for seeded µBI

LH laser adjusted for a beating frequency inside the gain curve of µBI (~30µm)









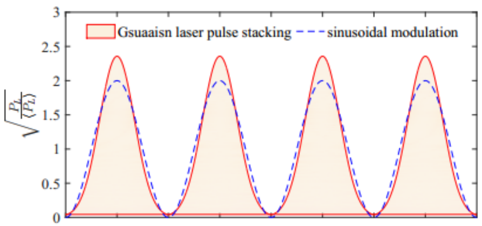
- LH induced **modulation** appears in the e-beam **energy spectrometer** after BC1.
- Spectrum **modulation increases** as the **compression** factor is increasing.
- **COTR** signal measured at the end of the undulator **confirms** that LH induced structures are **transported** to the whole machine.

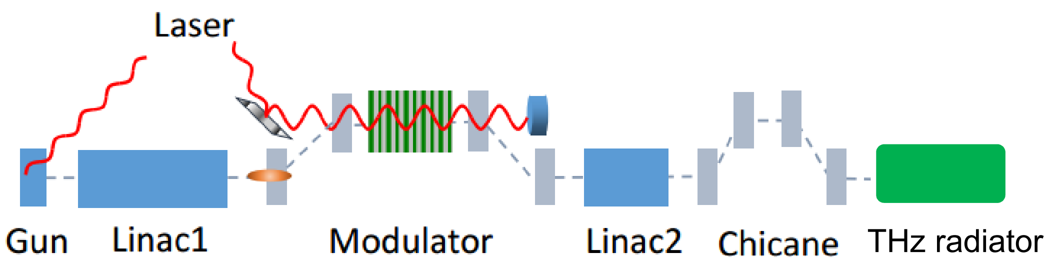
E. Roussel et al., Phys. Rev. Lett. 115, 214801 (2015)

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

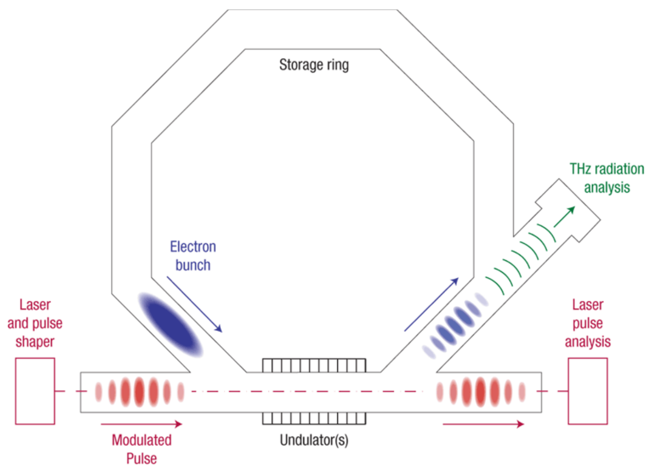
- We propose a method based on the slice energy spread modulation to generate density bunching in a relativistic electron beam (a la **laser heater setup**)

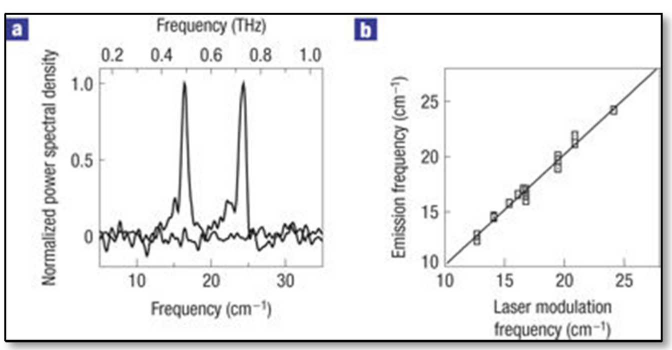
Amplitude-Modulated laser pulse





- Similar method has been used in storage ring THz generation





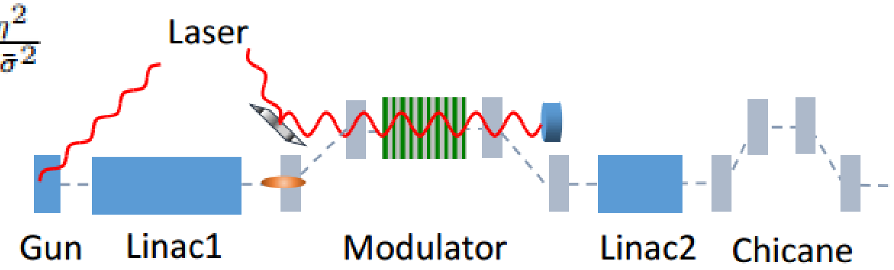
S. Bielawski et al. Nature Physics, 4(5), 390-393 (2008).
C. Evain et al., PRSTAB 13, 090703 (2010).

Theory

- We analyze how energy spread modulation is converted to density modulation
- For a beam with guassian energy spread σ, we find the bunching factor

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

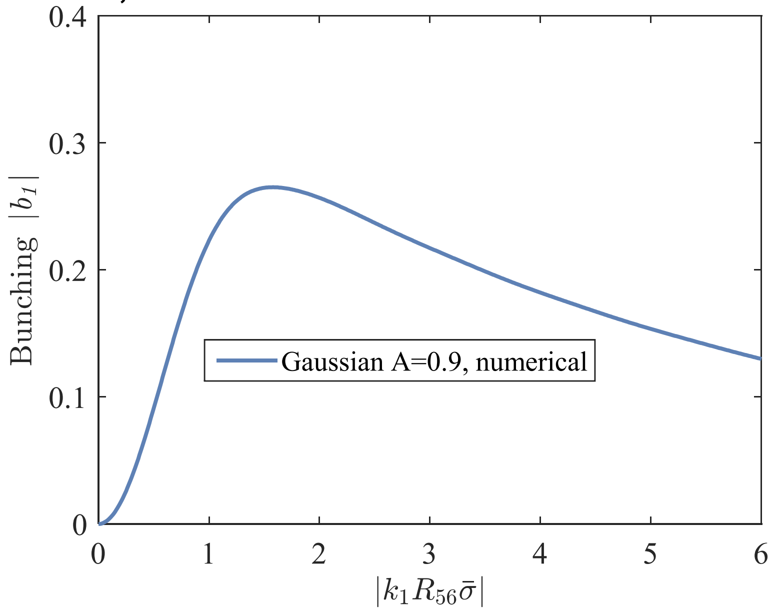
$$k_n = nk_0/(1 + hR_{56})$$



n harmonic #, k_0 initial mod. wavenumber, A is amplitude, h electron energy chirp, R_{56} is the chicane strength

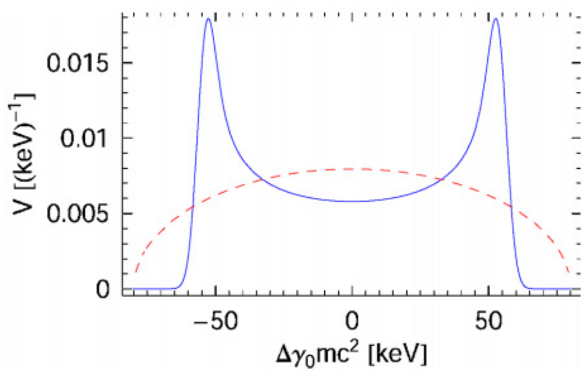
- For the first harmonic n = 1, the optimal chicane setting is

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

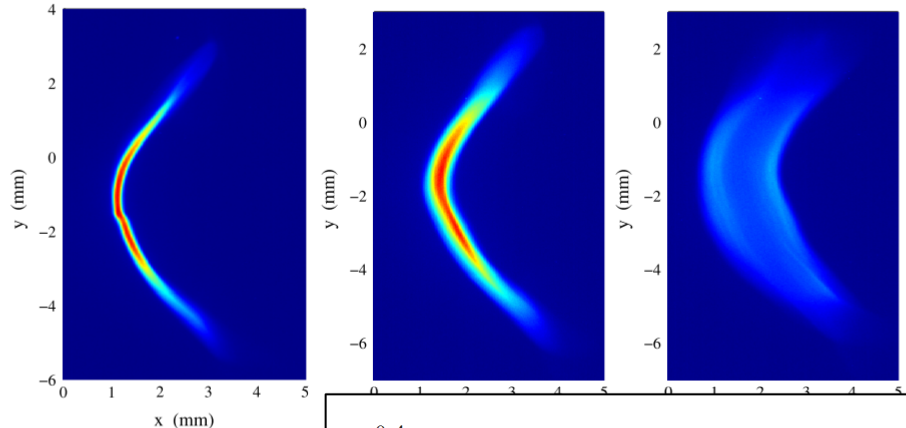


Theory

- The analysis above assume the beam has a Gaussian slice energy distribution, which is not true for the laser electron interaction.
- When the laser waist size in the undulator is much larger than the beam size, the resulting energy profile is a double-horn distribution

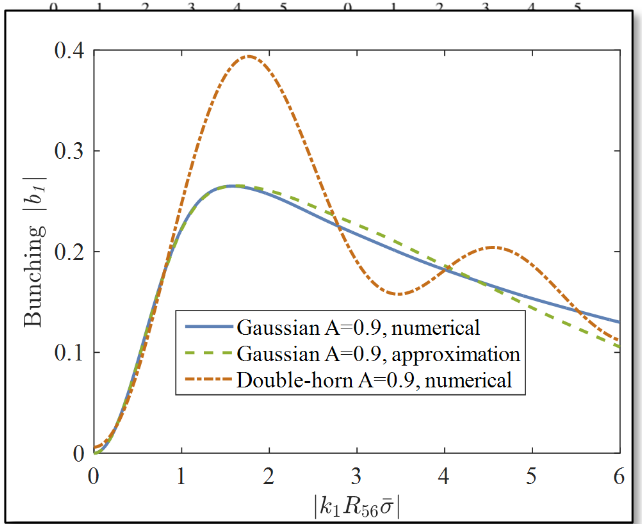


Z. Huang et al., PRST-AB 7, 074401 (2004)
PRST-AB 13, 020703 (2010)



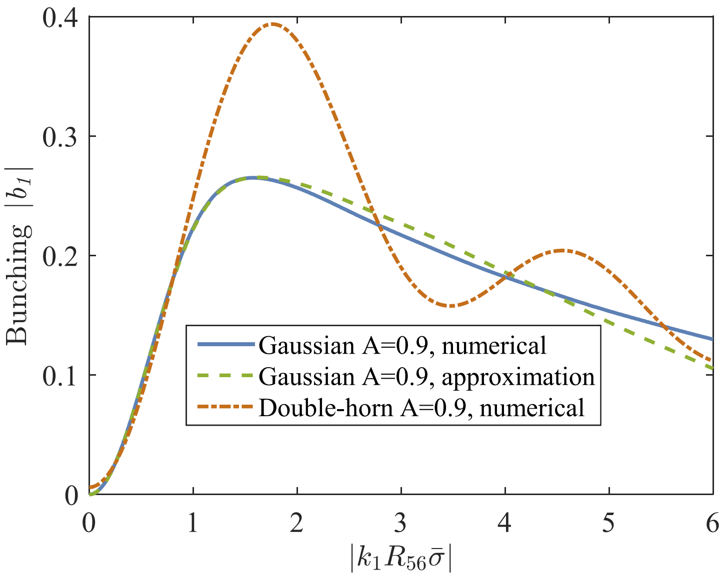
(a) no heating

- Double-horn energy distribution is more effective to increase the bunching factor in our study.
- The maximum bunching factor is up to ~0.4!

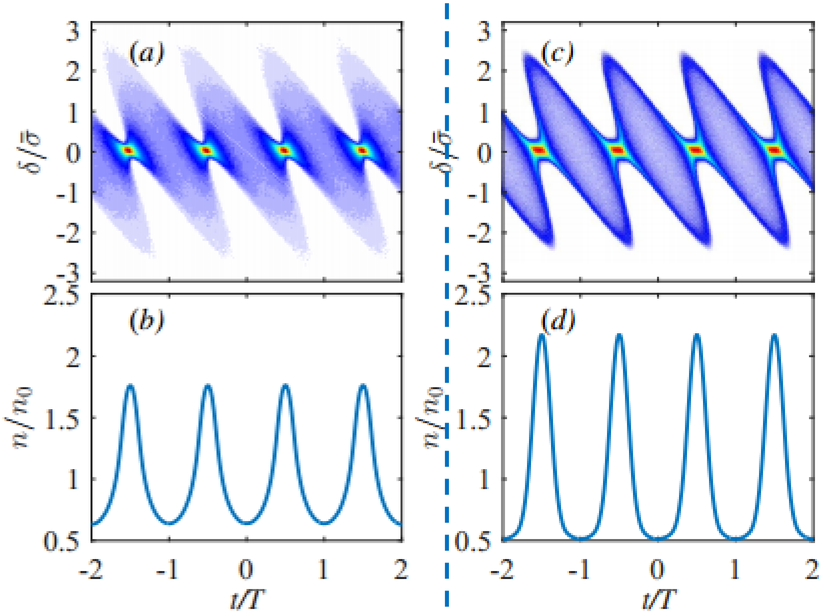


Theory

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



Gaussian | Double-horn



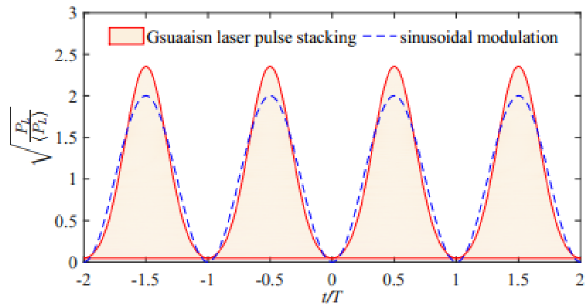
$b_1 \approx 0.27$ | $b_1 \approx 0.4$

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

Simulation setup

- Parameters similar to LCLS or FERMI injector

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



period $T = 0.5\text{ps}\ (0.25\text{ps})$

frequency $f_0 = 2\ \text{THz}\ (4\ \text{THz})$

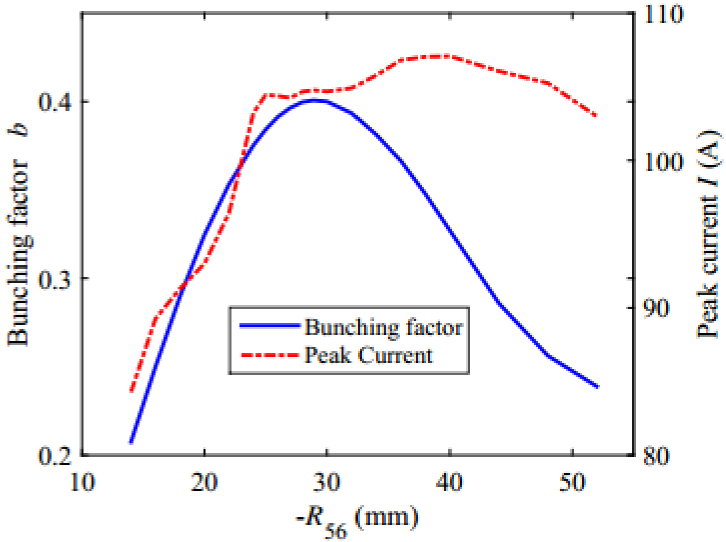
$\sigma_t = 60\text{fs}\ (30\ \text{fs})$

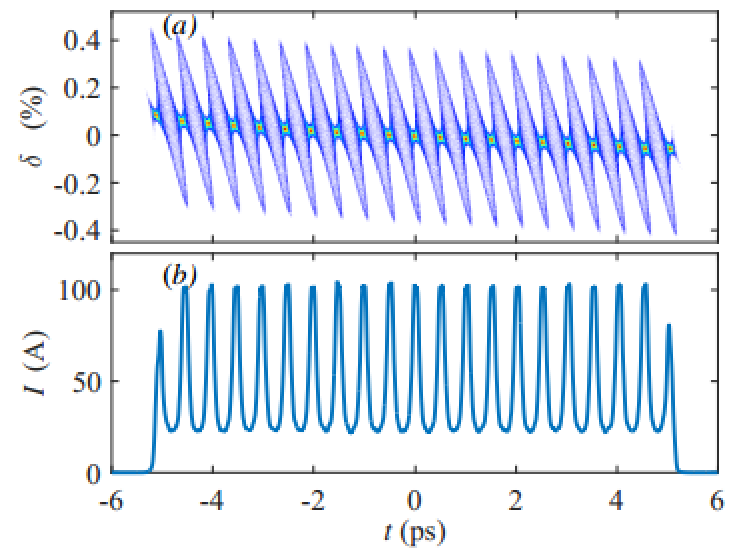
Parameter	Value	Units
Electron beam		
Charge	500	pC
Beam energy	135	MeV
Current Profile	flat-top	/
Bunch length	~ 10	ps
Intrinsic slice energy spread	10^{-4}	/
Norm. emittance	1	mm-mrad
rms beam size	200	μm
Modulator		
Laser wavelength	800	nm
Undulator period	5	cm
Period number	10	/
Laser waist size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

Elegant simulation results

- 2THz initial modulation, scan R_{56}, parameters: $P = 1GW,\ \bar{\sigma} = 190\text{keV}\ (1.4 \times 10^{-3})$





- 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)
- Similar results for 4 THz initial modulation. Electron energy chirp can be used to tune density modulation frequency from 2-6 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.)

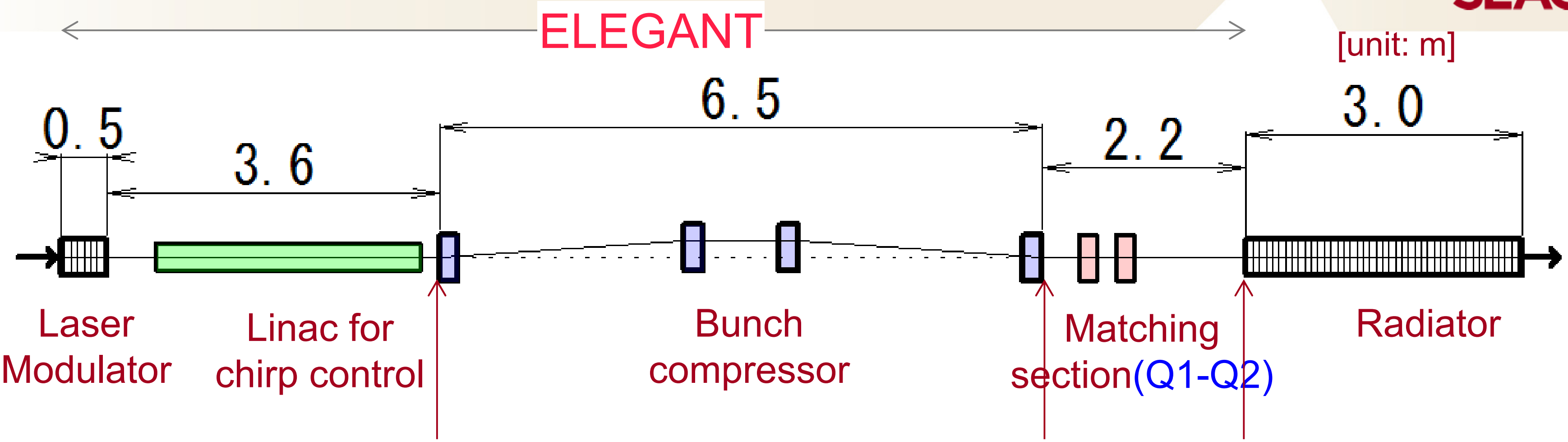
Parameter	Value
E-beam charge	1 nC
Beam energy	50 MeV
RMS beam size	0.2 mm
Bunch length (flattop)	10 ps
Modulator	
Undulator period	2.5 cm
Peak field/ K value	0.56 T /1.29
Undulator length/period	0.5 m / 20
Laser wavelength	800 nm
Laser RMS spot size	0.5 mm
Laser stacking separation	0.5 ps (2 THz)
Laser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

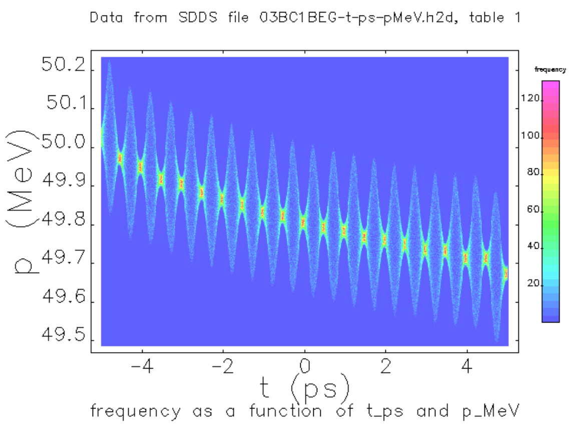
Relative energy modulation

$$\delta = \sqrt{\frac{P_L}{P_0}} \frac{KL_u}{\gamma^2 \sigma_r} [\mathrm{JJ}]_3$$

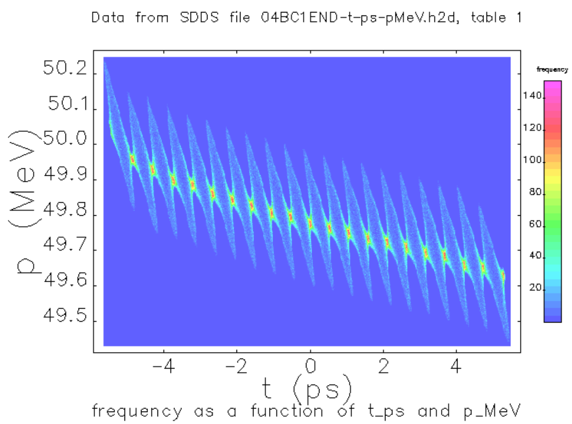
OPCPA laser at high-rep. rate (100 kHz, 100 W average power)

50 MeV simulation results

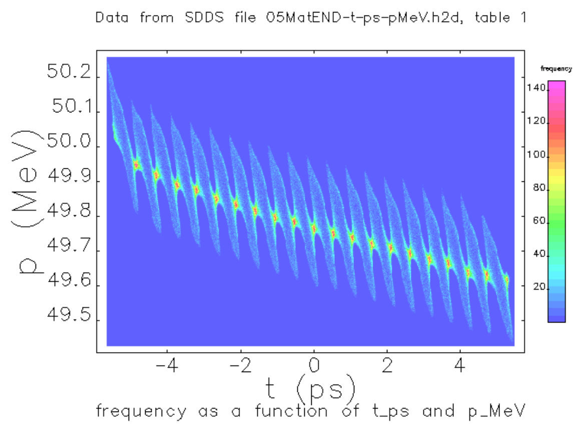




Before bunch compressor (2 THz modulation rms Espread=0.15%)



After bunch compressor (bunching=0.37)



After matching section (bunching=0.34)

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} = 2*b* = 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

Summary

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- Based on the slice energy spread modulation method, the bunching factor can be kept at ~0.4 for a wide frequency range (1-10 THz) and can be tuned by laser amplitude modulation frequency or electron energy chirp.
- THz pulse energy is estimated to be 10-100 μJ for a compact accelerator (40~50 MeV). Further optimization can yield mJ pulse energy.
- THz pulse shape can be controlled by both laser and e-beam techniques (narrowband, chirped, a few cycle pulses, all possible). Rep. rate in the kHz-MHz range is achievable.
- THz modulation experiments are planned at FERMI FEL as well as on a compact accelerator in Tsinghua University.

Acknowledgement

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