清華大學
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ACCELERATOR LABORATORY
of TSINGHUA UNIVERSITY

Tunable Bunch Train and Narrow-Band Terahertz Radiation Generation at Tsinghua University

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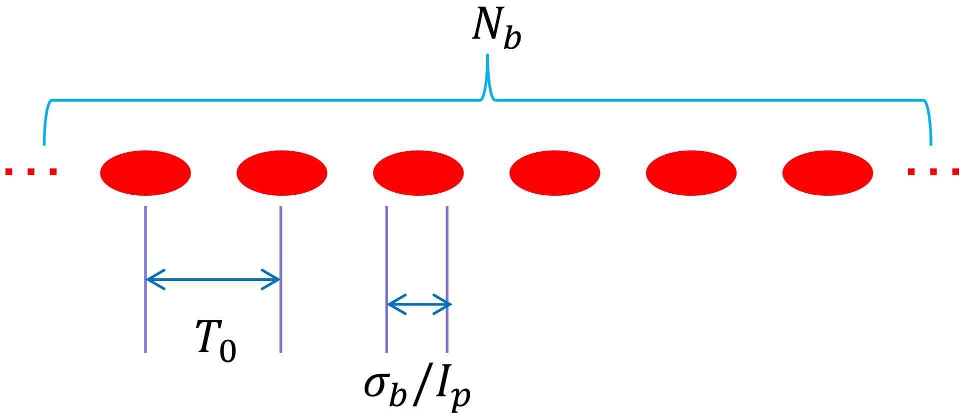
Tsinghua University

05/12/2017

DESY, Zeuthen

Electron Bunch Train

- Bunch train consists of a large number of equally spacing electron microbunches.



$$b(k) = \frac{1}{N_e e c} \int I(z) e^{-ikz} dz$$

Application of Bunch Train

- Narrow-band high-intensity THz radiation

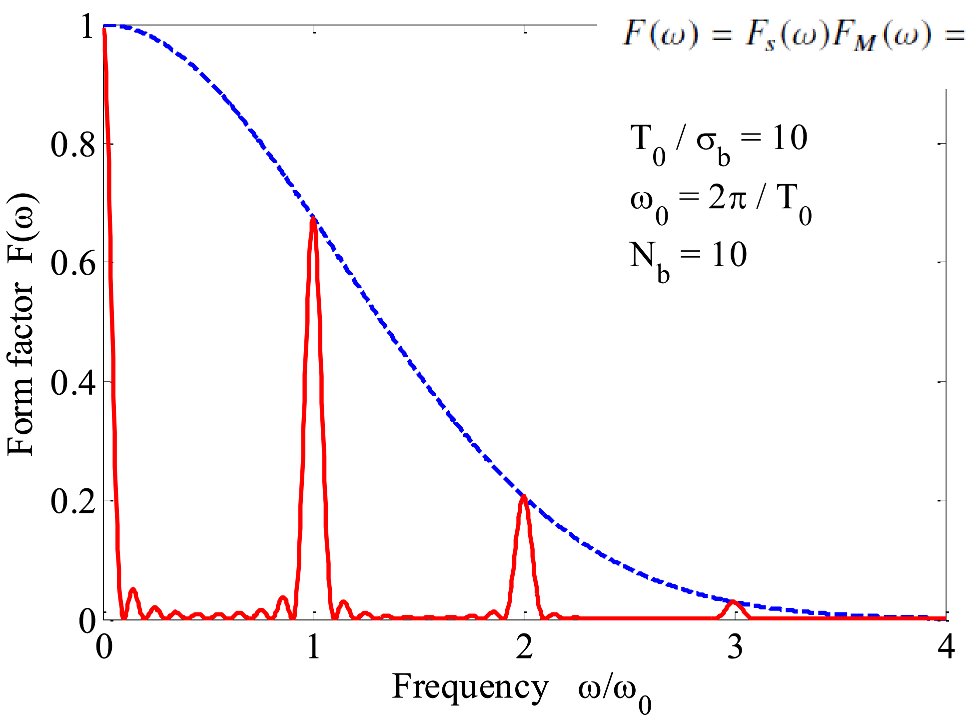
$$\frac{dW}{d\omega} = \frac{dW_1}{d\omega}[N_e + N_e(N_e - 1)F(\omega)]$$

Form factor $$F(\omega) = \left| \int \tilde{I}(t) e^{-i\omega t} dt \right|^2 = |b(\omega)|^2,$$

Single bunch $$F(\omega) = \exp\left(-\sigma_t^2 \omega^2\right)$$

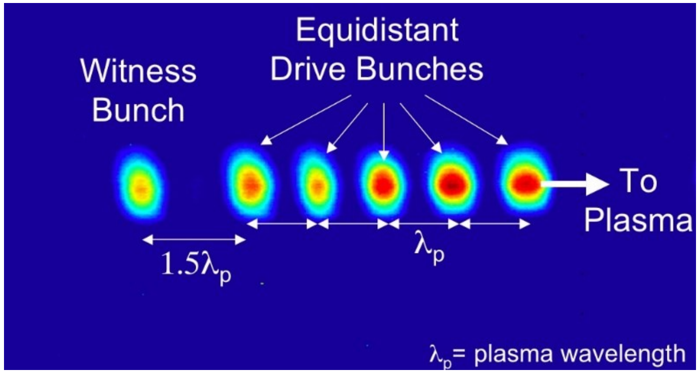
Bunch train

$$F(\omega) = F_s(\omega) F_M(\omega) = \exp\left(-\sigma_t^2 \omega^2\right) \left| \frac{\sin(M\pi\omega/\omega_0)}{M \sin(\pi\omega/\omega_0)} \right|^2$$



Application of Bunch Train

- Resonant excitation of plasma/dielectric wakefields.
- The plasma density is matched to the bunch train period for maximum wakefields acceleration or maximum transformer ratio in plasma wakefield acceleration.



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

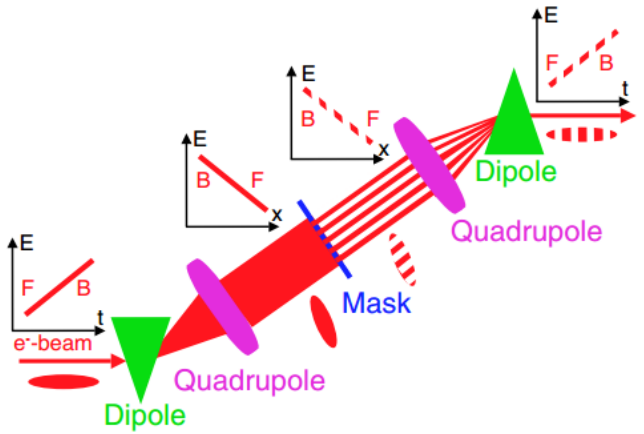
C. Jing et al., PRL 98, 144801 (2007)

- Requirements for bunch train:

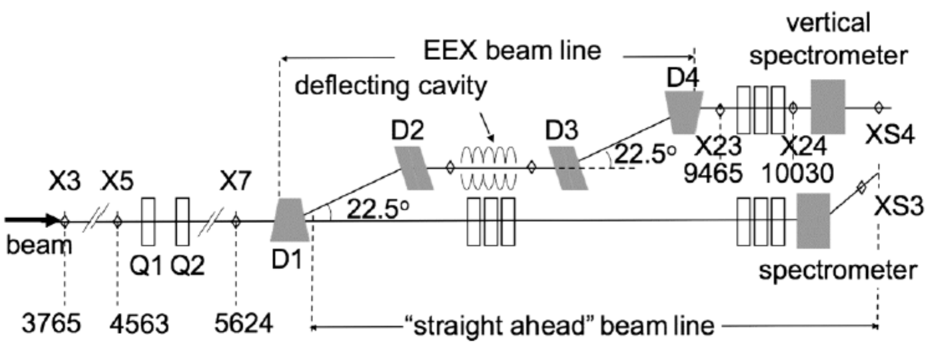
  Tunable bunching period (T_0), high bunching factor ($b(k)$), high peak current (I_p)

Bunch Train Generation

- Exchange transverse modulation to longitudinal distribution

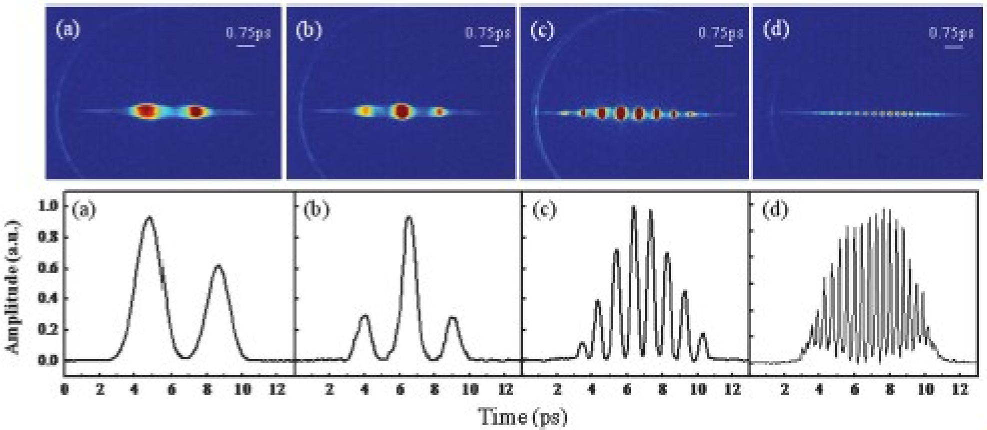


P. Muggli et al., PRL 101, 054801 (2008)



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

- Generate the beam modulation directly at the cathode with drive laser shaping



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

M. Boscolo et al., NIMA 577, 409 (2007)

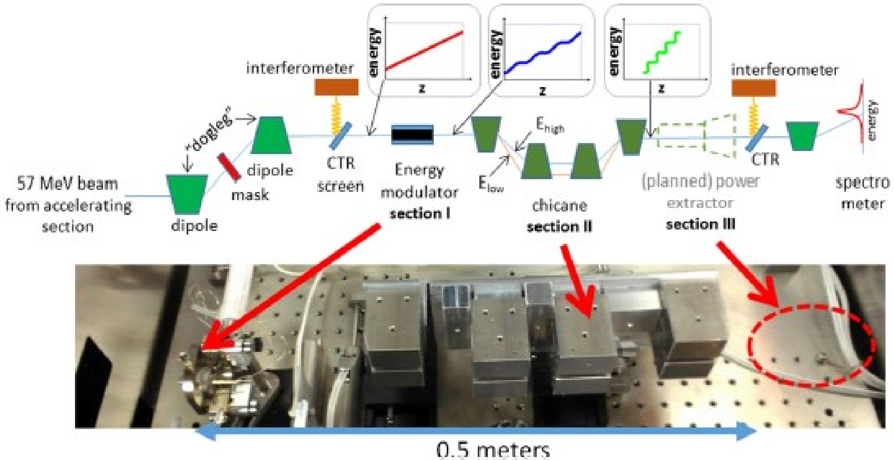
Y. Li et al., APL 92, 014101 (2008)

J. G. Neumann et al., JAP 105, 053304 (2009)

L. X. Yan, et al., IPAC 1st, Kyoto, Japan(2010)

Bunch Train Generation

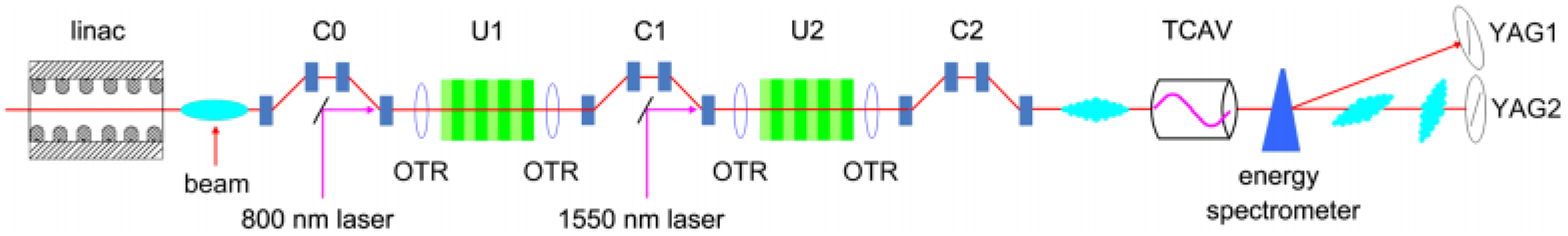
- Exchange wake-induced energy modulation to density bunching



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

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

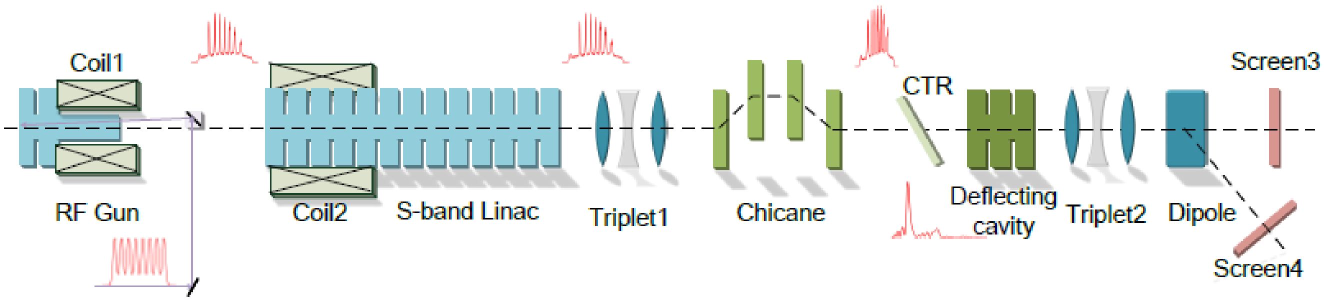
- Frequency beating or difference of the laser-induced density bunching



D. Xiang et al., PRST-AB 12, 080701 (2009) *M. Dunning et al., PRL 109, 074801 (2009)*

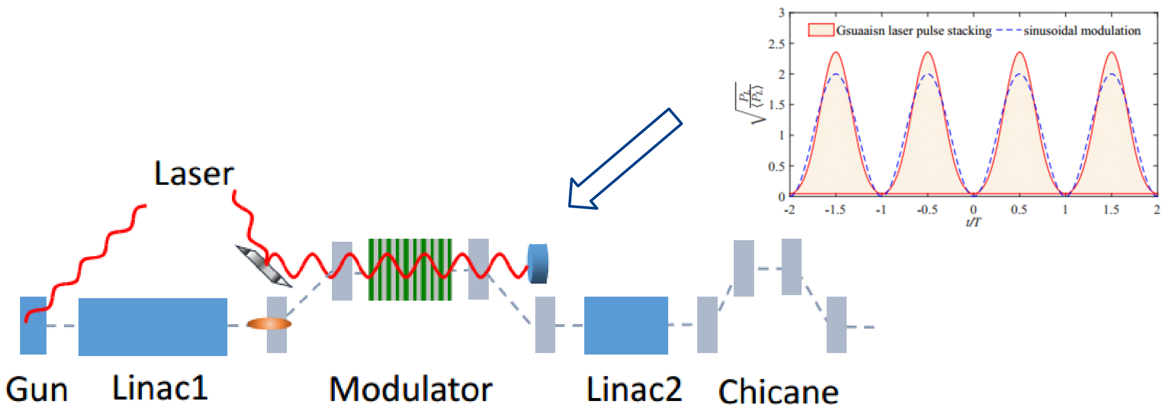
Two new methods

- In this talk, two new methods will be discussed to improve the quality of bunch train.
- The first method is based on the scheme of nonlinear longitudinal space charge oscillation to produce high-intensity electron bunch train.



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

- The second method is using slice energy spread modulation from the interaction with laser to obtain density bunching in electron beam.



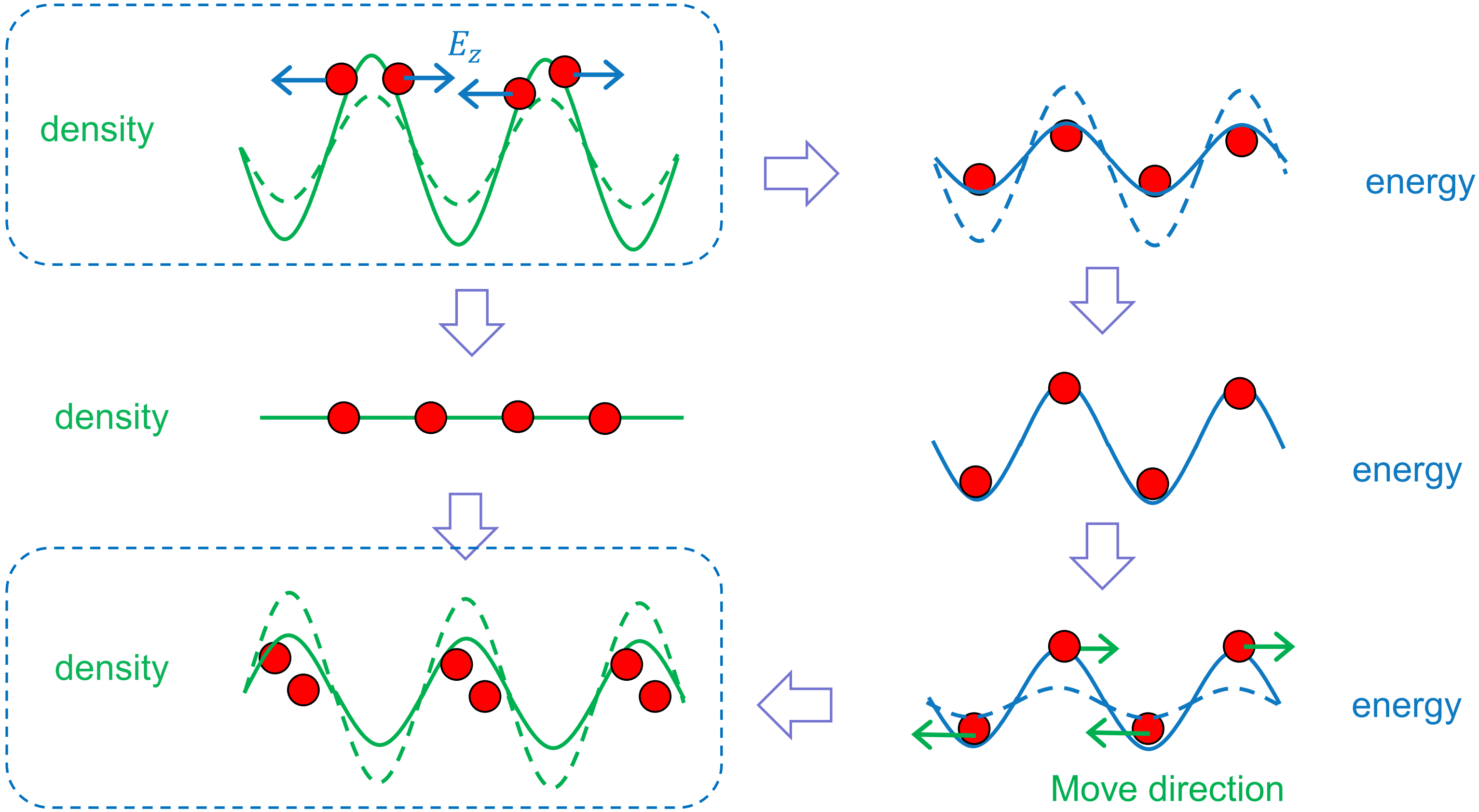
Z. Zhang et al., PRAB 20, 050701 (2017)

Tunable High-Intensity Bunch Train Generation based on Nonlinear Longitudinal Space Charge Oscillation

Zhen Zhang, Lixin Yan, Yingchao Du et al.

Space charge oscillation

- Space charge force dominants the evolution of the beam with initial modulation.
- Plasma oscillation predicts the periodic evolution between density and energy modulation.



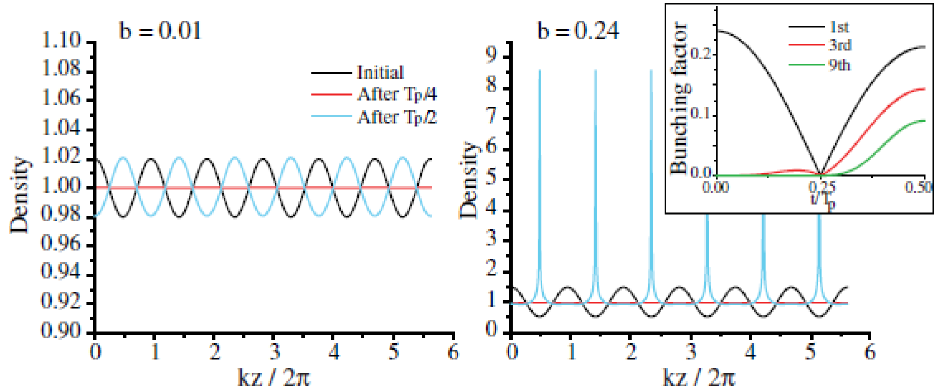
- To maintain the initial modulation, the oscillation should be close to zero or half oscillation period.

Nonlinear space charge oscillation

- The density bunching re-appears after half oscillation period, and can be enhanced if nonlinear components become significant. *P. Musumeci et al., PRL 106, 184801 (2011)*

- Use 1D fluid model to solve the longitudinal space charge oscillation

$$n = n_0\left(1 + 2b\cos(kz)\right)$$



$$n(z,t) = n_0\left(1 + 2b\cos(kz)\cos(\omega_p t)\right) \qquad n_{max}(\omega_p t = \pi) \approx \frac{1-2b}{1-4b} n_0$$

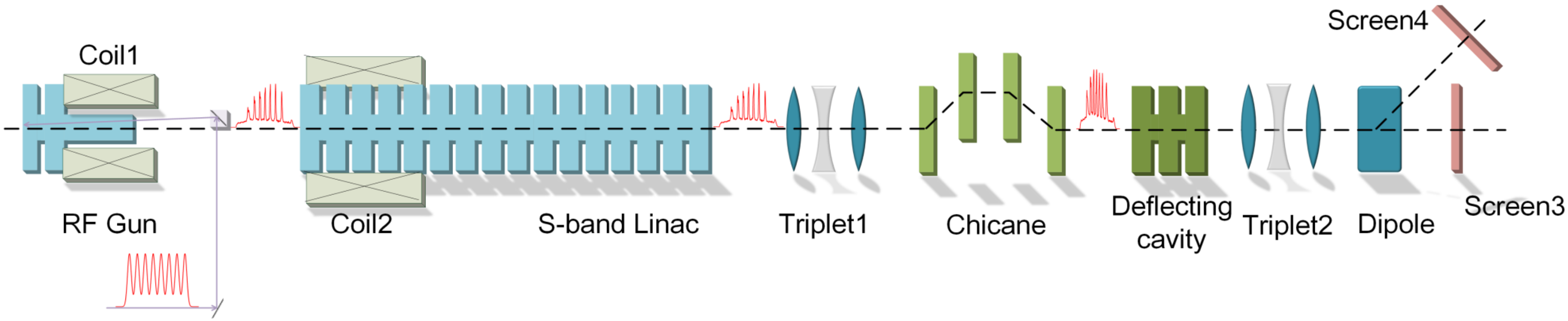
- Wave breaking happens at the nonlinear space charge oscillation.

- The method is proposed to generate high-intensity electron bunch train.

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

Experiment beam line

- The experiment was carried out at Tsinghua Thomson scattering X-ray source.



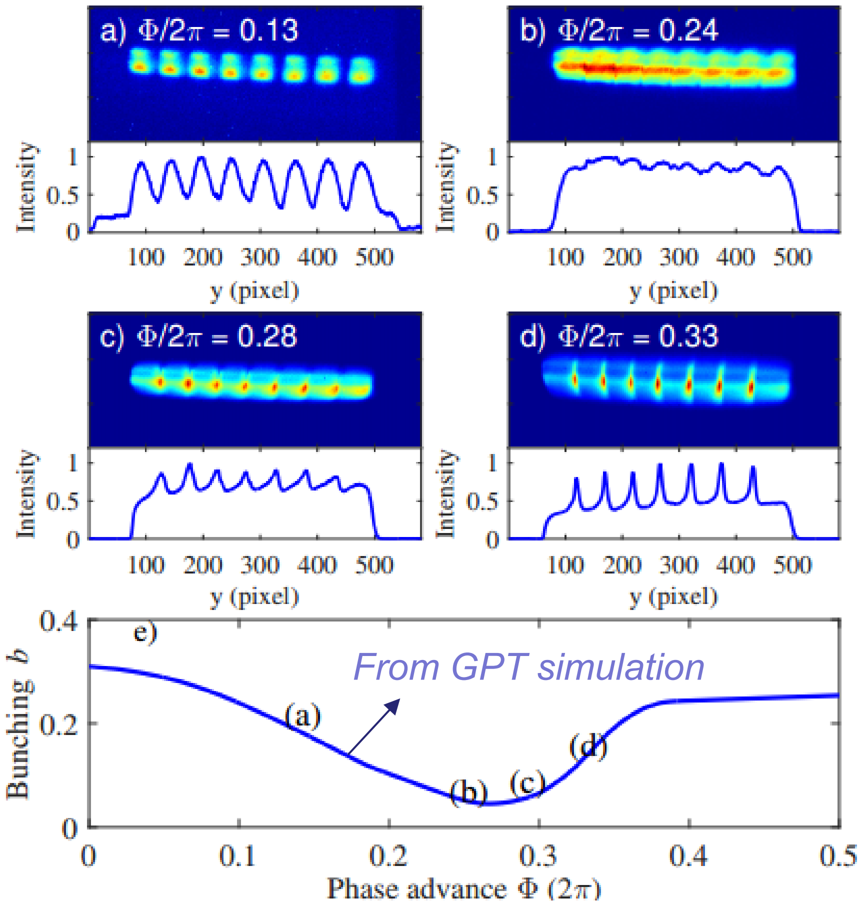
- Key parameters: *Initial density modulation* and *oscillation phase advance*

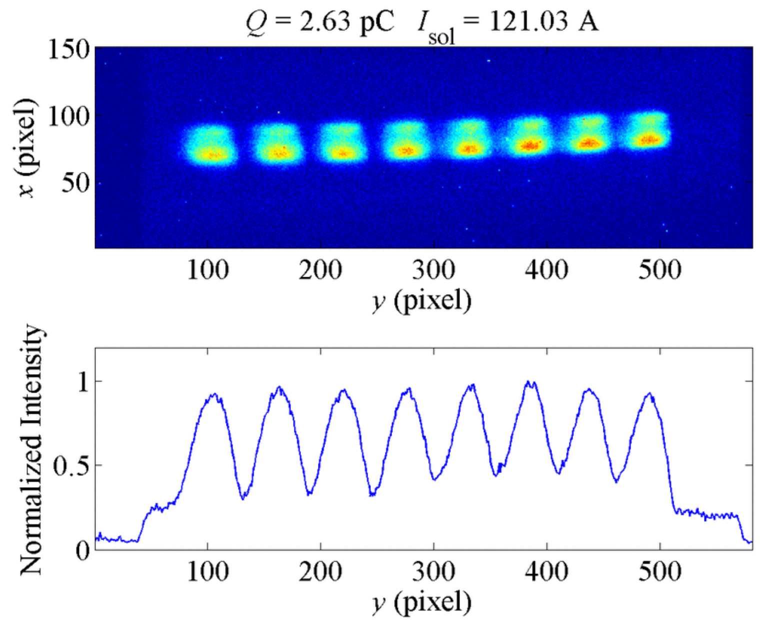
- *Initial density modulation* is generated by laser pulse stacking with 3 α-BBO crystals with fixed separation 1ps.

- *Oscillation phase advance* is controlled by beam charge, laser spot size at the cathode and solenoid focusing.

Oscillation evolution

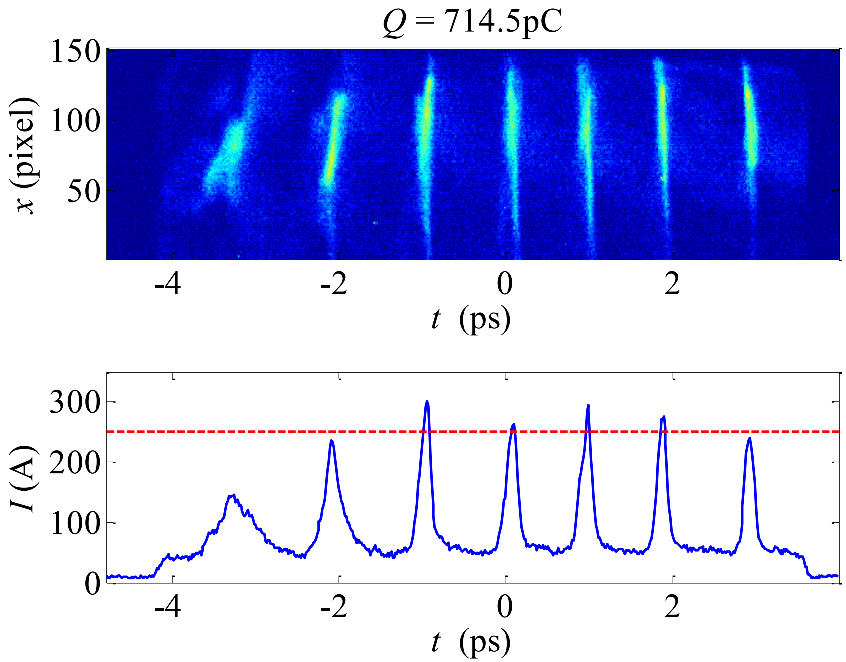
- Start from low charge and weak solenoid focus



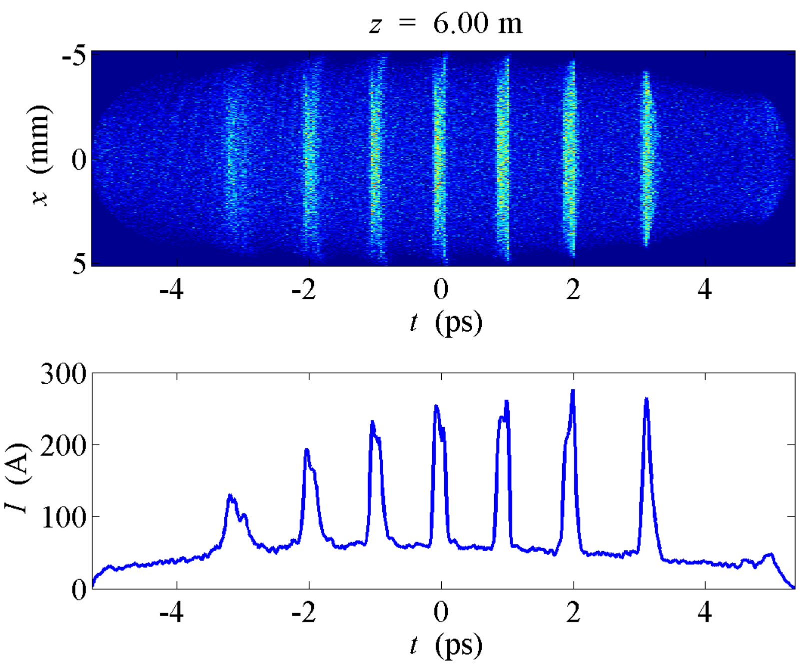


Oscillation evolution

- Measurements of high-intensity electron bunch train



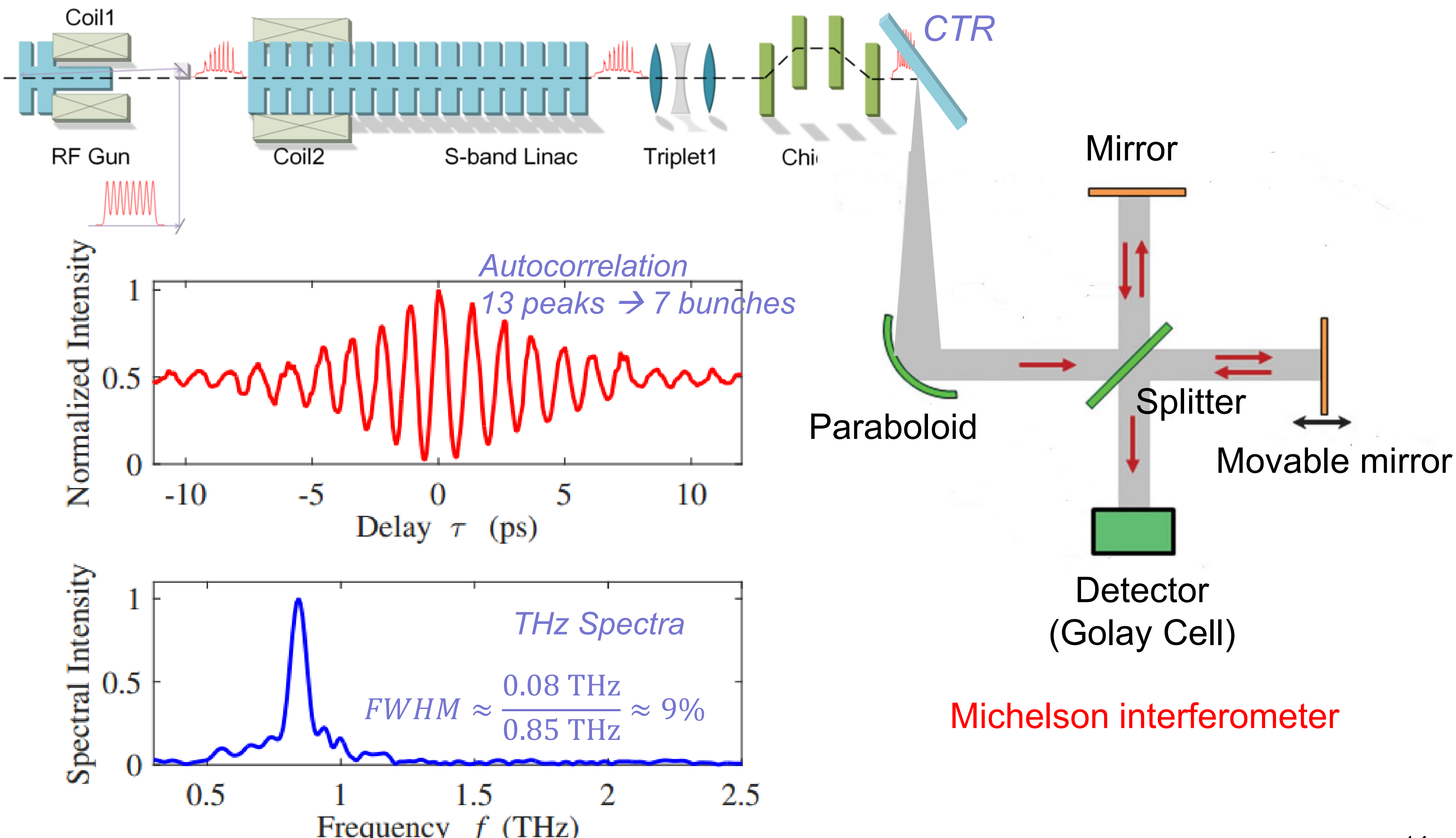
Experiment measurement



GPT simulation

THz Autocorrelation Measurement

- The electron bunch trains are used to generate THz radiation by CTR, and the spectra are solved through the autocorrelation by the interferometer.

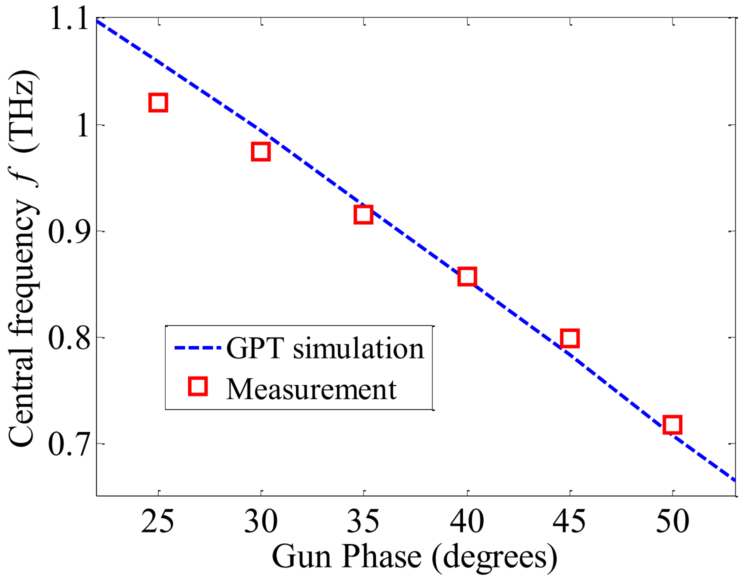


Michelson interferometer

Tunable Bunch Train Spacing

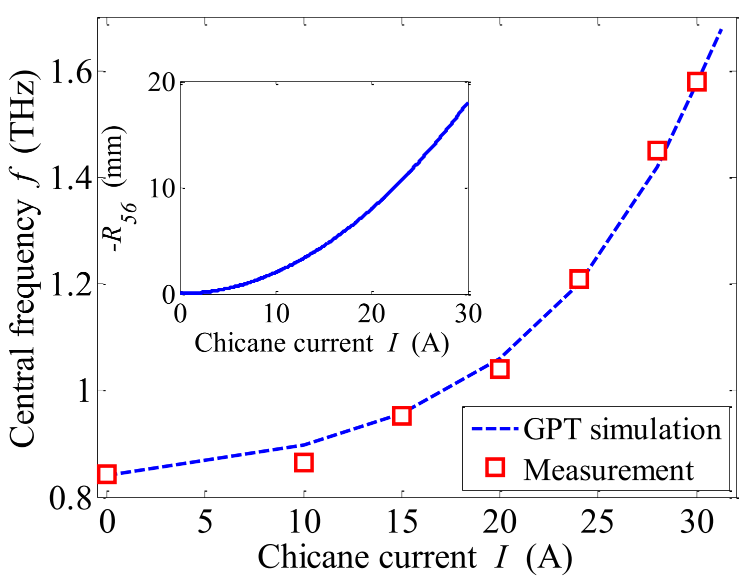
- The bunch train spacing can be controlled by the velocity bunching of the RF gun and the accelerator, or by the magnetic compression.

Velocity bunching
Gun



- Gun max. gradient ~106MV/m
- Accelerator phase 0 (max. acceleration)
- Chicane off
- Change the launching phase

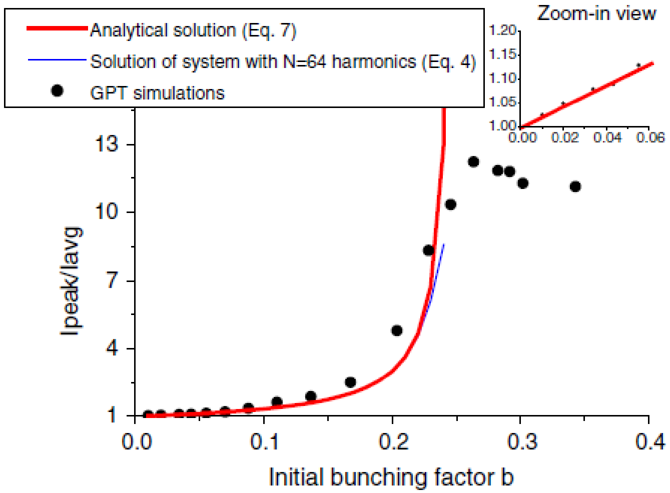
Magnetic compression
Chicane

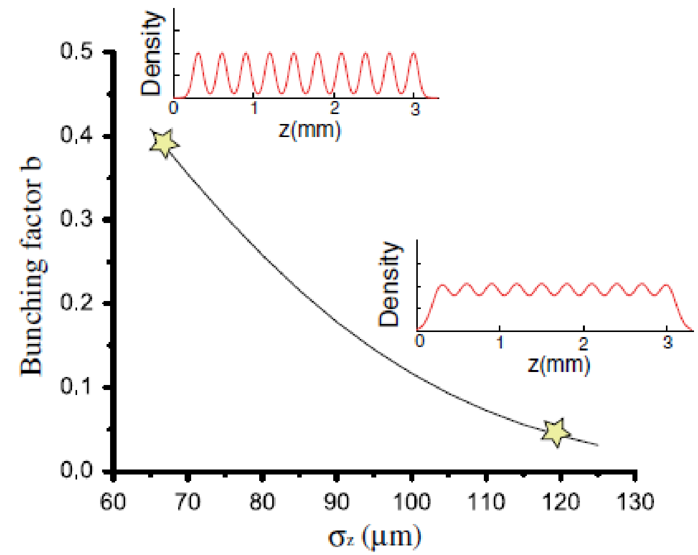


- Gun max. gradient ~106 MV/m
- Gun phase 45 degreeS
- Accelerator phase -37 degreeS
- Change the Chicane current

Optimization of THz Radiation Energy

- Simulation studies have shown that there is a optimal initial bunching factor that can yield largest peak current and largest THz energy.
- For a fixed 1-ps initial spacing, the initial bunching factor can be controlled by the single UV pulse width.



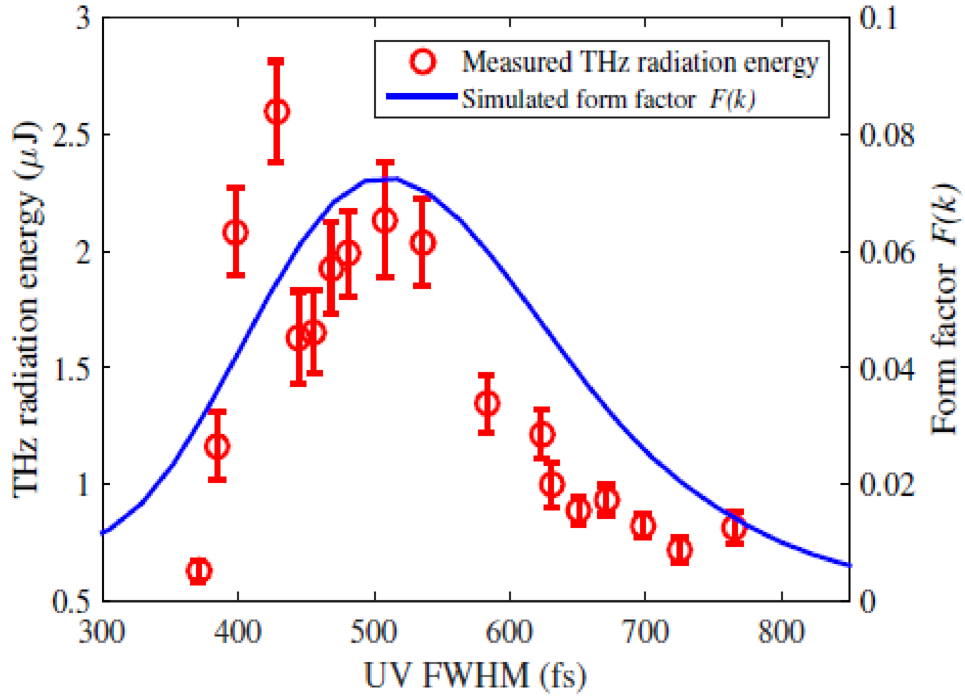


P. Musumeci et al., PRST-AB 16, 100701 (2013)

- The UV pulse length was varied by tuning the IR compression grating before third-harmonics generation process and measured by cross-correlation technique with an IR laser.

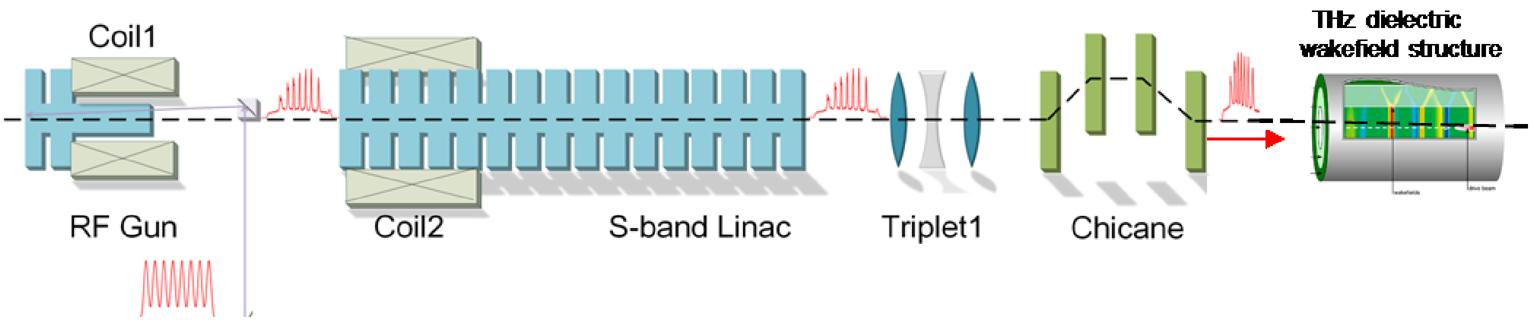
THz Radiation Energy

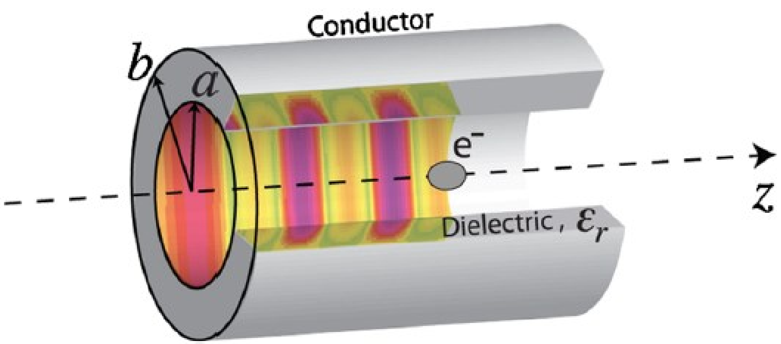
- THz radiation energy with different initial UV pulse length (initial density modulation).

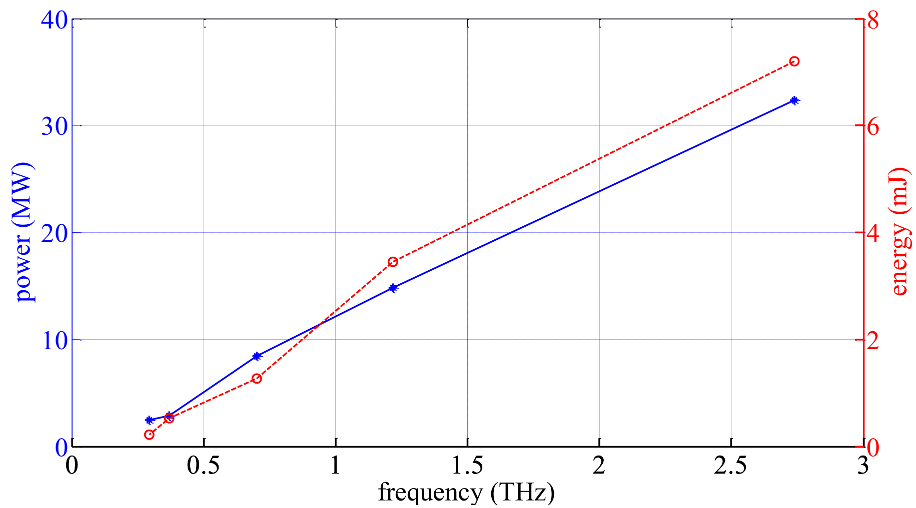


THz from Dielectric Wakefield Structures

- mJ level THz radiation can be produced by the electron bunch train based on dielectric wakefield tubes.







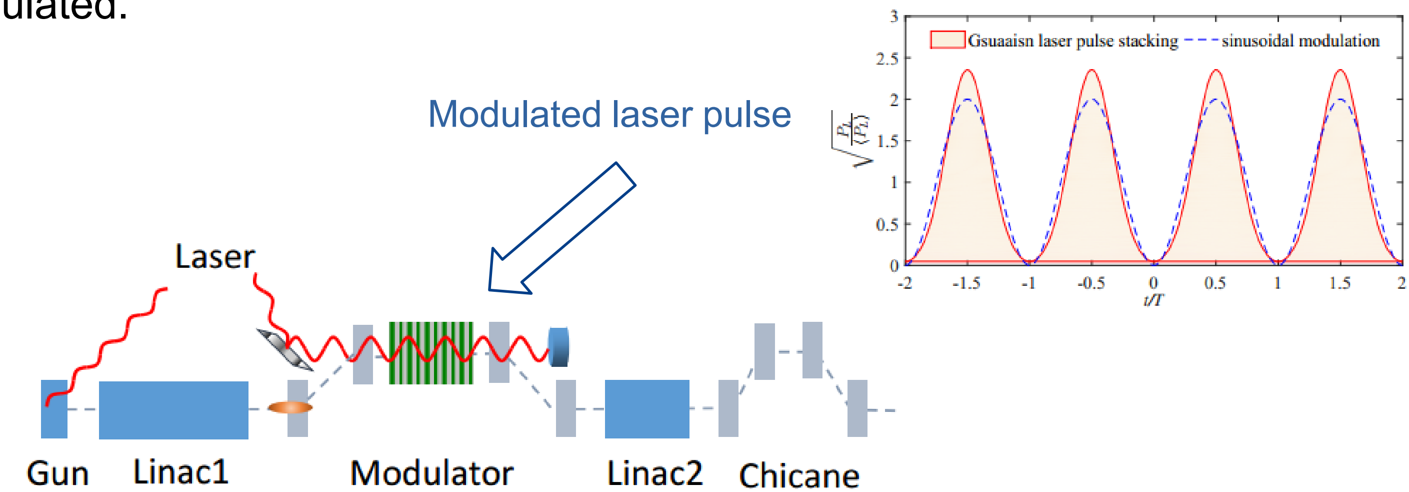
Generation of High-Power, Tunable Terahertz Radiation from Laser Interaction with a Relativistic Electron Beam

Zhen Zhang, Zhirong Huang (SLAC) et al.

Generate better bunch train

- We propose a new method to generate electron bunch train with *wide frequency range* (1~10THz) and *large bunching factor* (~0.4).

- The method is based on laser-electron interaction to modulate the slice energy spread. The beamline is similar with the laser heater but the laser power envelop is modulated.



- Strong density bunching can be generated in a relativistic electron beam after the chicane.

Theoretical analysis

- Assume the initial beam is uniform in current, but has a Gaussian slice energy spread $\sigma_\delta(z_0)$ that is a function of the longitudinal coordinate z_0

$$f_0(\delta_0, z_0) = \frac{I_0}{\sqrt{2\pi}\sigma_\delta(z_0)} \exp\left[-\frac{\delta_0^2}{2\sigma_\delta(z_0)^2}\right] \qquad \sigma_\delta(z_0) = \bar{\sigma}\left[1 + A\sin(k_0 z_0)\right]$$

- Add an energy chirp (h) and let the beam pass through a chicane (R_{56})

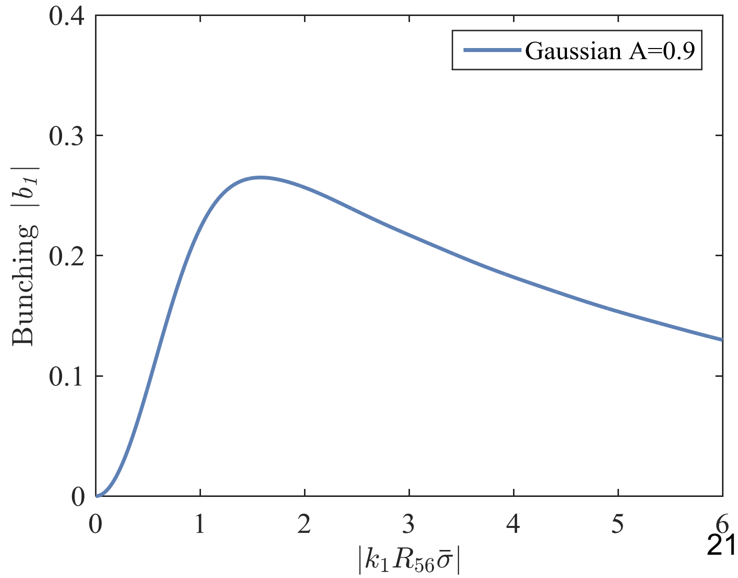
$$b_n = \frac{(-1)^n}{\sqrt{2\pi}\bar{\sigma}} \int d\eta J_n(k_n R_{56} A\eta) e^{-ik_n R_{56}\eta - \frac{\eta^2}{2\bar{\sigma}^2}}$$

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

- The maximum bunching factor available is ~0.27

- The optimal chicane setting is to satisfy

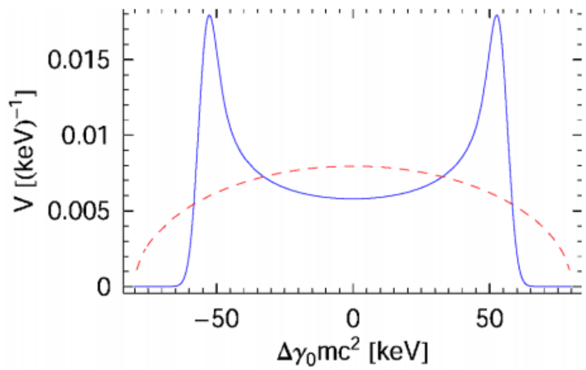
$$|k_1 R_{56}\bar{\sigma}| \approx 1.75$$



Theoretical analysis

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

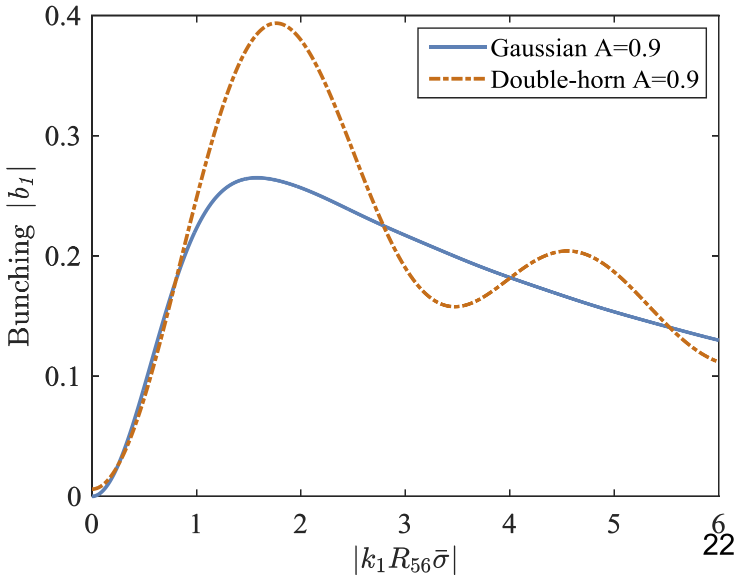
- When the laser waist size in the undulator is much larger than the beam size, the resulting energy profile is a double-horn distribution



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

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

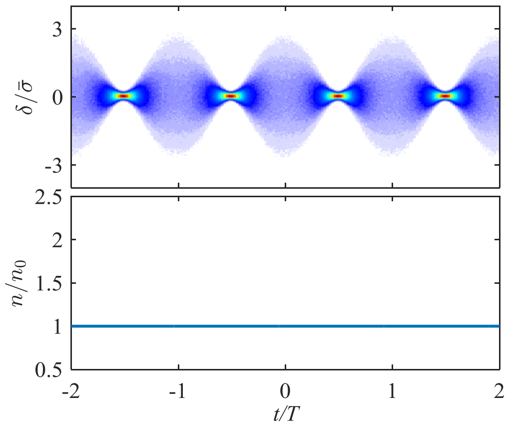
- The maximum bunching factor is up to ~0.4!!



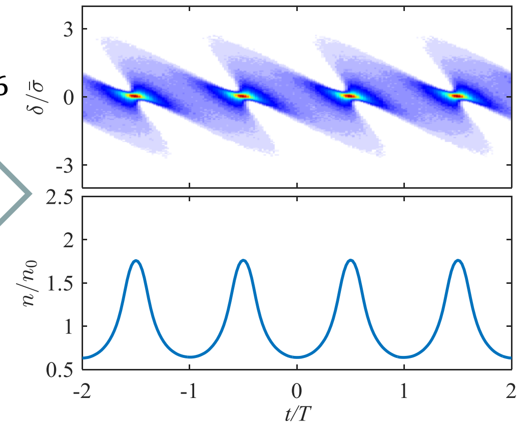
Theoretical analysis

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

Gaussian

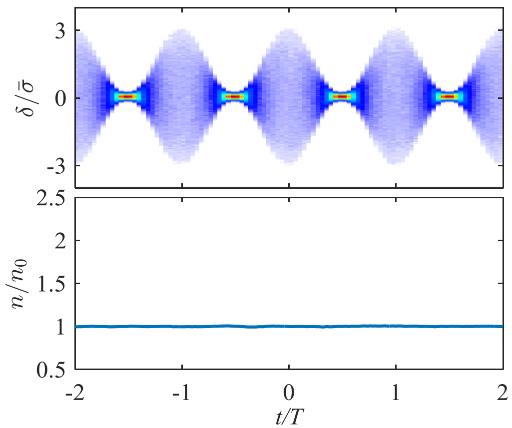


R_{56}

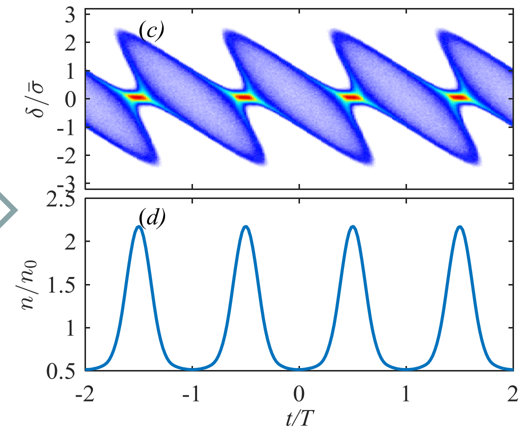


$b_1 \approx 0.27$

Double-horn



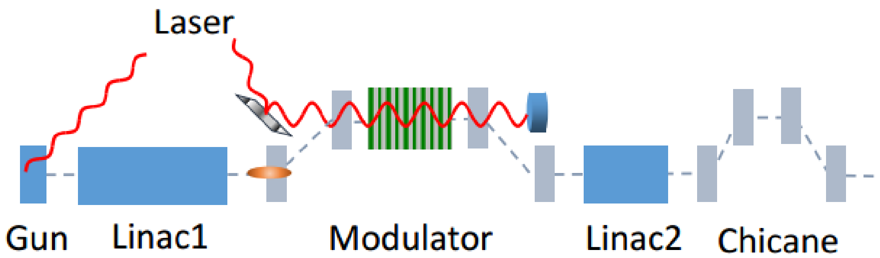
R_{56}



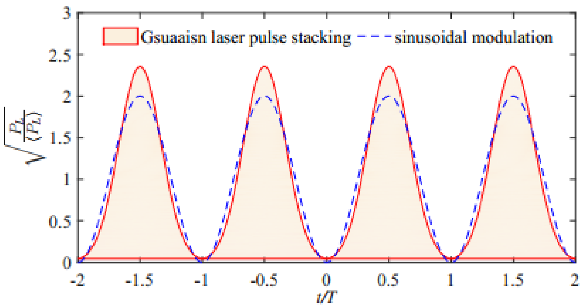
$b_1 \approx 0.4$

Simulations

- We use the code ELEGANT to simulate the laser modulation and beam dynamics with LCLS injector parameters (135MeV, 800nm laser)



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

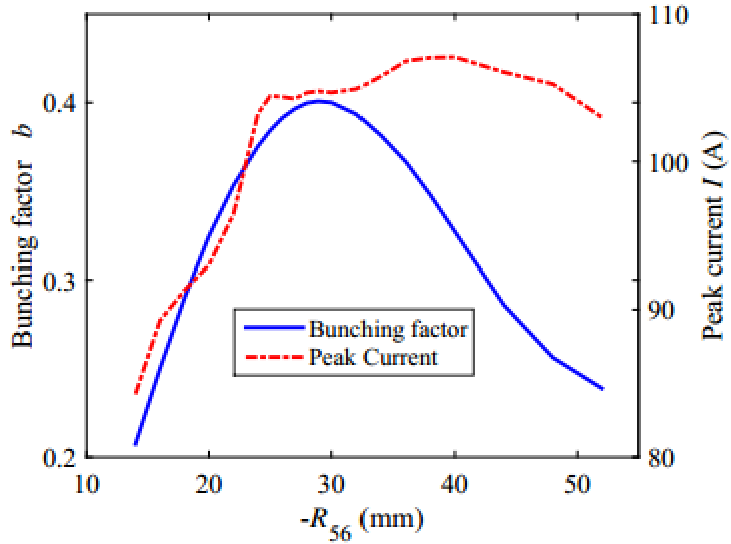


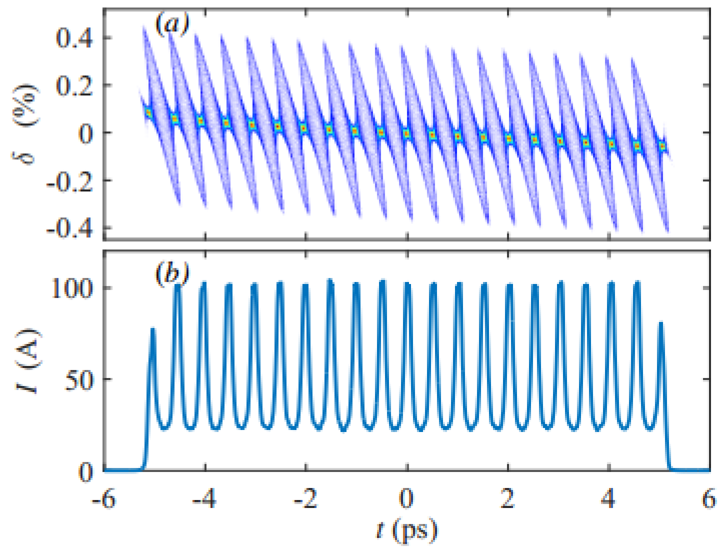
$$\Delta T = 0.5\text{ps}$$
$$\sigma_t = 60\text{fs}$$

- 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.

Simulations

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





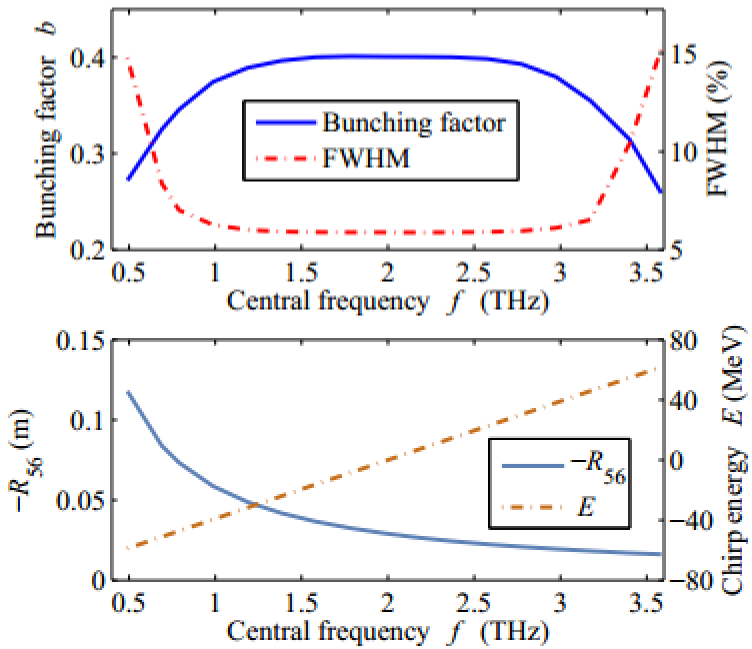
- The optimal condition $|k_1\bar{\sigma}R_{56}| \approx 1.75$ predicts the optimal chicane is -29.4mm, consisting with the simulations (-29mm).
- The peak current stays almost constant with larger R_{56}.

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

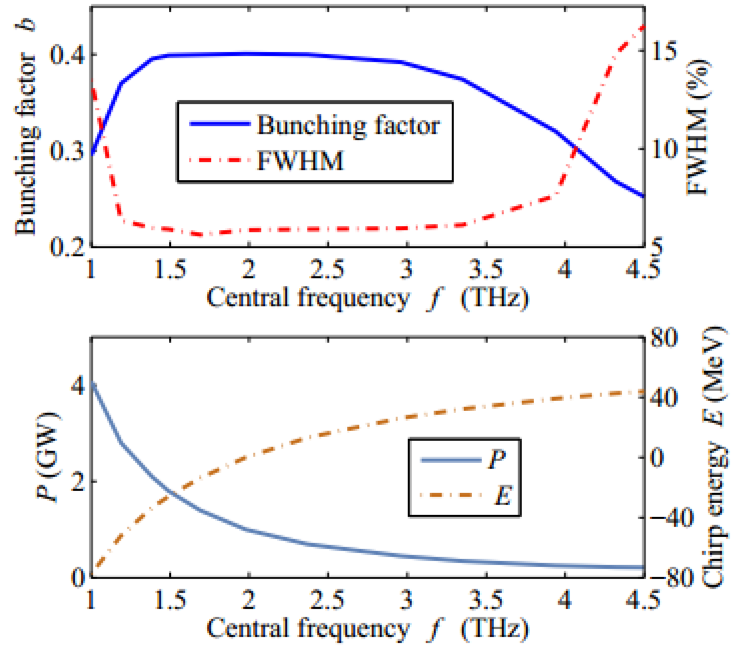
Tunability

- 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 $P = 1\text{GW}$



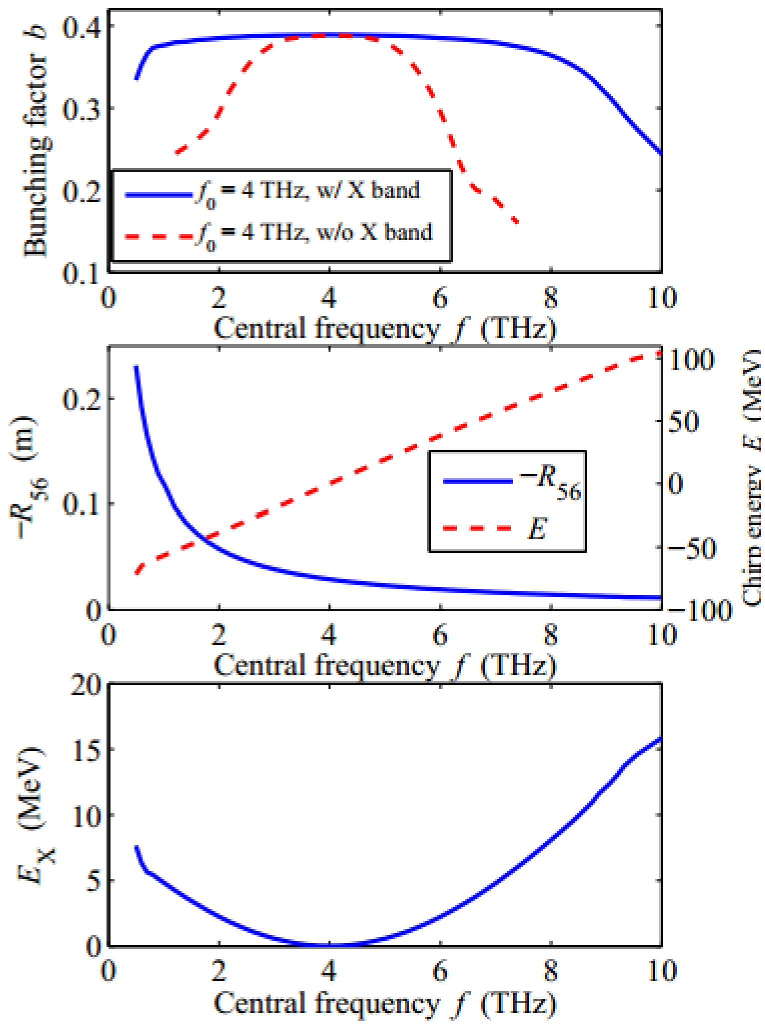
Keep $R_{56} = -29\text{mm}$



- The degradation of the bunching factor is due to the non-uniform compression.

Higher THz frequencies

- 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.**



Discussions

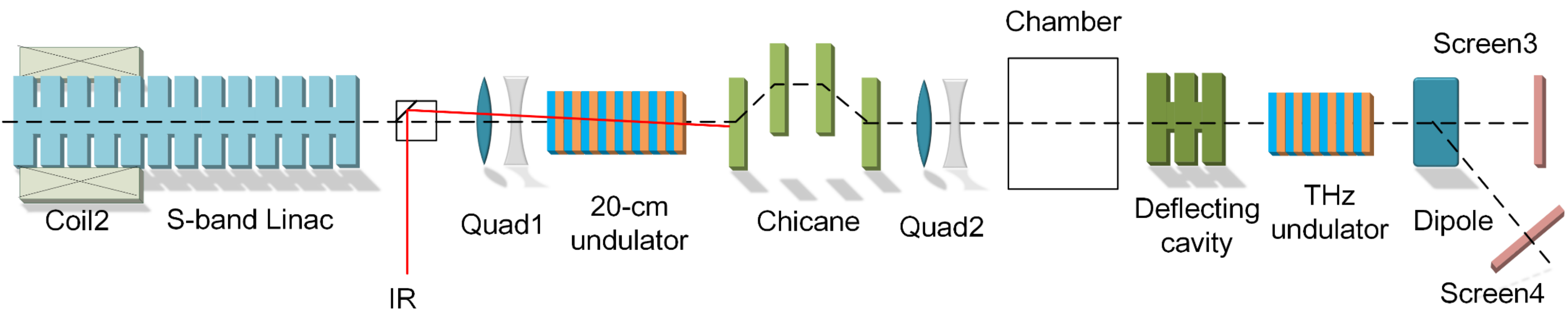
- Based on the slice energy spread modulation method, the bunching factor can be kept around 0.4 for a wide frequency range (1-10 THz), which is of great advantages in the generation of tunable narrow-band THz.
- THz frequency can be varied continuously by bunch compression (to 20 THz), or by changing the laser power envelope modulation period.
- Since there is no strong space charge force (for a relativistic beam) or beam loss during the process, the transverse beam quality can be preserved for matching, focusing and acceleration in the further applications.
- The method is also applicable for the electron beams from storage rings, energy recover linac or thermal-cathode injectors with higher repetition rate.
- Laser envelope shaping can be applied to shape THz field.

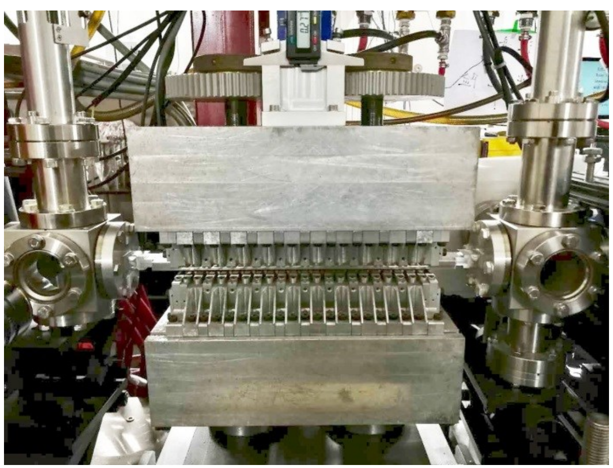
- The main requirement of the method is the electron beam energy needs to be ～100 MeV to be resonant with an optical laser. However, for electron beams with lower energies (~50 MeV), it is still possible to interact harmonically with the optical laser.

  (50 MeV, undulator period 2.5 cm, K=1.5, the third harmonic resonant wavelength is 760 nm)

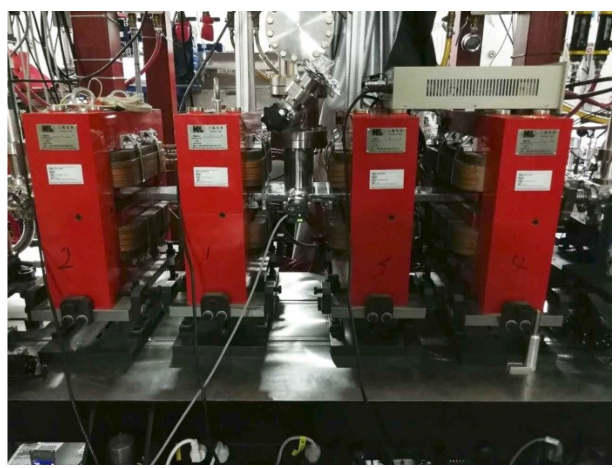
Scheduled experiments at Tsinghua

- We are ready for the beam commissioning for the interaction between 40MeV beam and 800nm IR laser in the undulator.

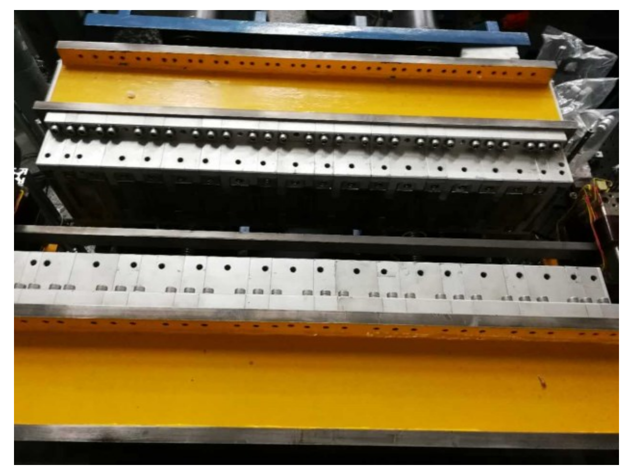




modulator



chicane



THz undulator

Thanks !