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Tunable High-Peak-Current e Bunch Train Generation and Its Application in THz Production

Lixin Yan
On Behalf of the Accelerator Laboratory of
Tsinghua University

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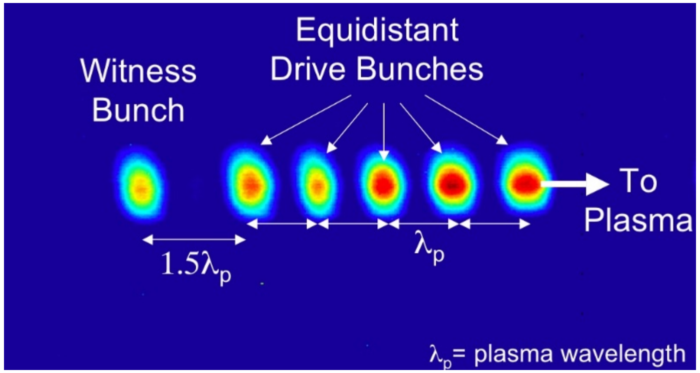
Outline

- Motivations/applications of high peak current bunch trains
- Methods to generate the bunch trains
- Introduction of nonlinear longitudinal space charge oscillation
- Bunch train experiments at THU
- Experimental measurement results
- THz radiation from dielectric wakefield structures
- Summary

Motivations

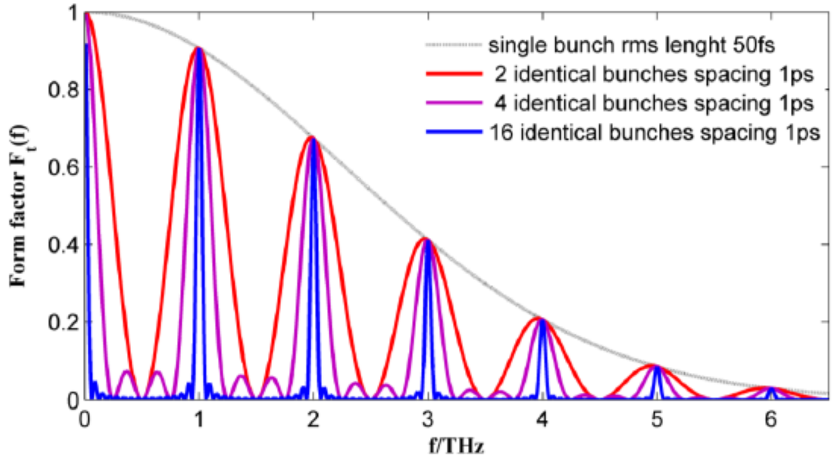
- Resonant excitation of plasma/dielectric wakefields. The plasma density and the bunch train can be adjusted for maximum wakefields or maximum transformer ratio for plasma wakefield acceleration.



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

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

- Tunable narrow-bandwidth high-spectral-intensity THz radiation generation.

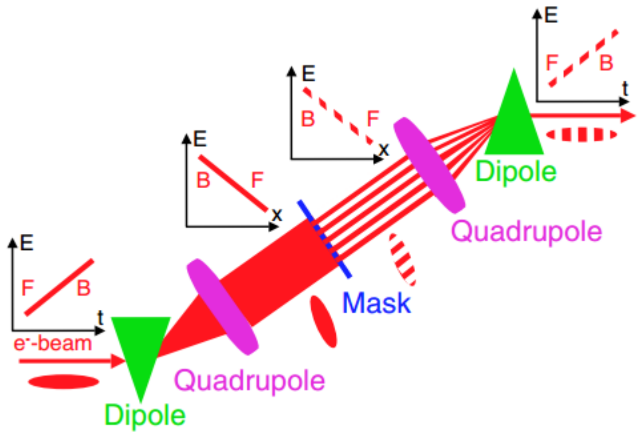


A. Gover et al., PRST-AB 8, 030701 (2005)

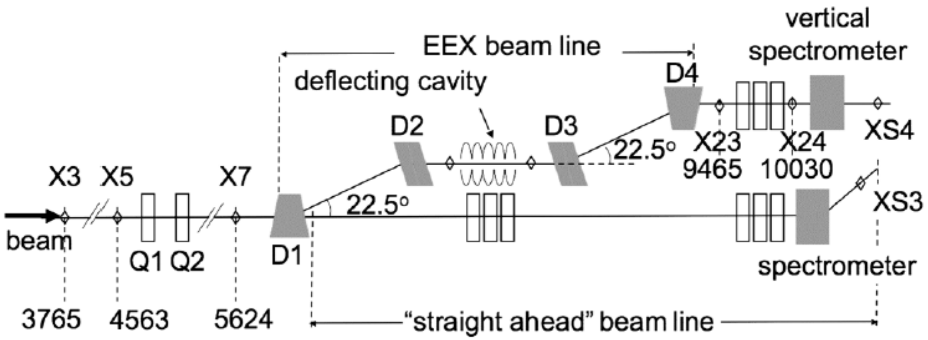
Y. Shen et al., PRL 107, 204801 (2011)

Bunch Train Generation

- Use a transverse mask in a dispersive region in combination with an energy chirp, or before a transverse to longitudinal beam line

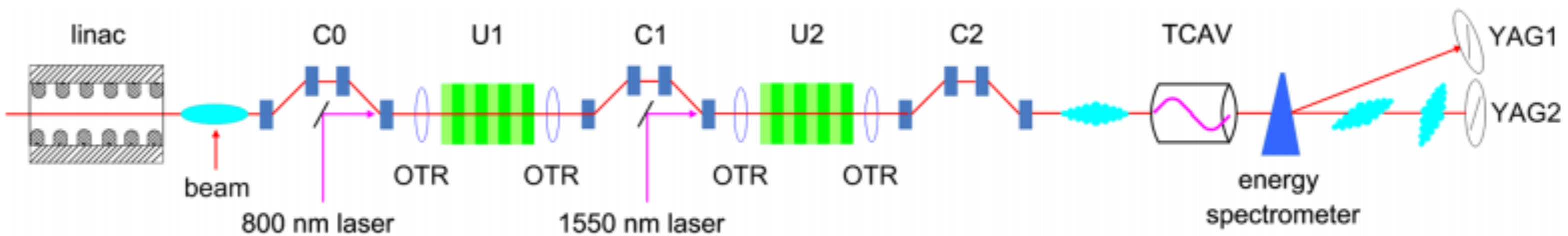


P. Muggli et al., PRL 101, 054801 (2008)



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

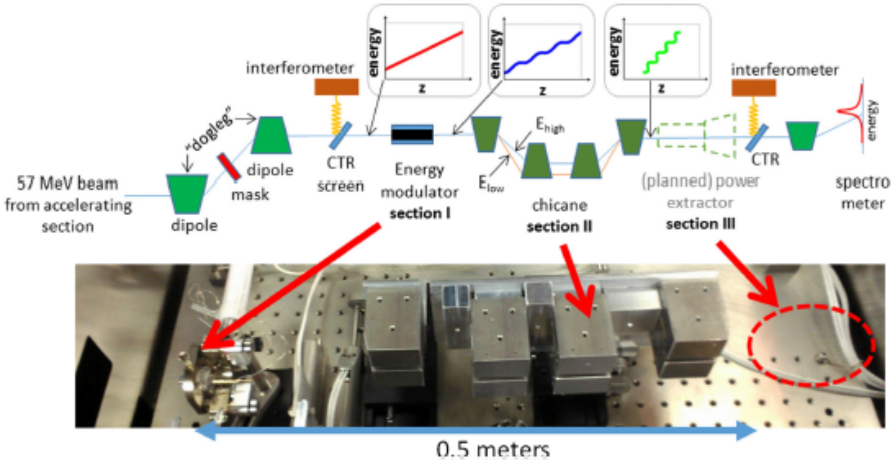
- Difference-frequency echo-based THz beam structure generation



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

Bunch Train Generation

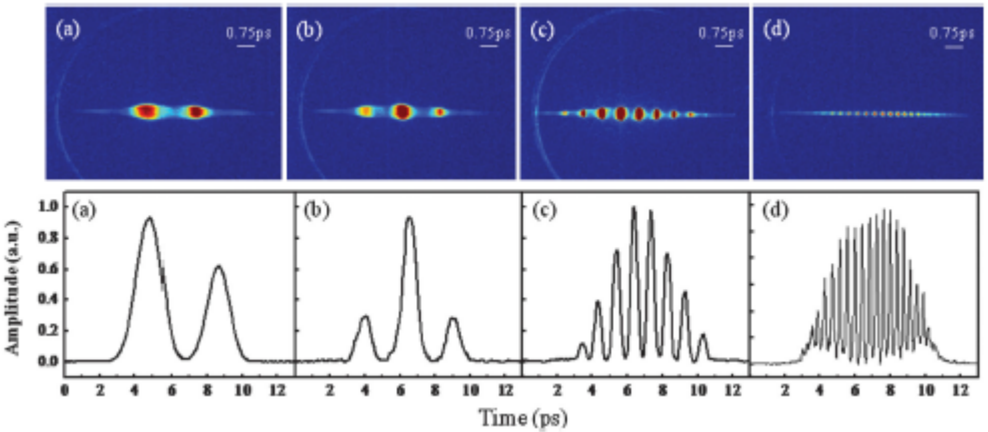
- Energy modulation by the self-excited wakefields in a dielectric or corrugated waveguide and subsequent conversion into a density modulation



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

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

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



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

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

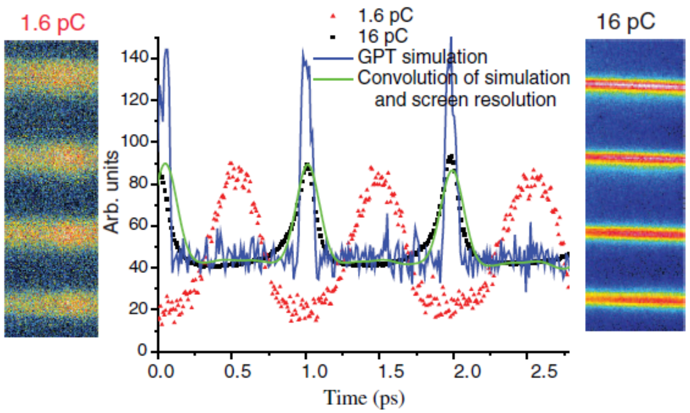
Y. Li et al., APL 92, 014101 (2008)

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

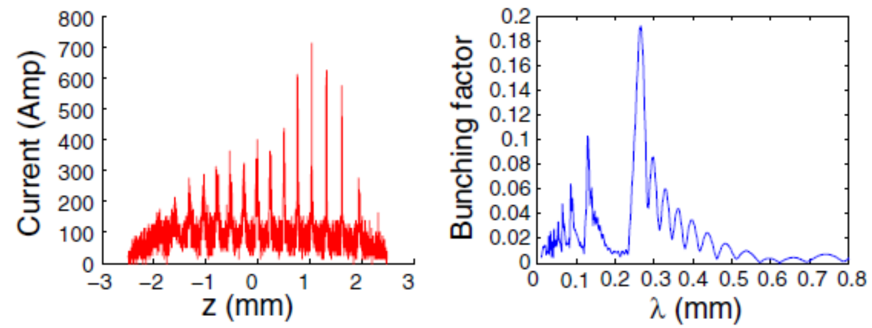
L. X. Yan, et al., IPAC 1st, Kyoto, Japan(2010)

Bunch Train Generation

- The problem arises on how to preserve modulation for large beam currents when longitudinal space charge (LSC) force might contribute to smearing out any structure in the temporal thus limiting the attainable peak currents.
- As opposed to trying to reduce the effects of LSC, we can take advantage of it to magnify the initial modulation to generate high peak current through Nonlinear Longitudinal Space Charge Oscillation (NLSCO).
- The proof-of-principle experiment was carried out at UCLA(up to ~20pC). Then the method was proposed to generate high peak current bunch trains.



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



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

Nonlinear Space Charge Oscillation

- The process of NSCO can be well formulated by the 1D cold fluid model.
- $n(z,t)$: electron density; $\Delta\gamma(z,t)$: deviation from reference energy

  $E(z,t)$: longitudinal space charge field; z is the coordinate along the bunch

$$\partial_t \Delta\gamma + c\Delta\gamma/\gamma^3 \ \partial_z \Delta\gamma = -eE/m_0 c \qquad \dot{\Delta\gamma}_m + \sum_n inkc/\gamma^3 \ \Delta\gamma_m \Delta\gamma_{m-}$$

$$\partial_z E = -en/\epsilon_0 \qquad \xrightarrow{\text{Fourier expansion}} \qquad E_m = -en_0 R_m / i\epsilon_0 m$$

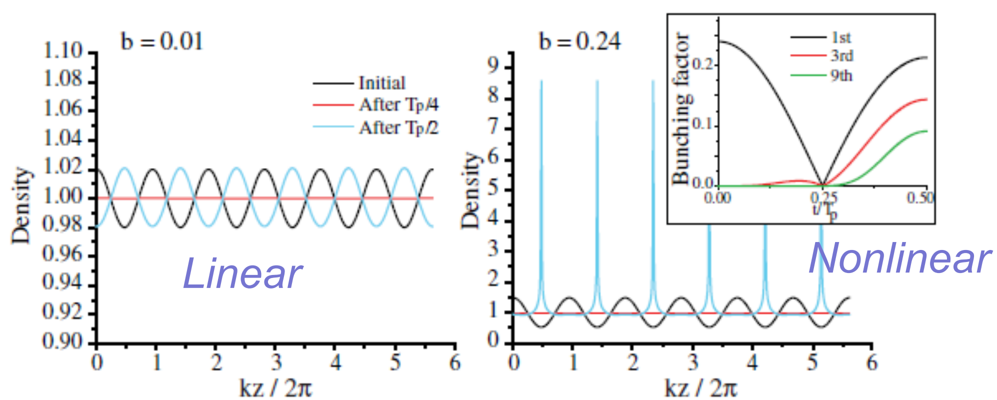
$$\partial_t n + c\partial_z n\Delta\gamma/\gamma^3 = 0 \qquad \dot{R}_m + \sum_n imkc/\gamma^3 \ R_{m-n} \Delta\gamma_m$$

Bunching factor

- With the initial condition $n(z,0) = n_0 (1+2b\cos(kz))$ or $R_0 = 1$ and $R_{\pm 1} = b$

$$\rightarrow \quad n(z,t) = n_0 \left[1 + \cos(\omega_p t) \sum_m mc_m(t) \cos(mkz)\right]$$

After a half plasma period, the modulation will be completely recovered



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

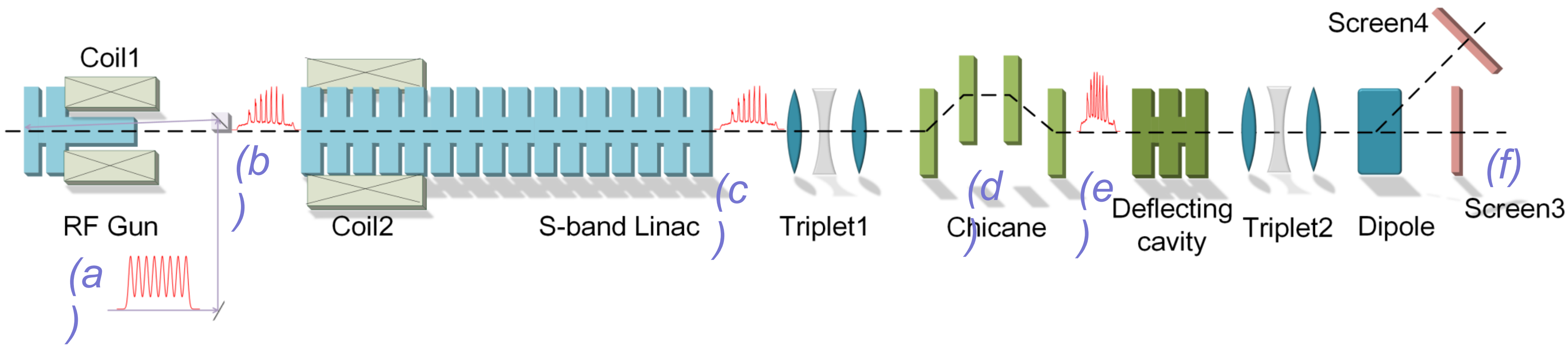
After a half plasma period, the initial modulation will be greatly magnified because oscillation harmonics appear and interfere constructively

Bunch Train Experiment at THU

- We take advantage of NSCO to generate multi-bunch trains with

  (1) Large charge (~700pC) and high peak current (~300A)

  (2) Tunable uniform spacing from ~0.5THz to ~1.6 THz



a) Generate 8 equally spacing laser pulses using 3 α-BBO birefringent crystals;

b) Optimize the laser spot and gun solenoid to control the plasma phase advance $(\sim\pi)$ before the acceleration section;

c) Accelerate the beam to high energy to freeze the temporal profile;

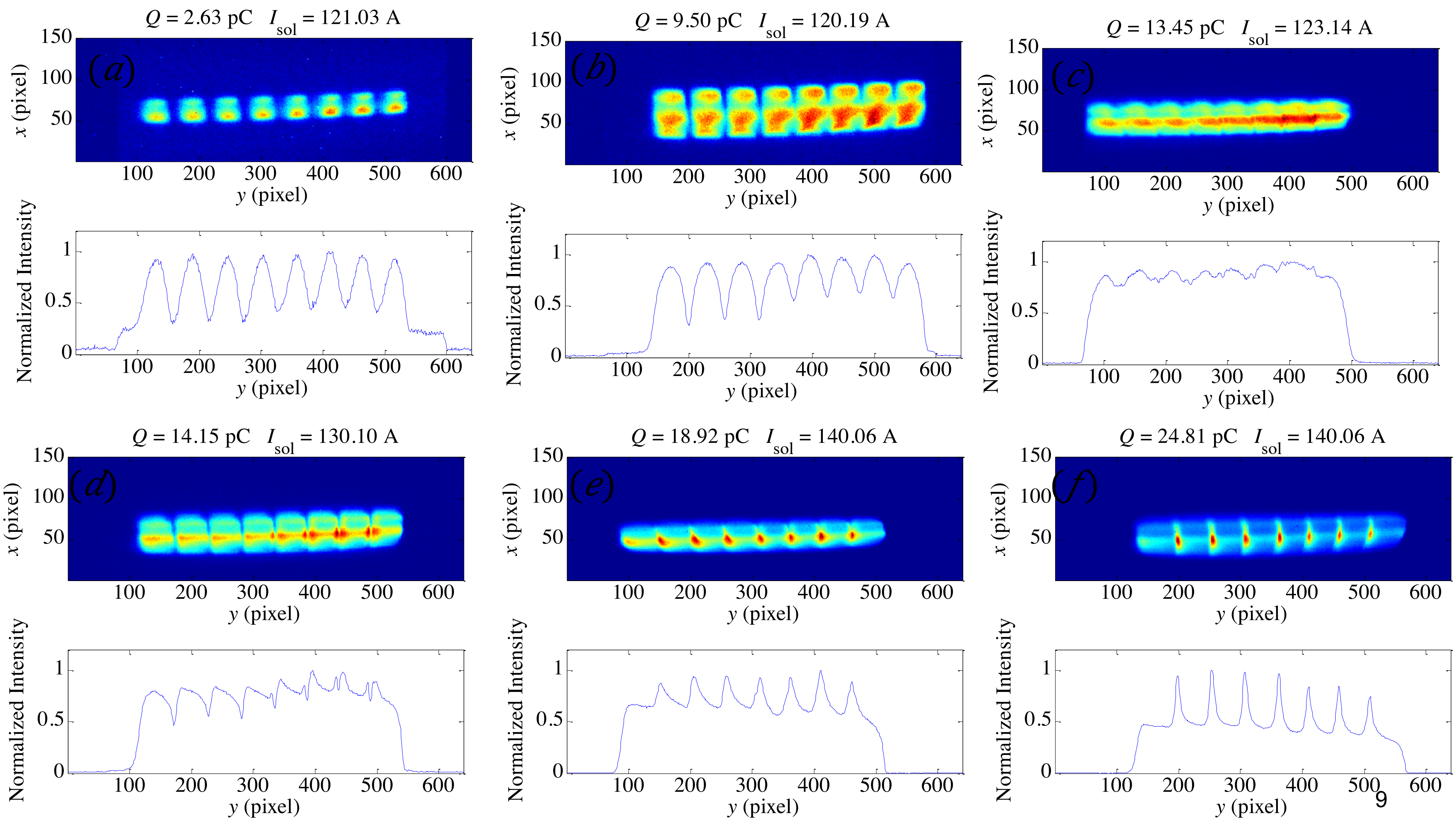
d) Tune the chicane compression to vary the bunch train spacing continuously;

e) CTR radiation and auto-correlation measurement (not shown here);

f) Temporal profile measurement through the downstream deflecting cavity.

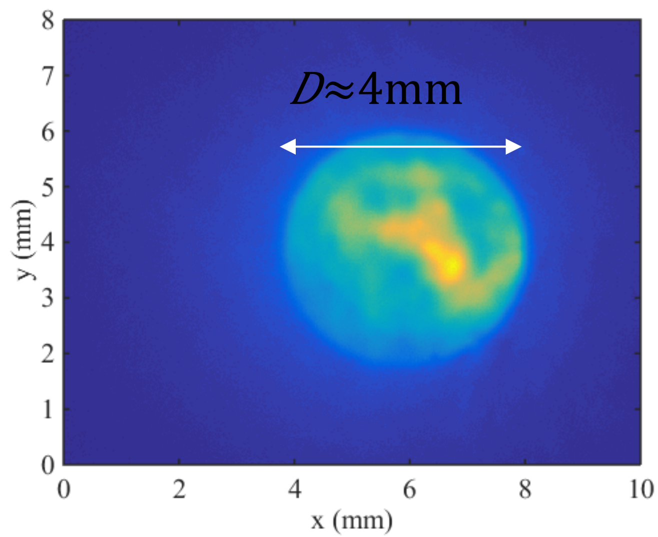
NSCO Start-up

- Starting from low charge and weak solenoid focusing, we can increase the plasma oscillation phase advance and observe the temporal profile evolution.

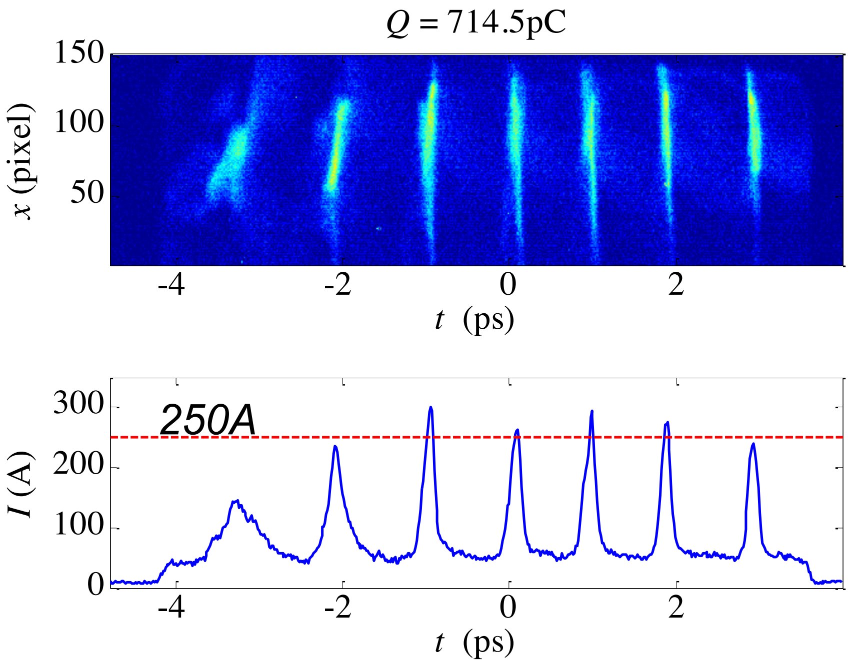


High Peak Current Bunch Train

- With large beam charge (~720pC), optimizing the laser spot size and solenoid focusing, we obtained high peak current bunch trains in the experiment.
- In order to resolve the temporal prole, under large beam charge, we use a 70-μm horizontal slit before the deflector to cut the beam transversely.



Virtual cathode on YAG screen



Experiment measurement

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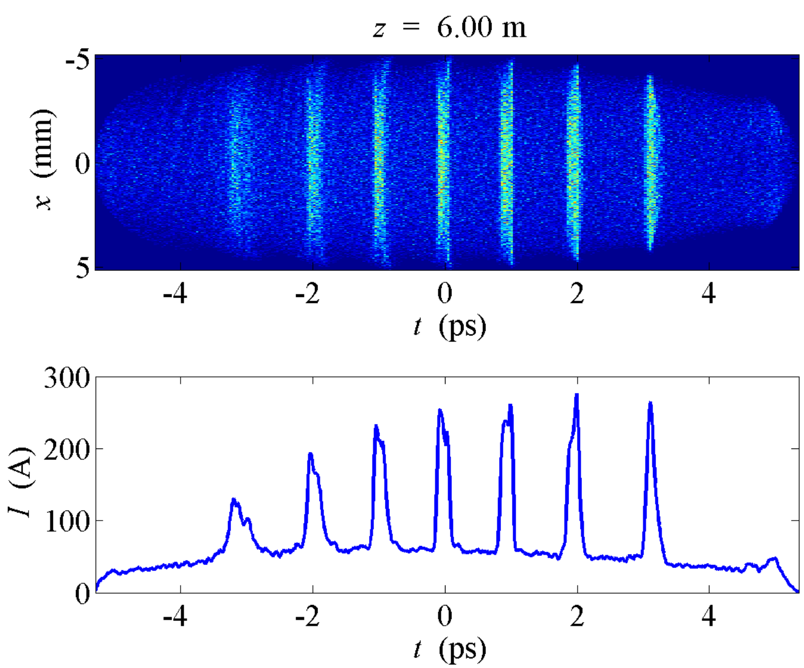
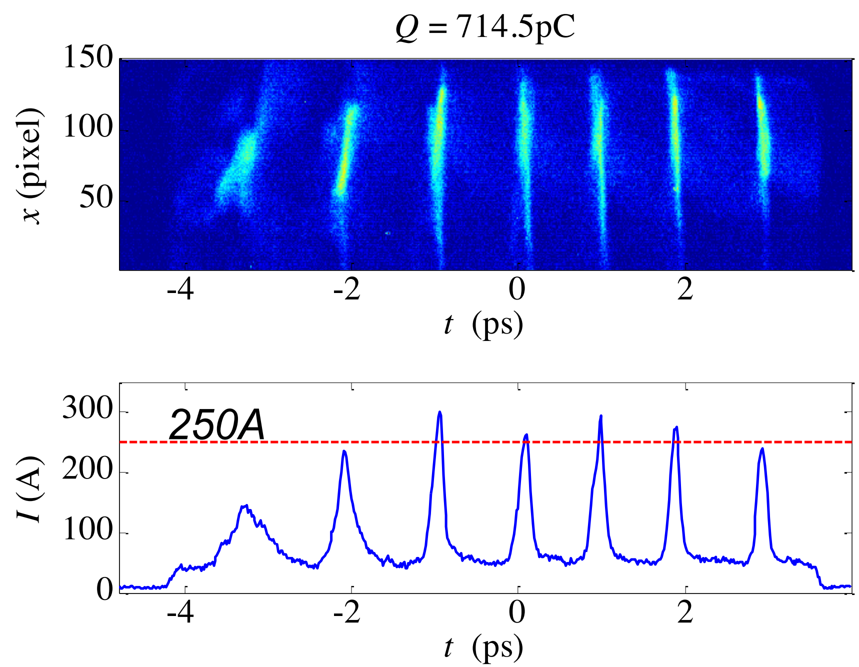


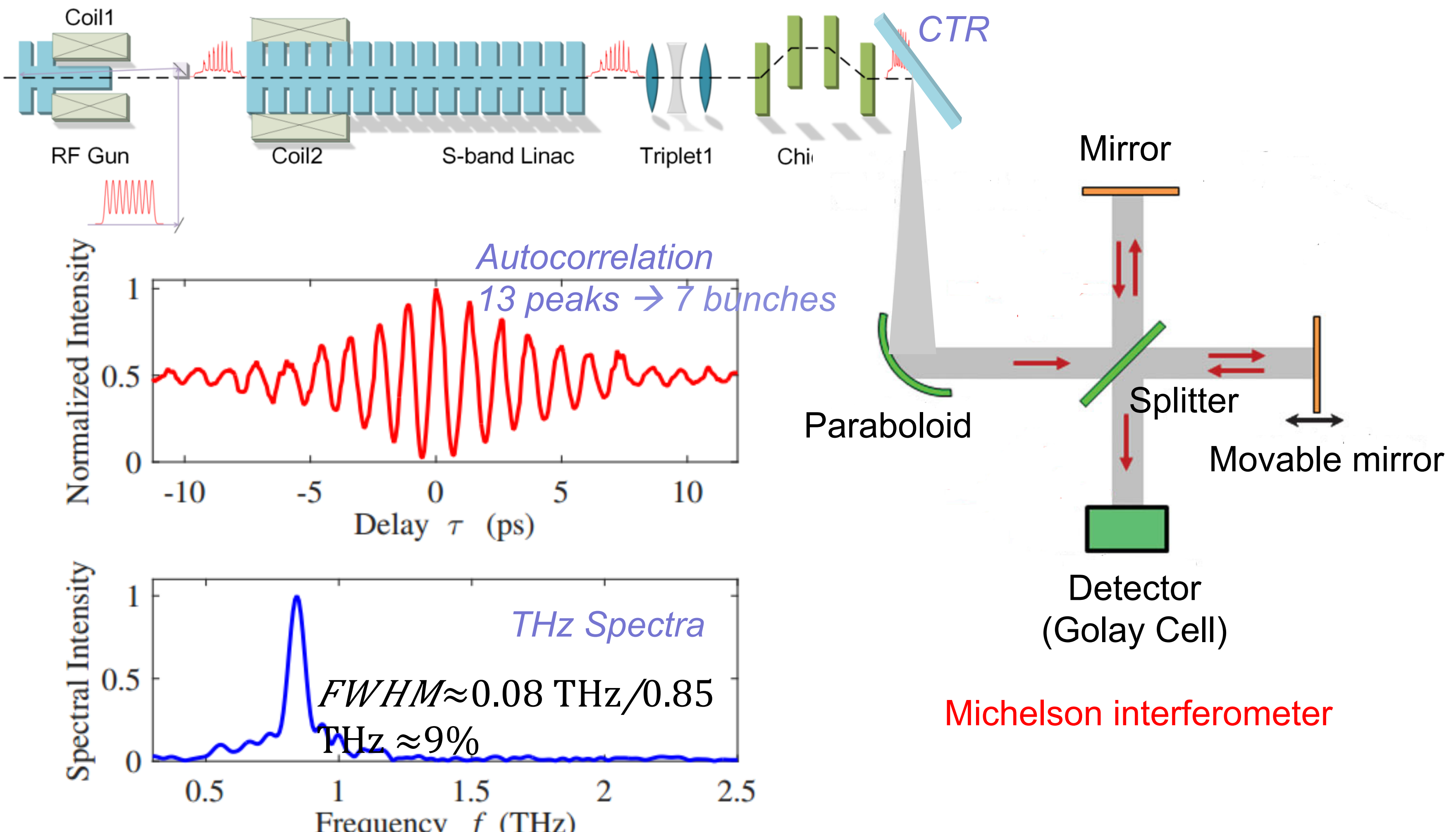
GPT simulation



Experiment measurement

THz Autocorrelation Measurement

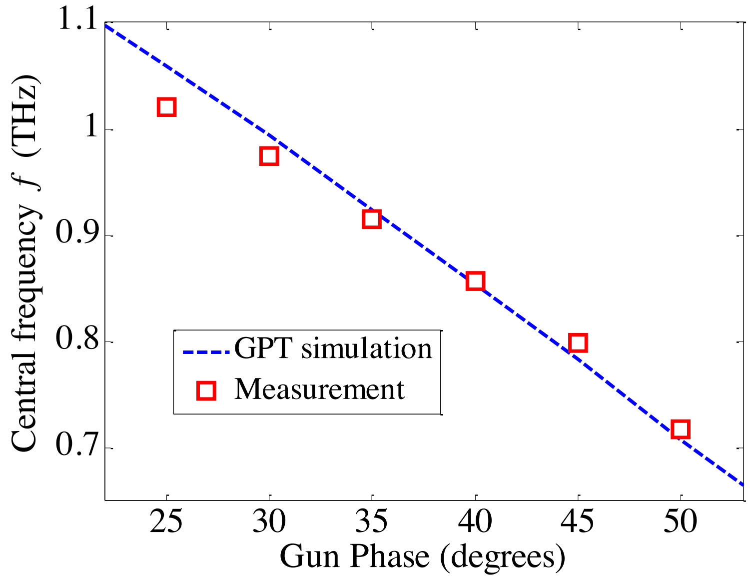
- The electron bunch trains are used to generate THz radiation by CTR, and the spectra are solved through the autocorrelation by the interferometer.



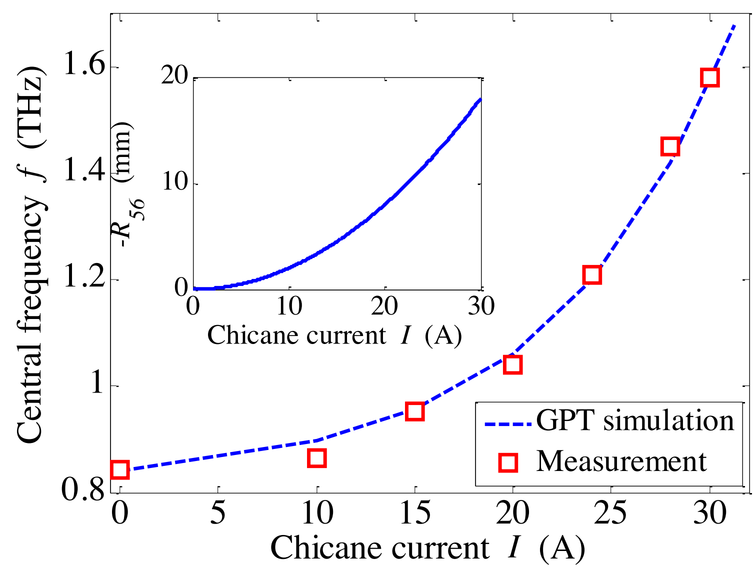
Tunable Bunch Train Spacing

- 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



Magnetic compression
Chicane

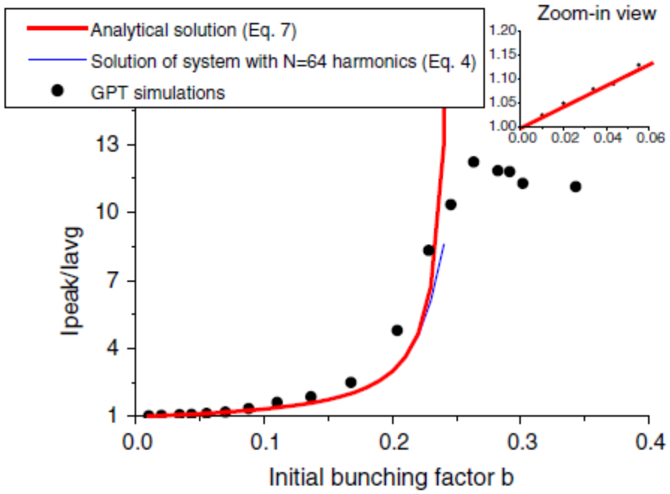


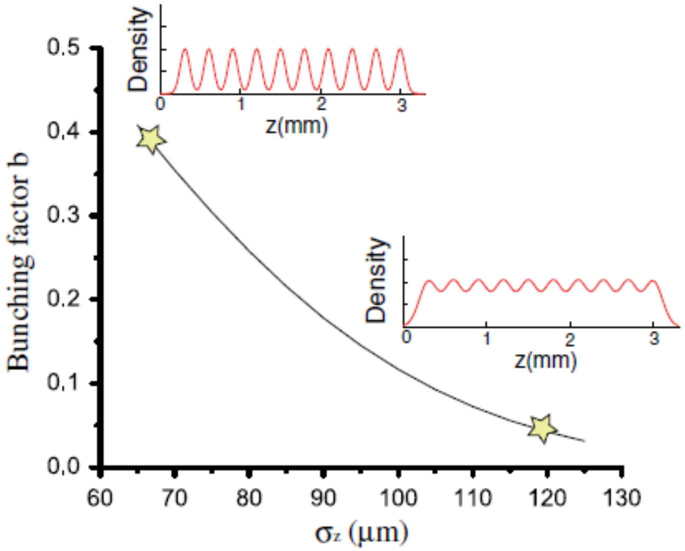
- Gun max. gradient ~106MV/m
- Accelerator phase 0 (max. acceleration)
- Chicane off
- Change the launching phase

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

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.



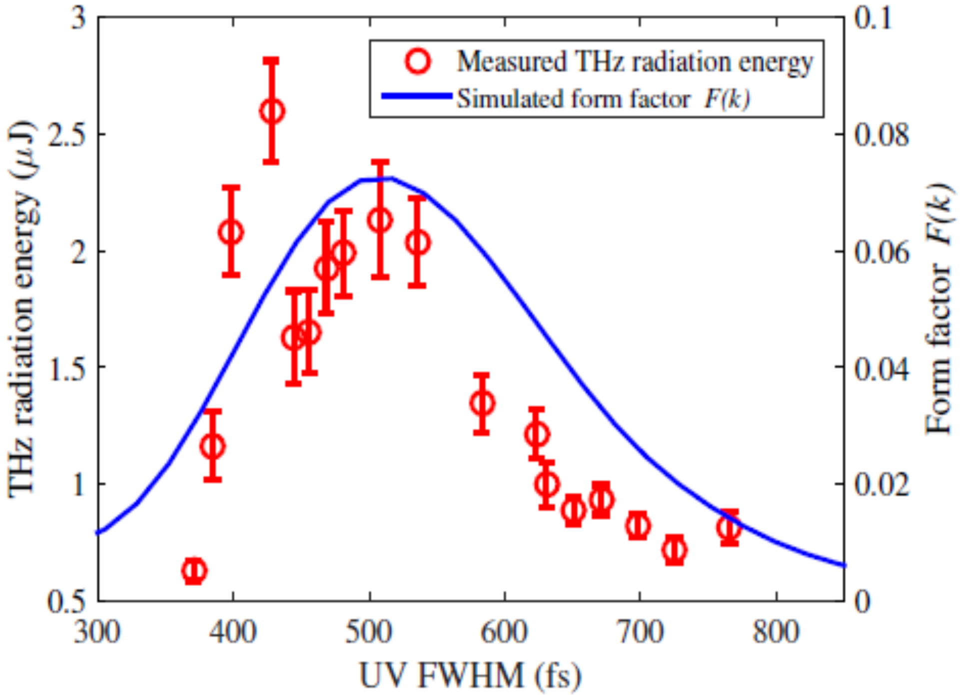


P. Musumeci et al., PRST-AB 16, 100701 (2013)

- 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 measurement by changing the grating separation to control the initial beam modulation.

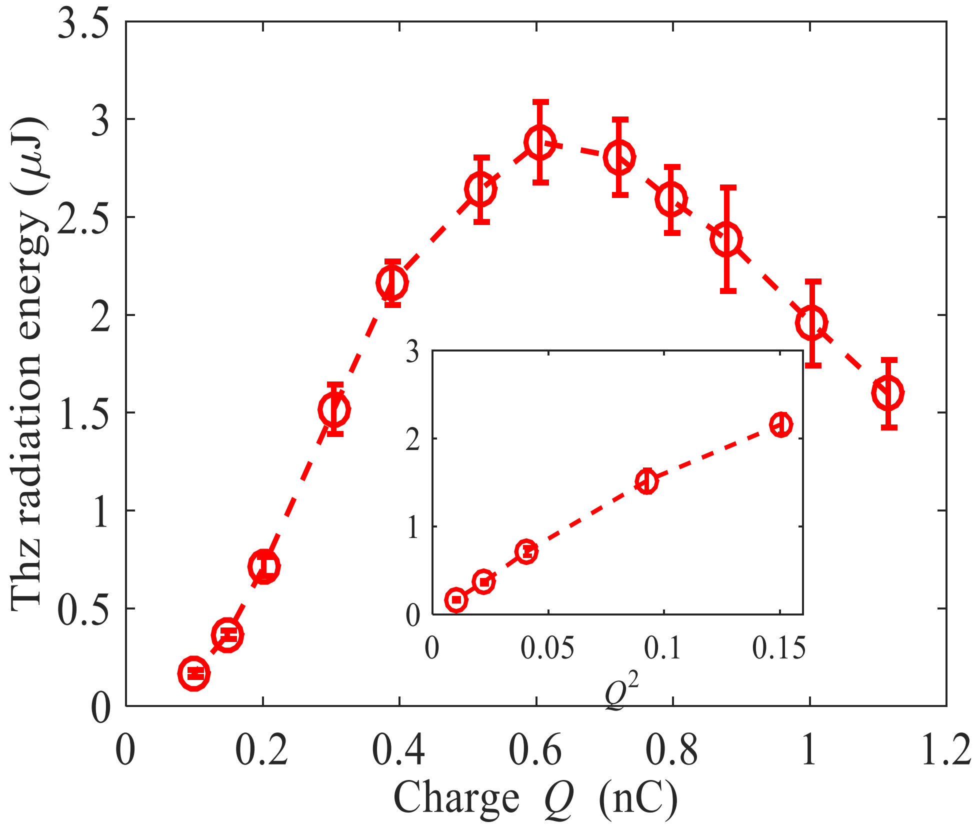


- ✓ The laser pulse is of minimum pulse length at 6mm grating position.
- ✓ There is a optimal grating separation for maximum THz radiation energy.
- ✓ These results demonstrate that there is an optimal initial bunching for high peak-current bunch train generation.

Z. Zhang, L. X. Yan, Y. C. Du et al., PRL, 116, 184801(2016)

THz Radiation Energy

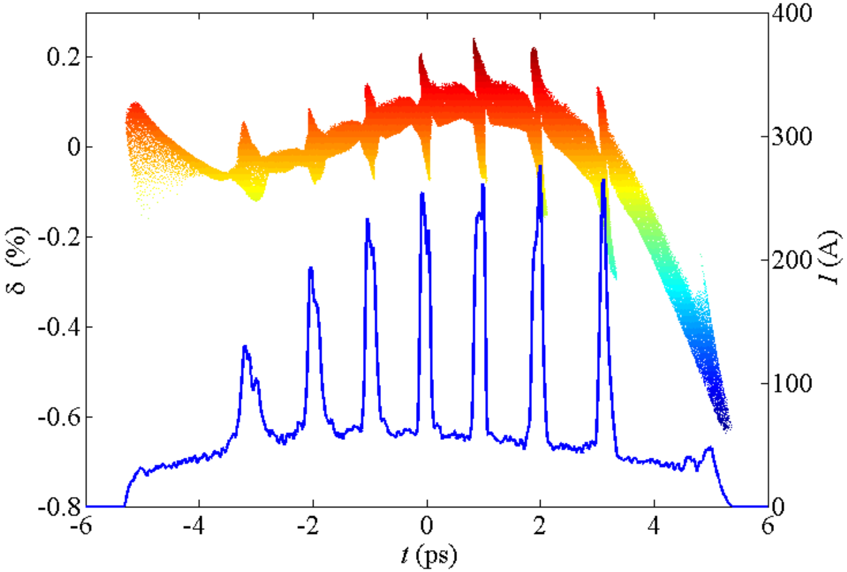
- We also measure the maximum THz radiation energy for different beam charge by optimizing the gun solenoid. The laser spot size on cathode is kept constant when varying the beam charge.

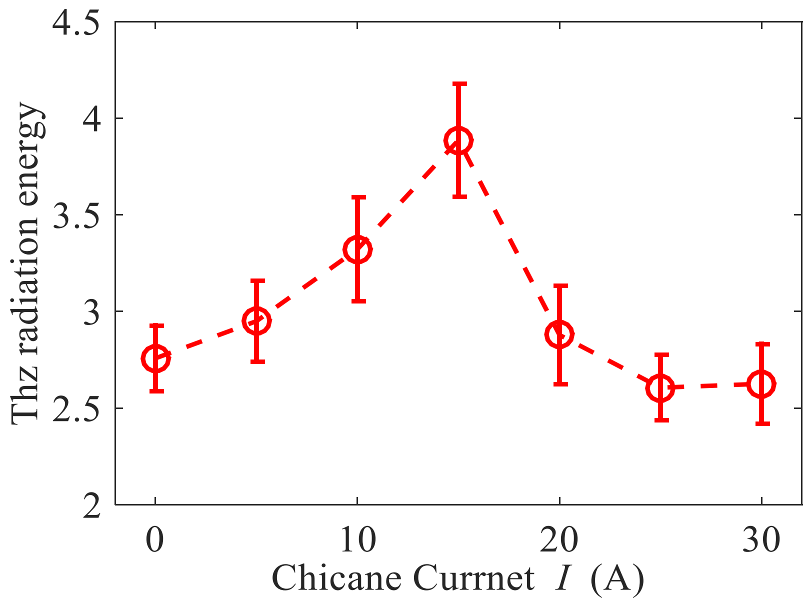


- ✓ The diameter of laser spot on cathode is ~4mm.
- ✓ There is a optimal beam charge (600pC~700pC) that yields largest THz radiation energy.
- ✓ The inset shows that the THz energy is proportional to square of the charge when the charge is less than ~200pC.

Chicane Enhancement

- There are large local energy chirps where the spikes arise. Then we can use the chicane to control the spikes while not changing the spacing between them.
- If the local energy chirp is positive (head particle has lower energy), we can enhance the spikes to higher current and increase high-harmonic components in THz radiation.

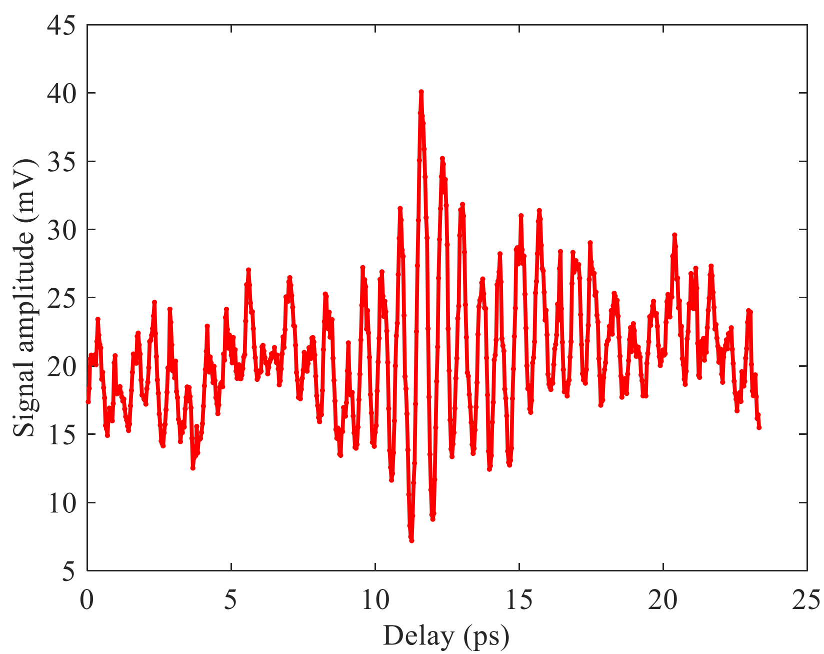


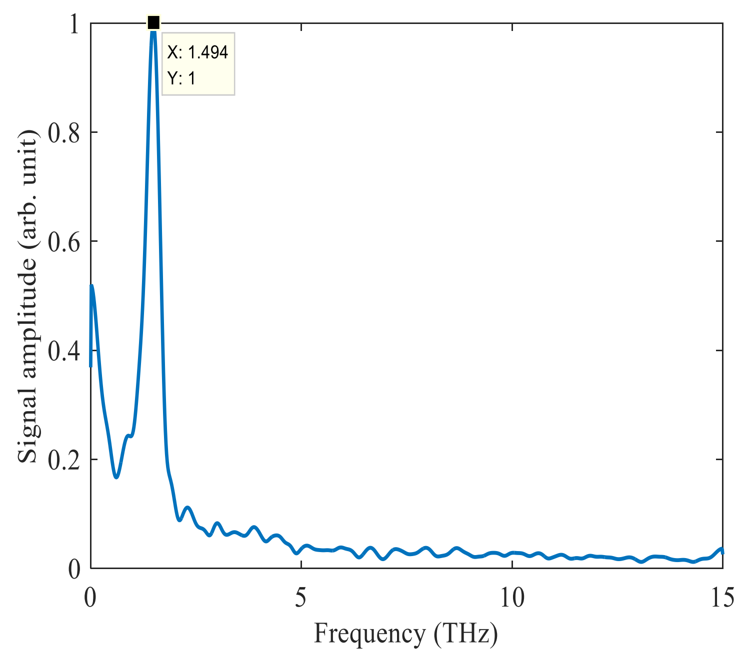


- We observed THz radiation enhancement when the chicane was set properly at some values.

Play with more bunches

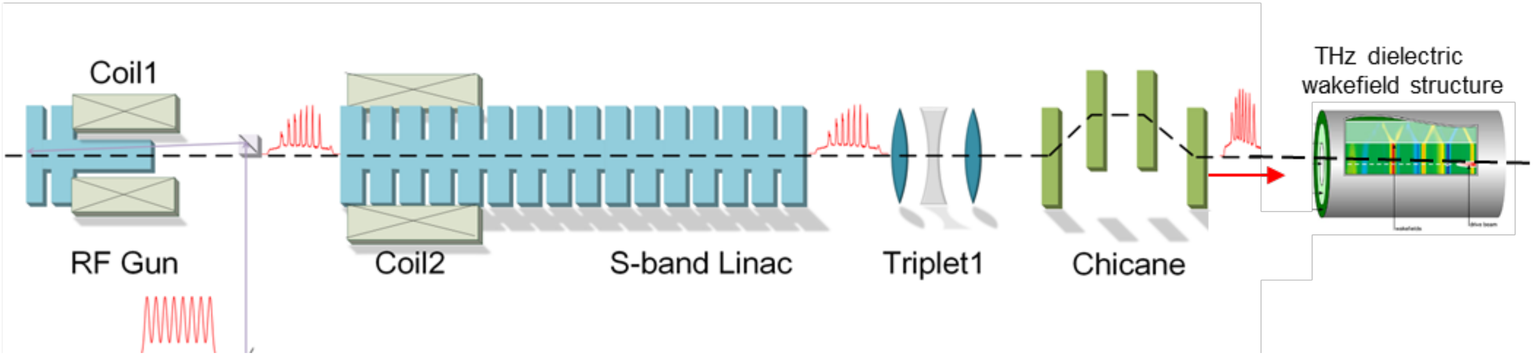
- We also tried 16 bunches in the experiment and measured the auto-correlation of the CTR signal.
- 4 α-BBO crystals and shorter UV pulse width (FWHM ~300fs)

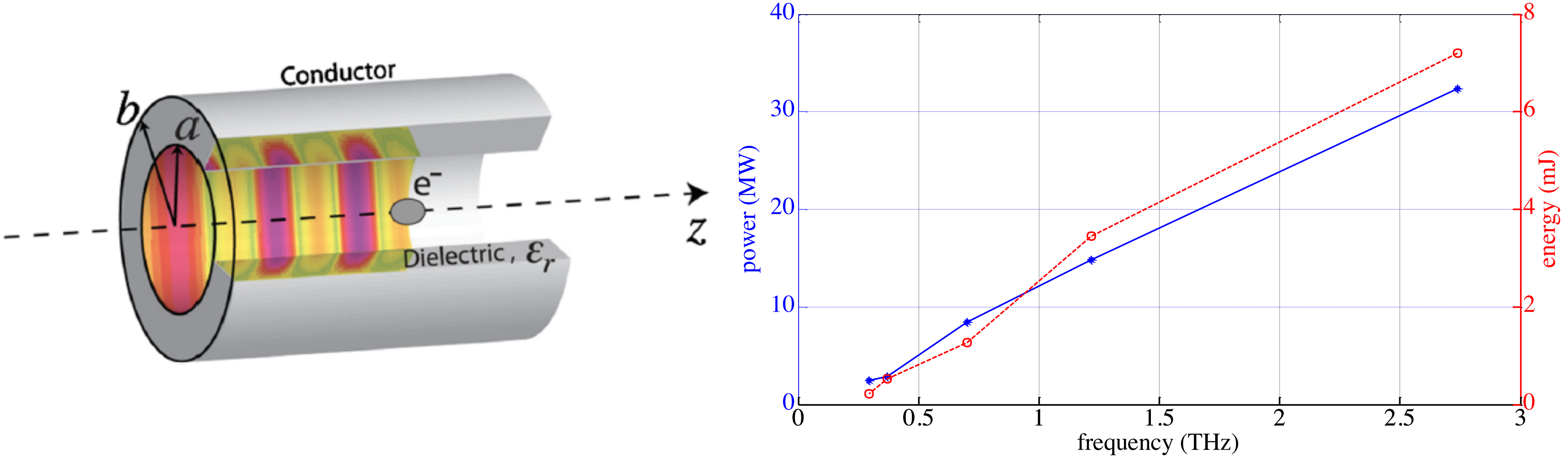




THz from Dielectric Wakefield Structures

- Preparations for the experiment on THz radiation from dielectric wakefield structures by the electron bunch trains is ready at our lab.





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

Summary

- high-peak current electron bunch trains have important applications in plasma wakefield acceleration and tunable narrow-band THz production.
- Based on nonlinear longitudinal space charge oscillation, for the first time, we demonstrated the generation of tunable uniform THz-repetition-rate (0.5-1.6THz), high beam charge (~700pC), high peak current (~300A) electron bunch trains.
- Using these bunch trains, we have performed experiments on THz production based on Coherent Transition Radiation.
- Experiment for THz production based on the electron bunch trains with dielectric wakefield structures is on schedule.

Thanks !