LEDS 2023

Elettra Sincrotrone Trieste LEAPS Compact ENEA

Widely tunable high power THz source based on ultrashort electron beams

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On behalf of Accelerator Laboratory of
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Tsinghua University

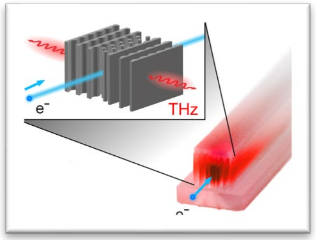
ACCELERATOR LABORATORY
of TSINGHUA UNIVERSITY

Outline

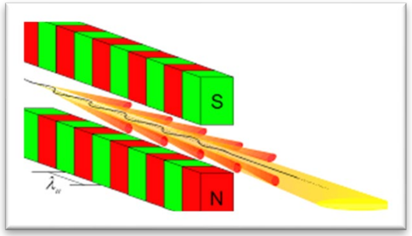
- Introduction
  - ✓ Accelerators for THz & THz for accelerators
  - ✓ Review of current accelerator-based THz sources
- From single bunch to bunch train
  - ✓ Superradiant radiation from bunched electrons
  - ✓ THz bunch train generation
- Experimental results on THz bunch train
  - ✓ Generation and measurement of tunable e- bunch trains
  - ✓ Generation and control of THz by electron beam
- Summary

Accelerator for THz & THz for Accelerator

- Accelerators have great potential in high power THz radiation generation, especially in covering the so-called ‘THz-gap’ (1-10THz).



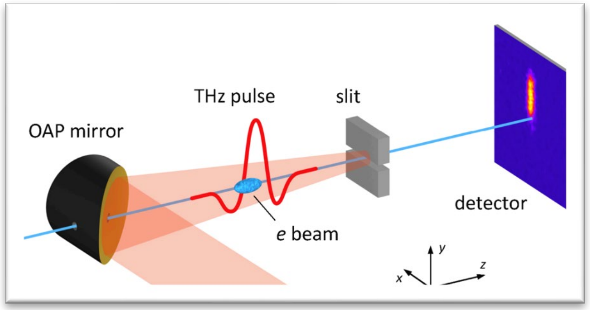
Waveguide



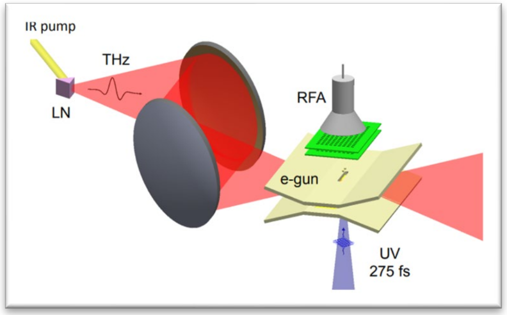
Undulator radiation

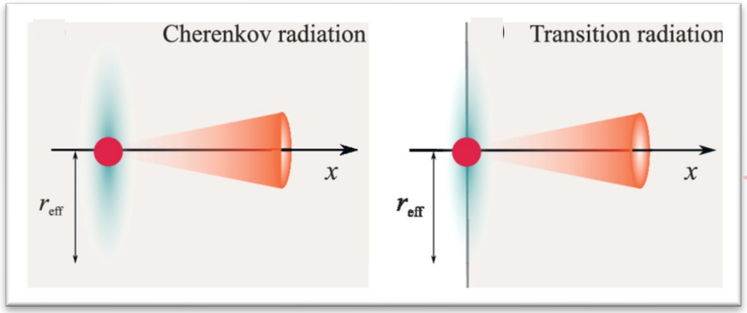
THz for Accelerator

Diagnostics



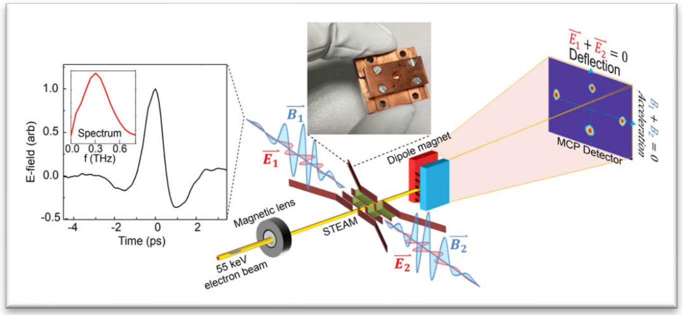
THz electron gun



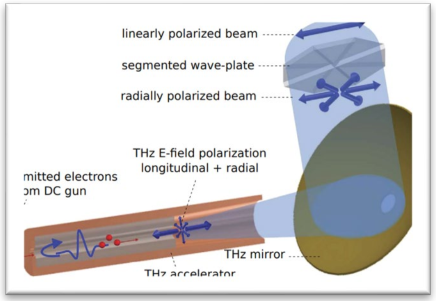


Cherenkov radiation Transition radiation

Accelerator for THz



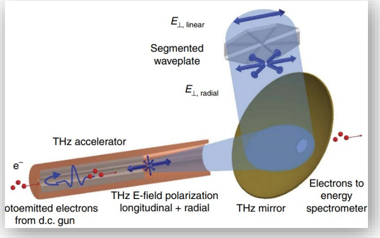
Phase space manipulation



THz acceleration

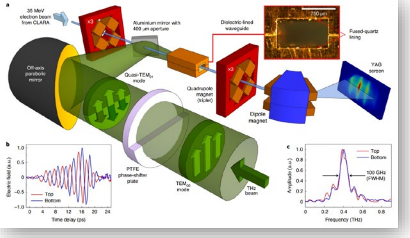
THz for accelerator

- THz acceleration of electrons



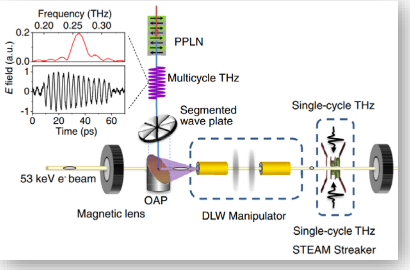
THz acceleration

Nature Comm 2015



relativistic acceleration

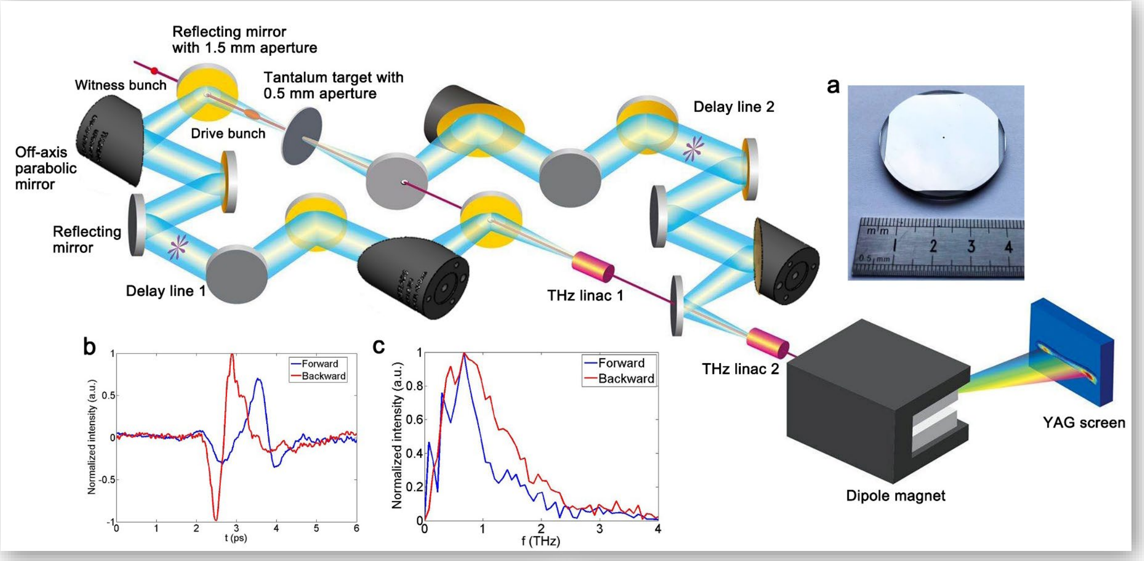
Nature Photonics 2020

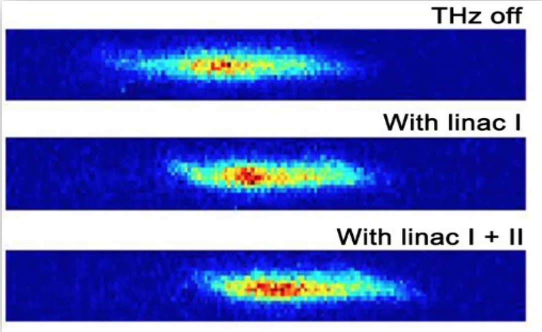


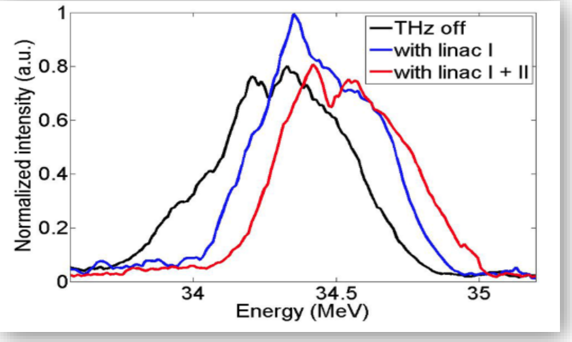
cascaded acceleration of low energy beam

PRX 2020

- Cascaded THz-driven acceleration of relativistic electron beams in DLWs using CTR from drive bunch



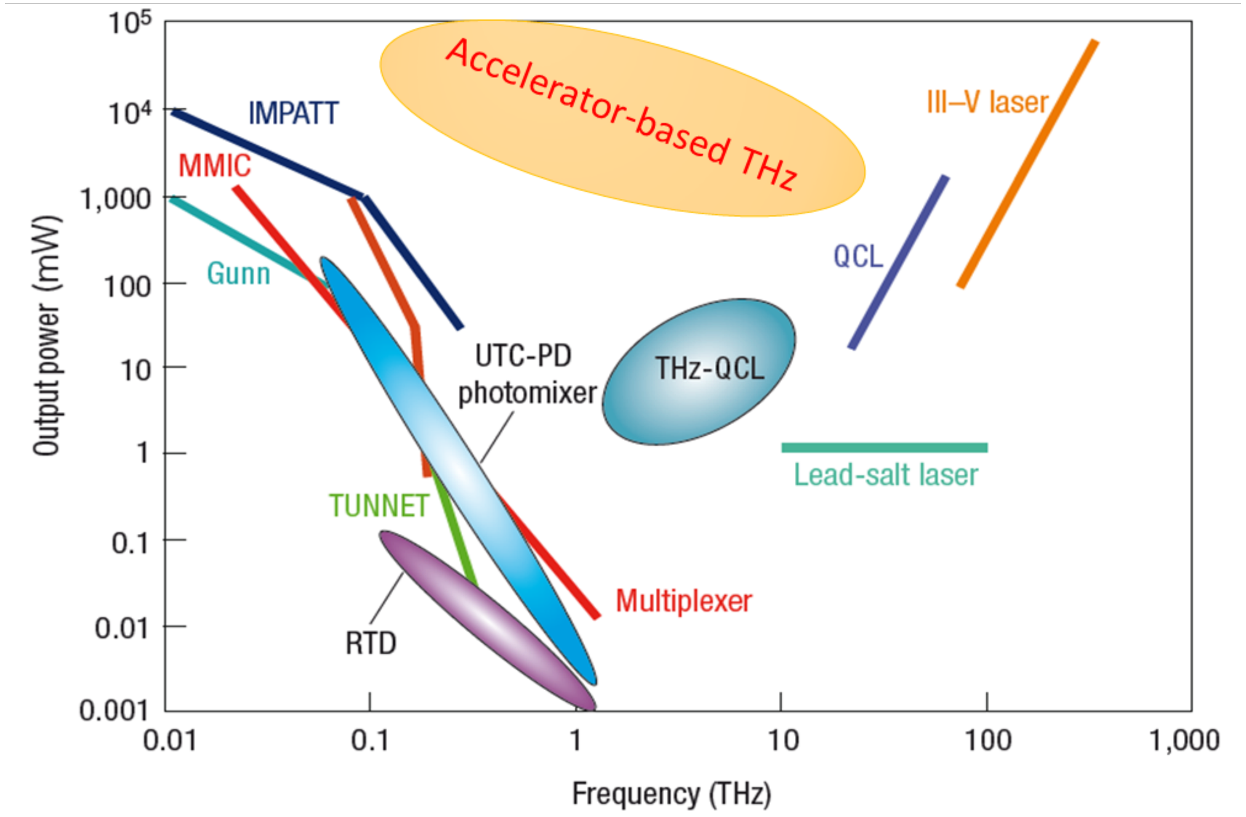




HX Xu, LX Yan, et al, Nature Photonics 2021

Accelerator for THz

- Accelerators have great potential in high power THz radiation generation, especially in covering the so-called ‘THz-gap’ (1-10THz).

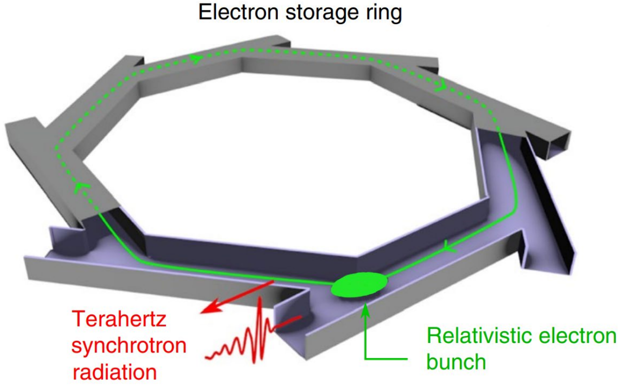


Adapted from Tonouchi, M. Nature Photon 1, 97–105 (2007).

Review of current accelerator-based THz sources

- Synchrotrons

THz Beamline	Peak Power	Pulse Energy
ANKA-IR[1] (SR)	1.3W	2pJ
BL5a@DELTA[2] (CHG)	10W	1nJ
MLS-IR[3] (Low-α)	35W	0.12nJ



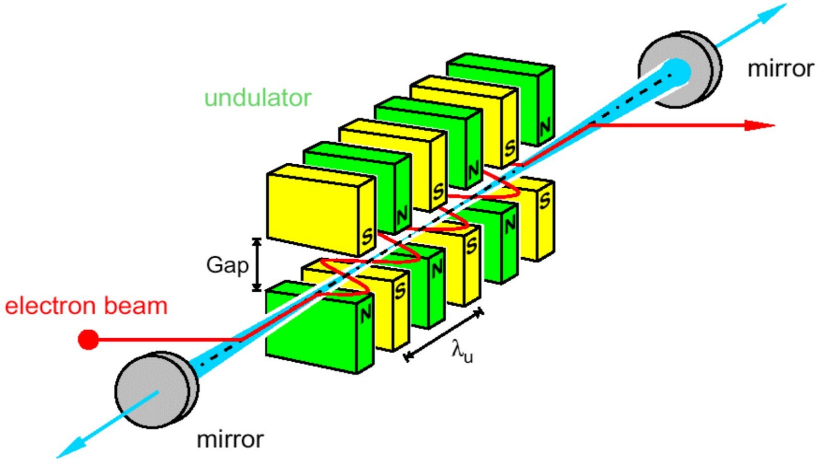
⇒ Generally incoherent
Low pulse energy
and large storage ring

- Oscillators-based THz FEL

THz Beamline	THz Tuning Range	Peak Power	Micro Pulse Energy
FLARE[4]	0.25-3THz	100kW	<5μJ
FELIX[4]	2-120THz	150MW	<40μJ
CTFEL[5]	0.67-4.2THz	100kW	1μJ

⇓

Moderate pulse energy and complicated design
(High rep-rate beam, Superconducting, THz Cavity, Multi-Beamline)



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[1] Müller, A. S., et al. Characterizing THz coherent synchrotron radiation at the ANKA storage ring. 14th European Particle Accelerator Conference. Proceedings of EPAC. 2008.
[2] Ungelenk, P., et al. Continuously tunable narrowband pulses in the THz gap from laser-modulated electron bunches in a storage ring. *Physical Review Accelerators and Beams* 20.2 (2017): 020706.
[3] Müller, R., et al. Status of the IR and THz beamlines at the Metrology Light Source. Journal of Physics: Conference Series. Vol. 359. No. 1. IOP Publishing, 2012.
[4] Redlich, Britta. The infrared and THz user facility FELIX in Nijmegen.
[2] Kui, Zhou, et al. Status and upgrade plan of CAEP THz-FEL facility. High Power Laser and Particle Beams 34.10 (2022): 104013-1.

Towards a compact THz source

- Single Pass THz Sources

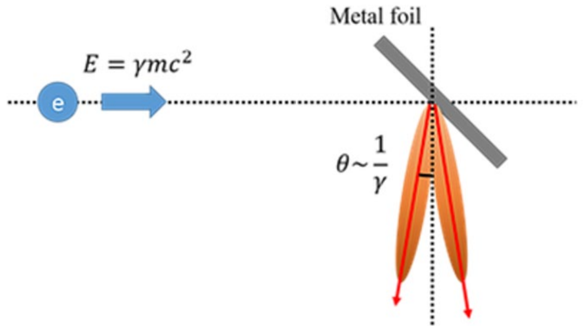
Beamline	THz Tuning Range	Pulse Energy
LCLS[1]	3-30THz	200μJ
FACET[1]	0.5-5THz	600μJ
TELBE[2]	0.1-3THz	2μJ

Broad-band CTR

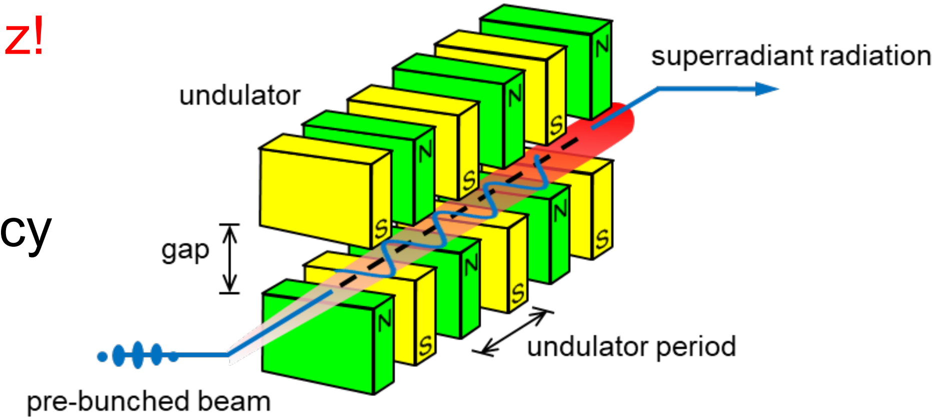
Undulator radiation

⇓

High peak power (pulse energy)



- A compact beamline can be specifically optimized for THz!
- To obtain high power THz radiation in a wide range, pre-bunch techniques are to be extended to a larger frequency range with larger beam charge.



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[1] Wu Z, Fisher A S, Goodfellow J, et al. Intense terahertz pulses from SLAC electron beams using coherent transition radiation[J]. Review of Scientific Instruments, 2013, 84: 022701.

[2] Michel P. ELBE Center for High-Power Radiation Sources[J]. Journal of large-scale research facilities, 2016, 2, A39.

Superradiant Radiation from Bunched Electrons

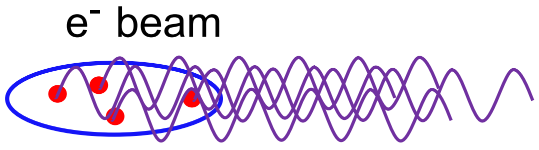
- Bunched electron beams can generate superradiant THz radiation

Total radiation power of electron bunch is formulated as:

$$P(\omega) = P_{point}(\omega)[N_e + N_e^2 b^2(\omega)]$$

Buncing factor: $b^2(\omega) = f(\omega) = \left|\int e^{-i\omega z/c} S(z)dz\right|^2$

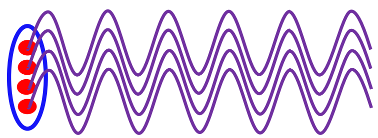
$\boxed{\sigma \gg \lambda}$



Incoherent radiation

$$P_\omega \propto N P_{\text{point}}$$

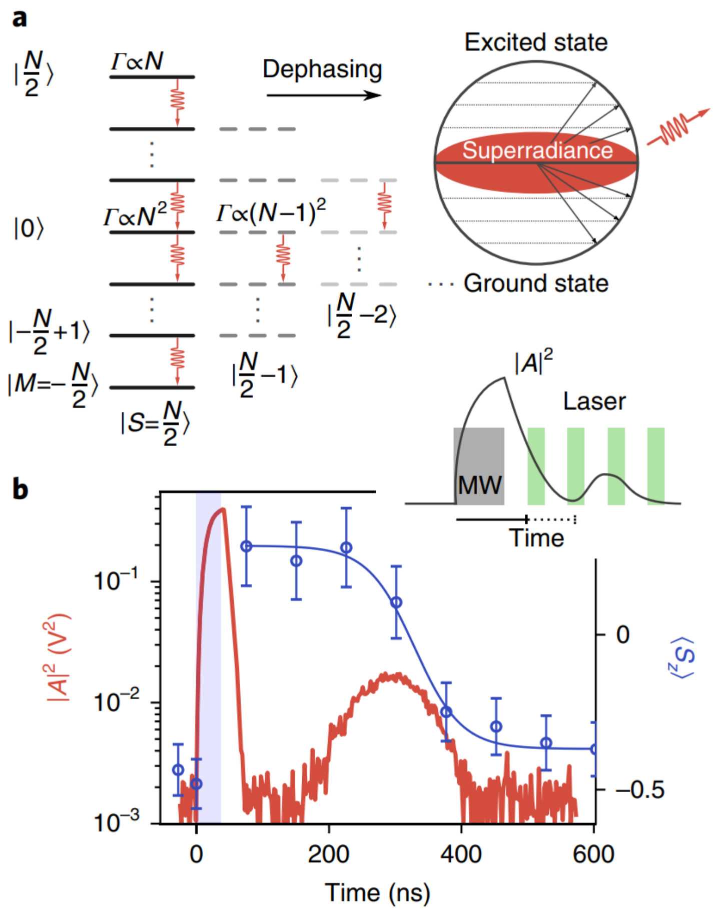
$\boxed{\sigma \ll \lambda}$



Coherent radiation

$$P_\omega \propto N^2 P_{point}$$

oscillating free electron as dipole



electron beams

atoms, quantum dots, color centers

Superradiant Radiation from Bunched Electrons

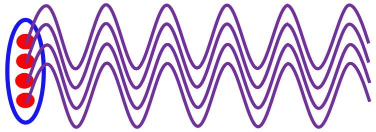
- Coherent THz radiation of e beam depends on the bunch length.

Total radiation power of electron bunch formulated as: $P(\omega) = P_{point}(\omega)[N_e + N_e^2 b^2(\omega)]$

$P_{\mathrm{point}}(\omega)$: the radiated power from a single point electron

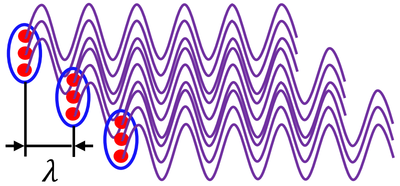
N_e : number of electrons in a bunch, $100pC$ $(N_\mathrm{e}{\sim}10^9)$

Buncing factor:$b^2(\omega) = f(\omega) = \left|\int e^{-i\omega z/c} S(z)dz\right|^2$



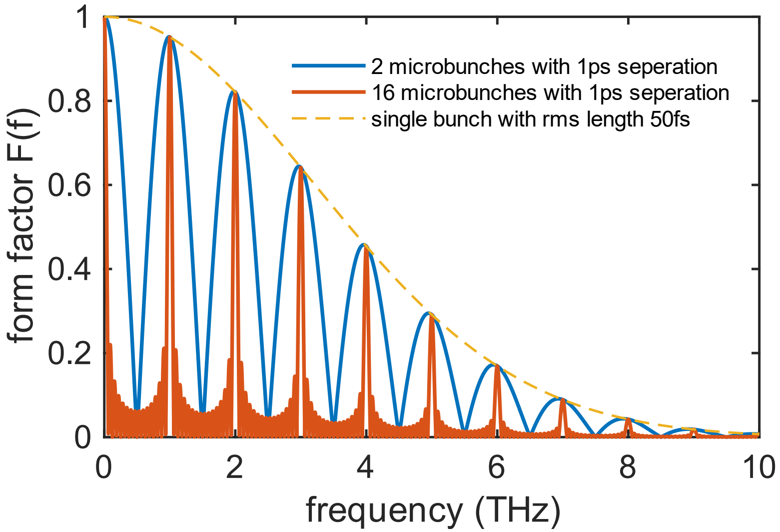
Coherent radiation

$P_\omega \propto N^2 P_{point}$



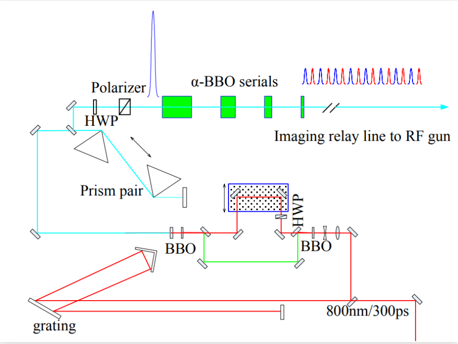
Coherent radiation from bunch train

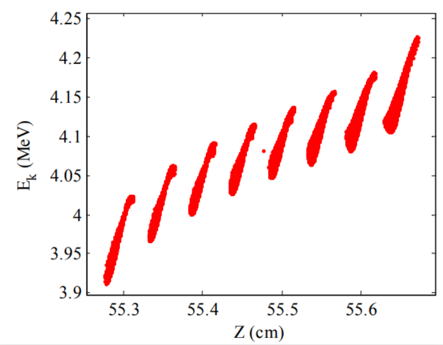
$P_{\omega_0} \propto (MN)^2 P_{point}(\omega_0)$



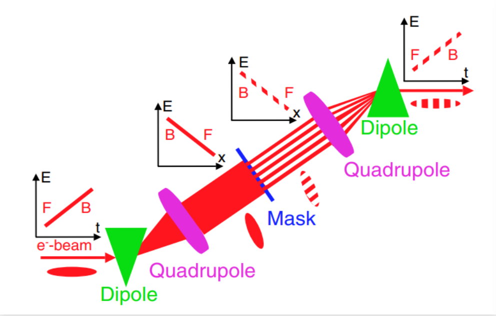
THz Bunch Train Generation: General Principle

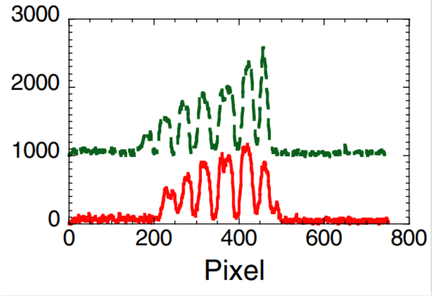
- To generate the density modulation at THz frequency range, we can
  - ✓ Directly generate bunch train by modulated drive laser





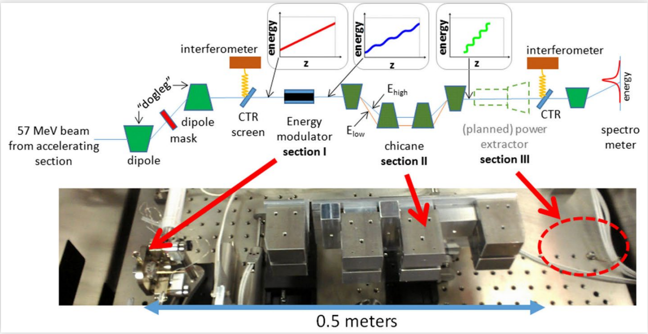
  - ✓ Modulate the longitudinal profile by mask (emittance exchange)

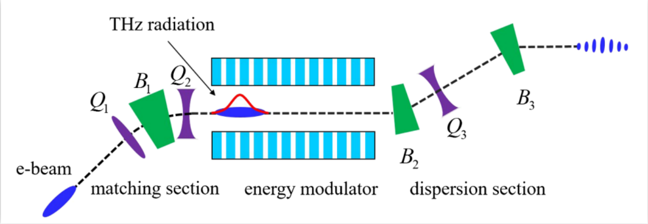


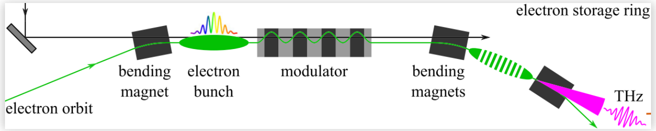


IPAC 10 (2010), PRL 101, 054801 (2008), PRL 108, 144801 (2012)

  - ✓ Modulate the energy profile and disperse the electron beam





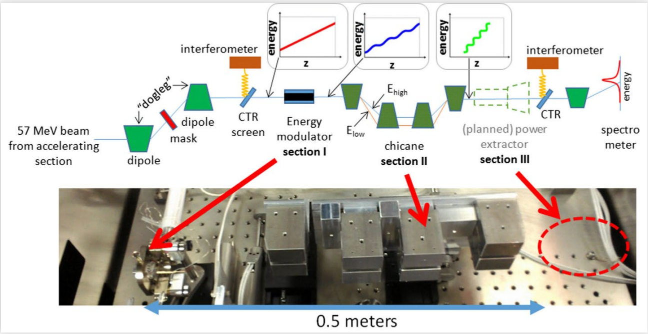


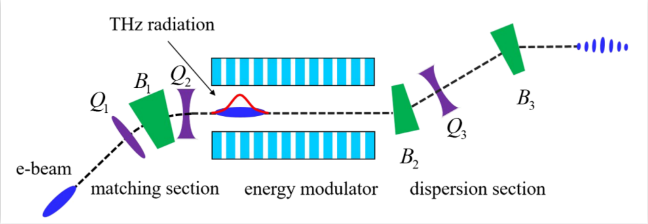
PRL 111, 134802 (2013), PRAB 20, 020706 (2017), PRAB 22, 060701 (2019)

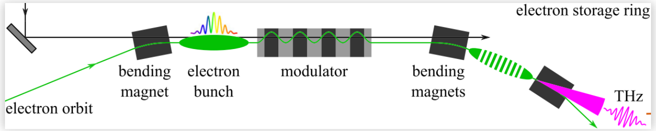
THz Bunch Train Generation: General Principle

- To generate the density modulation at THz frequency range, we can

✓ Modulate the energy profile and disperse the electron beam



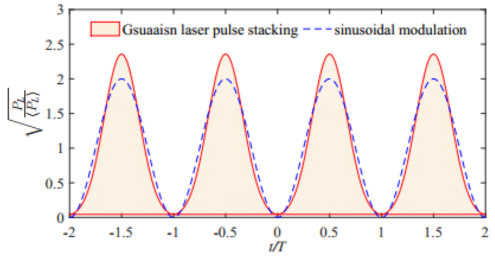




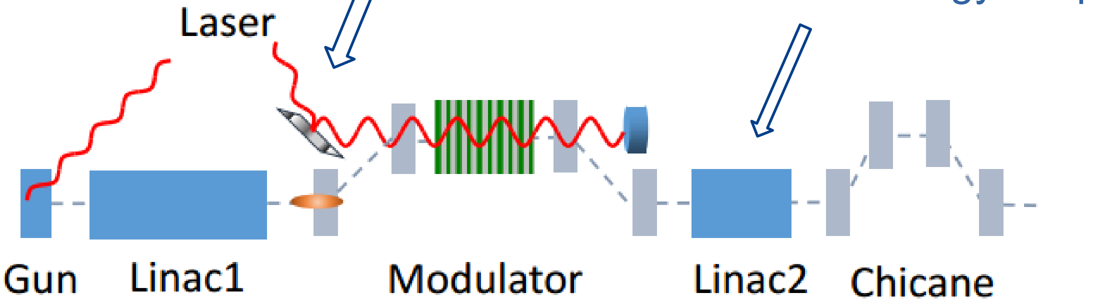
PRL 111, 134802 (2013), PRAB 20, 020706 (2017), PRAB 22, 060701 (2019)

THz Bunch Train Generation: Laser Modulation

- To breakthrough the limitations of above methods, expanding to cover wider tuning range
- Seeking for new schemes to generate bunch trains with more flexibility.
  - ✓ We proposed a scheme to generate electron bunch train with *wide frequency range* (1~10THz) and *large bunching factor* (~0.4),suitable for *large beam charge*.
  - ✓ The method is based on laser-electron interaction to modulate the slice energy spread.

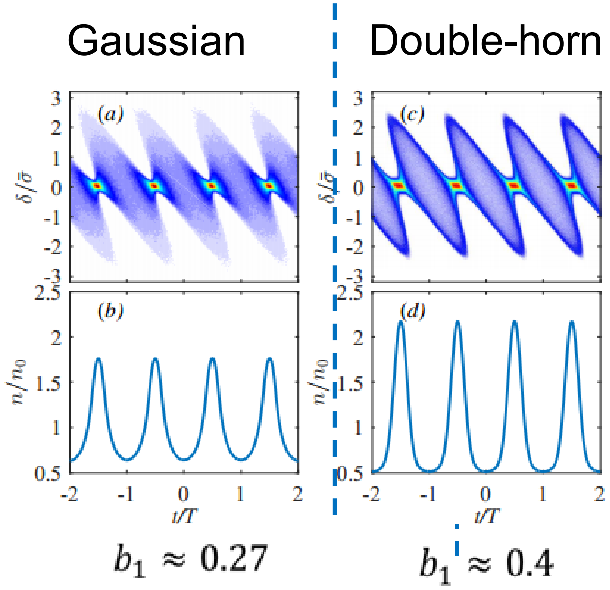


Deeply modulated laser pulse
With THz structure



Introduce energy chirp

Dispersion section

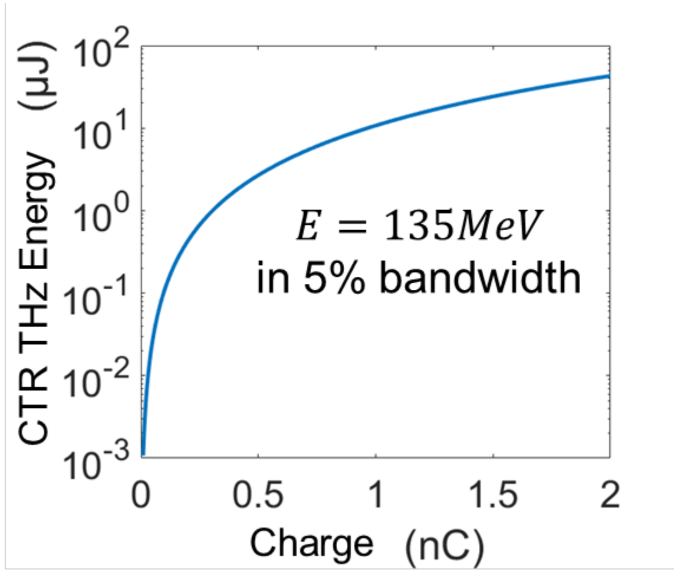


- ✓ The modulation happens after acceleration, so it is suitable for large beam charge.

Z Zhang, LX Yan, et al, PRAB, 20, 050701(2017)

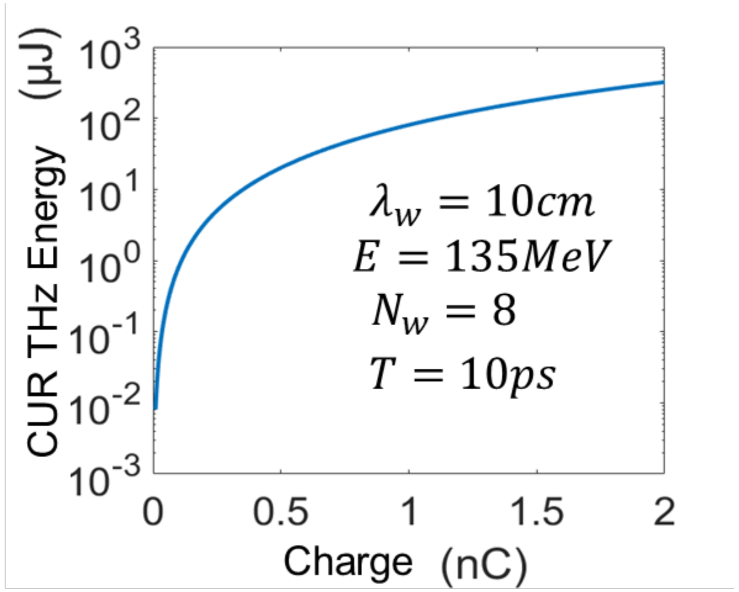
THz Bunch Train Generation: Laser Modulation

- By CTR, CUR, et al, tunable high power THz radiation can be generated. Radiation enhancement is expected by increasing beam charge.
- mJ level narrow band THz radiation energy (hundreds of MW power) with longer undulator.



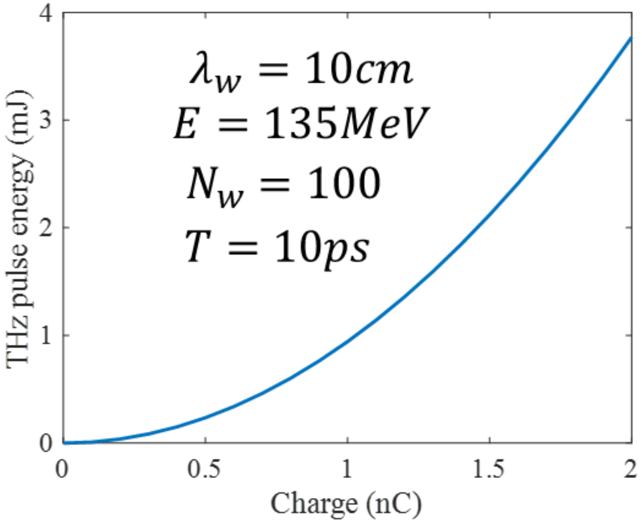
Coherent Transition Radiation

- >10 μJ, 1MW, 2THz@1nC
- >40 μJ, 4MW, 2THz@2nC



Coherent Undulator Radiation

- ~150 μJ, 15MW, 2THz@1nC
- ~600 μJ, 60MW, 2THz@2nC



Coherent Undulator Radiation

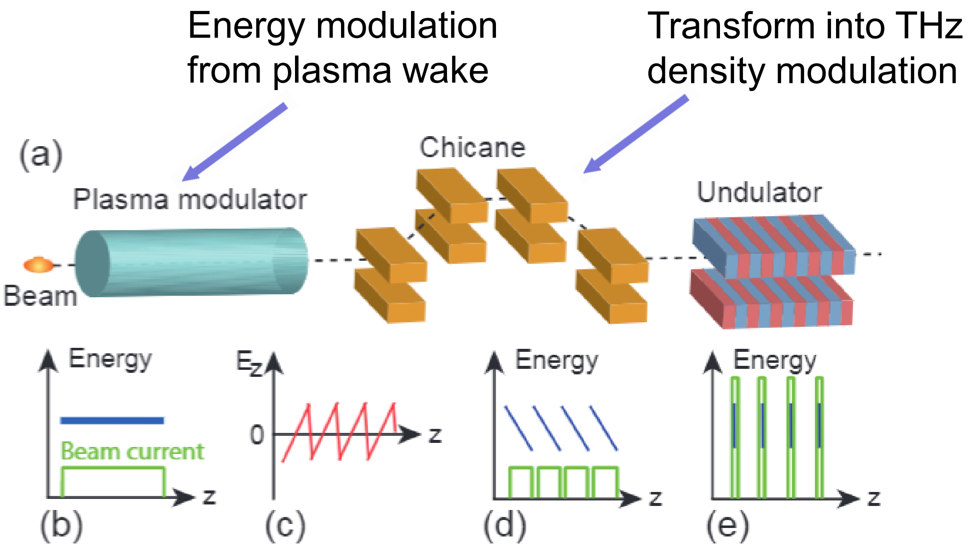
- ~900 μJ, 90MW@2THz 1nC
- ~3.8 mJ, 380MW@2THz 2nC

Courtesy to Koichi Kan @Osaka University

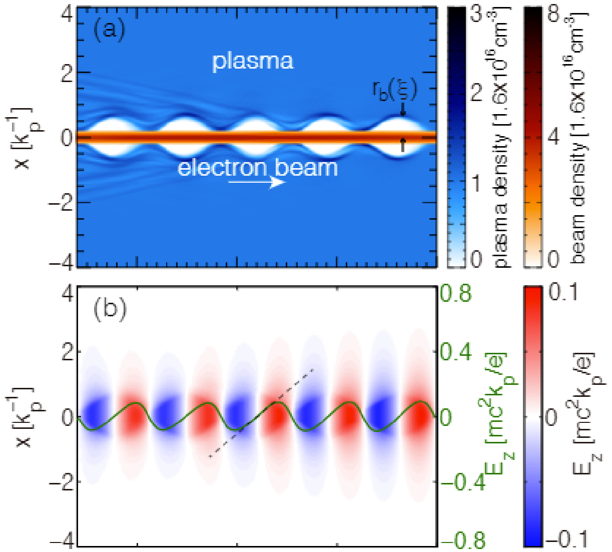
THz Bunch Train Generation: Plasma Wake Modulation

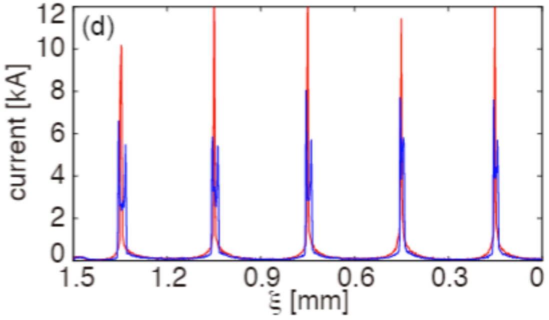
- Using nonlinear plasma wake invoked by the e beam ($n_e>n_p$) to generate sawtooth-shape longitudinal energy modulation.
- Then with chicane to transform into density modulation thus form THz bunch train with high bunching factor (up to 0.8). Up to 10mJ THz energy and ~kW level average THz power

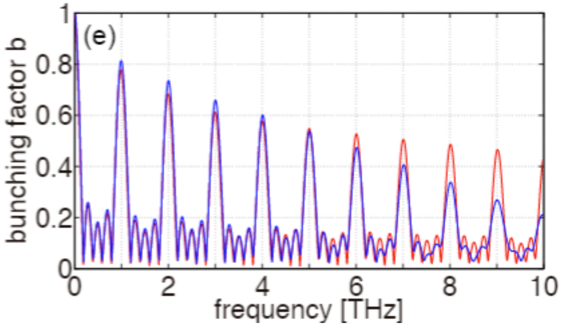
Parameter	Value	Units
Beam charge	2.5	nC
Beam energy	135	MeV
Slice energy spread	0.02	MeV
Peak current	0.5	kA
Flat top	5	ps
Normalized emittance	2	mm· mrad

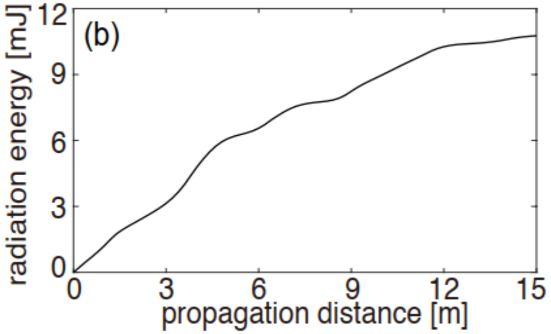

Energy modulation from plasma wake

Transform into THz density modulation





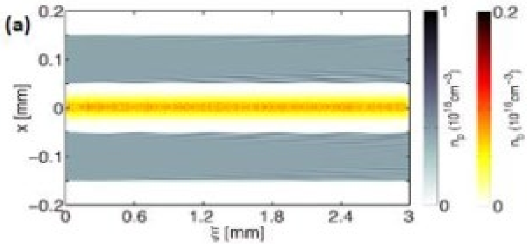


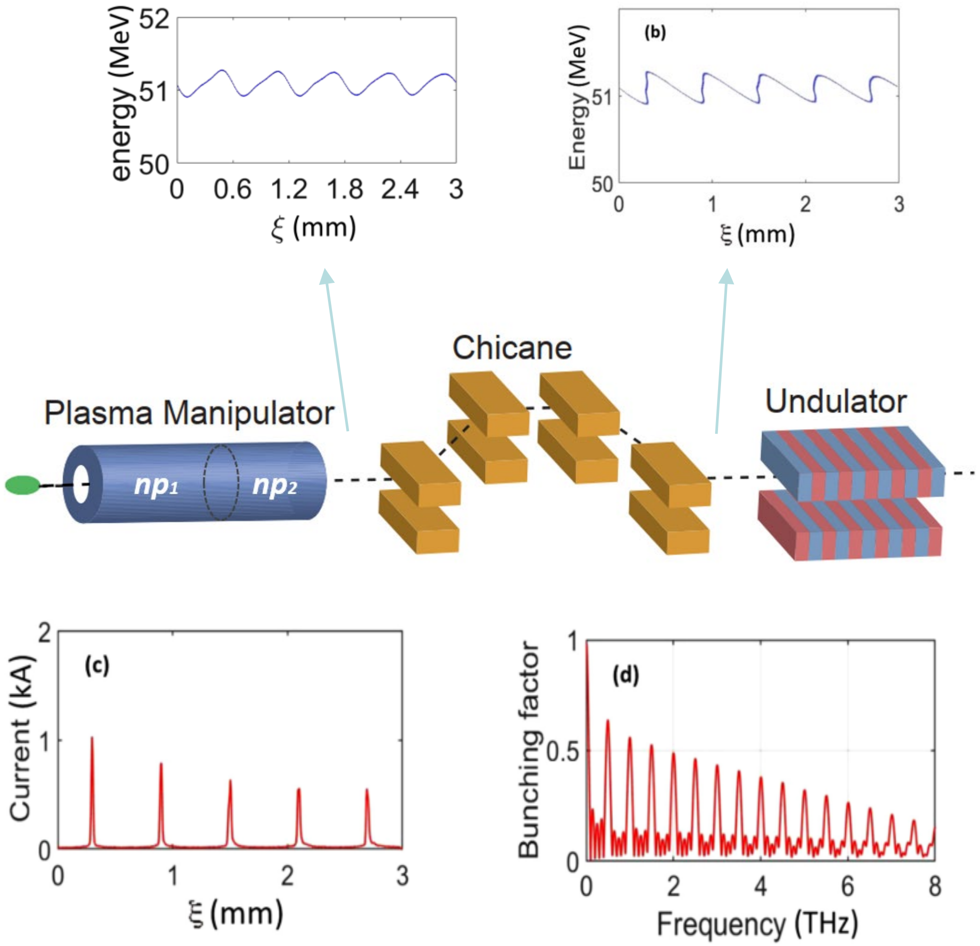


HQ Feng, et al, PRApplied 15, 044032(2021)

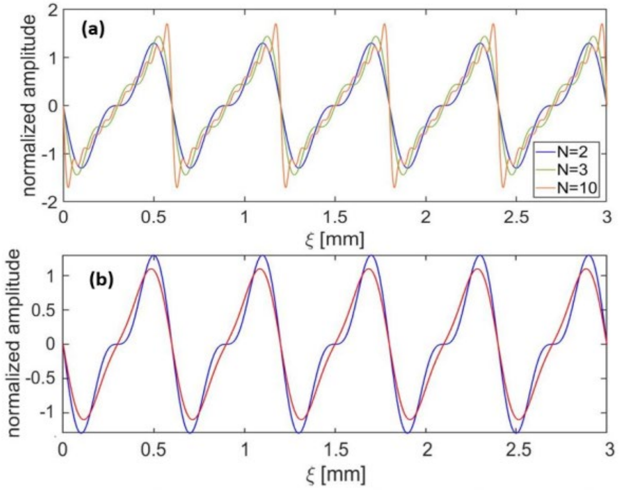
THz Bunch Train Generation: Plasma Wake Modulation

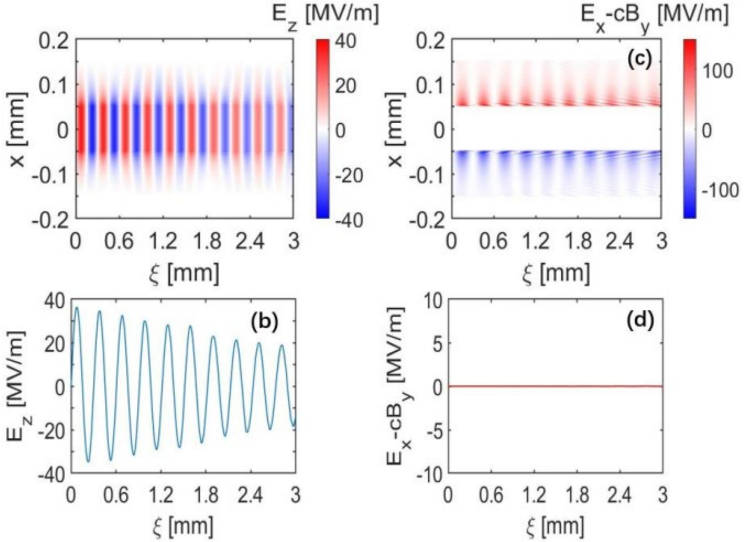
- A scheme of using hollow plasma channel to modulate relatively low charge and low current beam is proposed.
- The combination of multistage hollow channel plasma with a chicane can generate high-quality microbunch trains with a bunching factor 0.7@0.5THz，0.4@5THz.





SEGMENTED HOLLOW CHANNEL FOR ENERGY MODULATION





HQ Feng, et al, Phys. Plasmas 28, 103101 (2021)

THz Bunch Train Generation: Experiments

- Summarize the performance of different methods for bunch train generation:

articles	organization	Beam charge/pC	Tuning range/THz	Bunching factor
PRL 101, 054801 (2008)	BNL	~50	0.7-1.4	
PRL 105, 234801 (2010)	FERMI	~15	0.37-0.86	
PRL 106, 184801 (2011)	UCLA	~22	1.0	~0.2
PRL 107, 204801 (2011)	BNL	~100	0.26-2.6	
PRL 109, 074801 (2012)	SLAC	~40	12-17	~0.02
PRL 108, 144801 (2012) *PRL 111, 134802 (2013)*	ANL	~100	0.68-0.9	~0.3
PRL 116, 184801 (2016)	THU	~700	0.6~1.6	~0.2
PRL 109, 074801 (2019)	DESY	~1100	0.19-0.3	~0.2
		small	*Very limited*	*small*

Nonlinear Space Charge Oscillation for THz Bunch Train

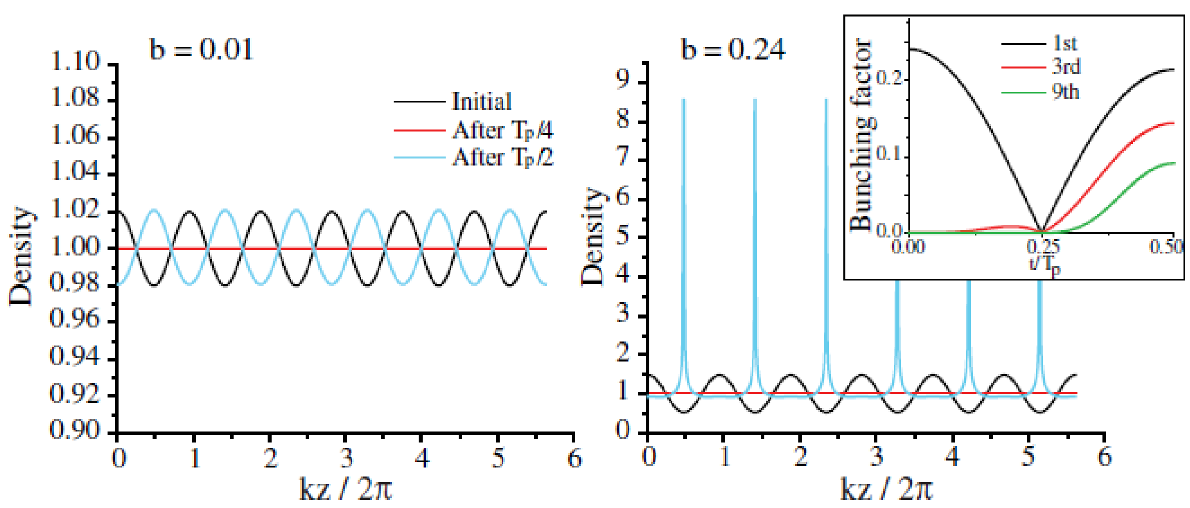
- **Space Charge Oscillation:** for electron beam with small initial density modulation, its density distribution oscillates during the beam transport where it converts into energy modulation after ¼ plasma oscillation period and revivals after ½ period.
- **Nonlinear Space Charge Oscillation:** with large initial density modulation, the interference of higher spatial harmonics leads to density spikes.

$$n(z,t) = n_0\left[1 + \cos(\omega_p t)\sum_{m=1}^{\infty} m c_m(t)\cos(mkz)\right]$$

$$\eta(z,t) = \frac{\gamma^2 k_p}{k}\sin(\omega_p t)\sum_{m=1}^{\infty} c_m(t)\sin(mkz)$$

$$E(z,t) = -\frac{m_0\omega_p^2}{ek}\cos(\omega_p t)\sum_{m=1}^{\infty} c_m(t)\sin(mkz)$$

$$\omega_p = \sqrt{\frac{e^2 n_0}{\epsilon_0 m_0 \gamma^3}}, c_m(t) = \frac{(-1)^{m+1}}{m}\frac{2}{2\sin^2\left(\frac{\omega_p t}{2}\right)} J_m\left(4mb\sin^2\left(\frac{\omega_p t}{2}\right)\right)$$



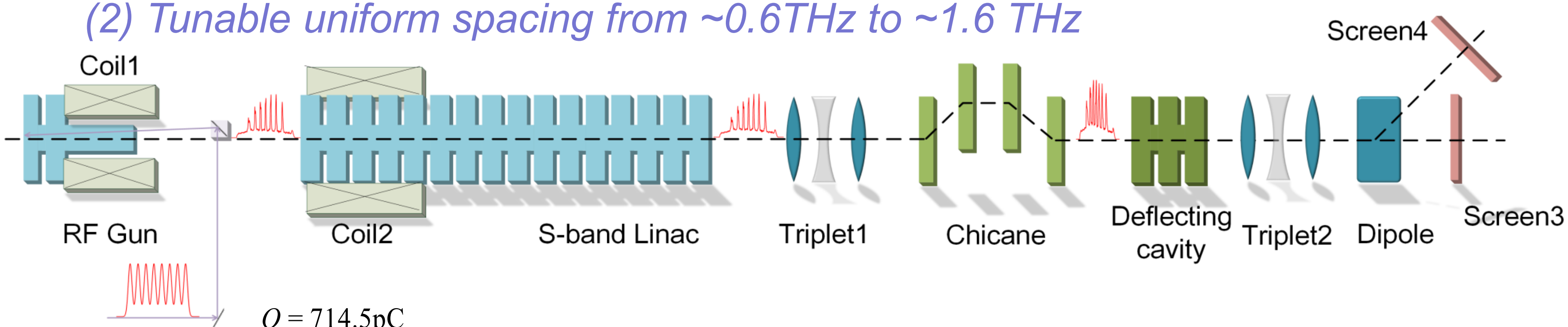
Phys. Rev. Lett.106.184801 (2011)
Phys. Rev. ST Accel. Beams 16, 100701 (2013)

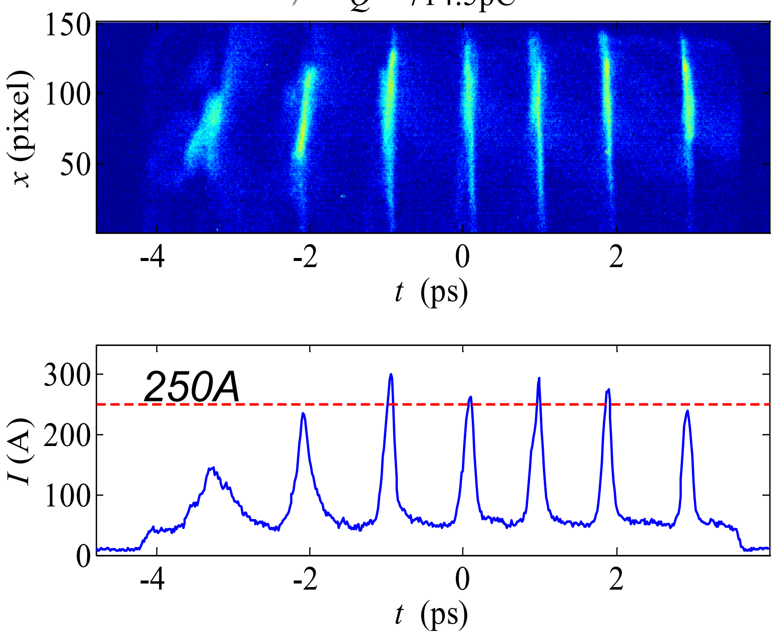
Nonlinear Space Charge Oscillation for THz Bunch Train

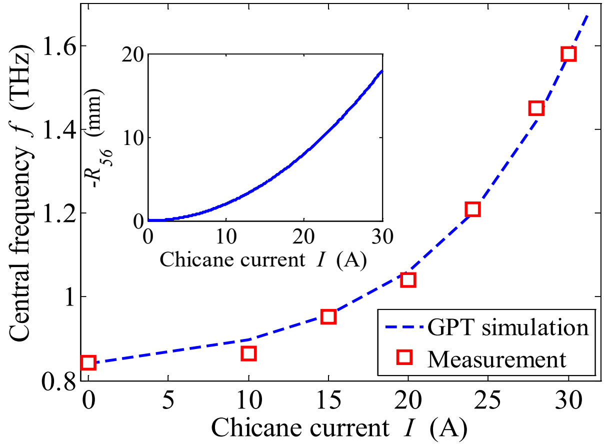
- We take advantage of NLSCO to generate multi-bunch trains with:

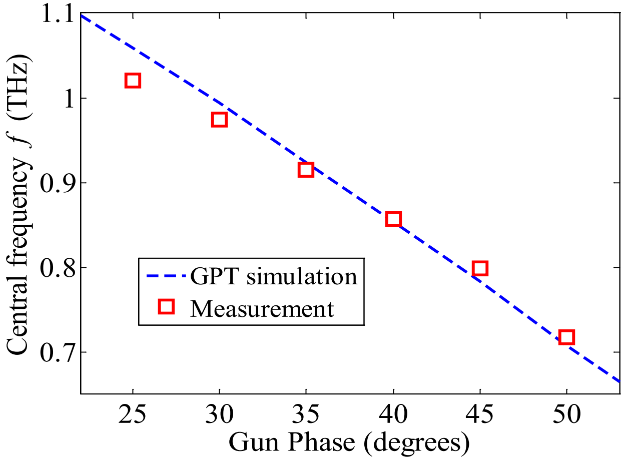
  (1) Large charge (~700pC) and high peak current (~300A)

  (2) Tunable uniform spacing from ~0.6THz to ~1.6 THz





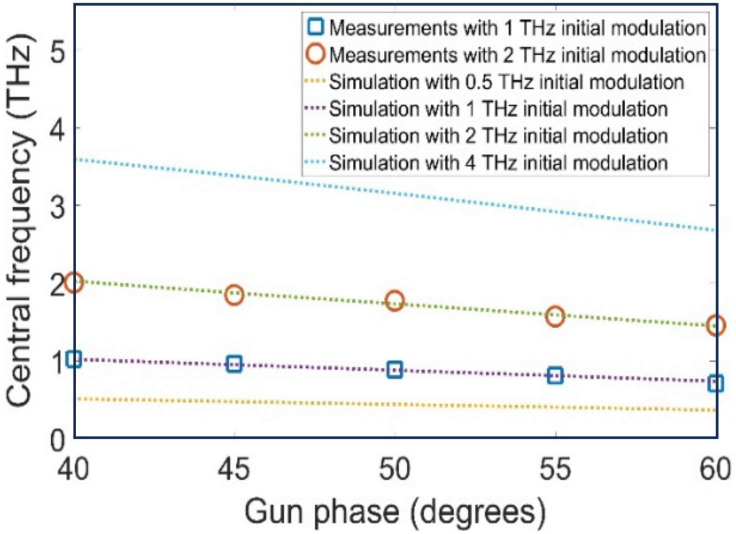


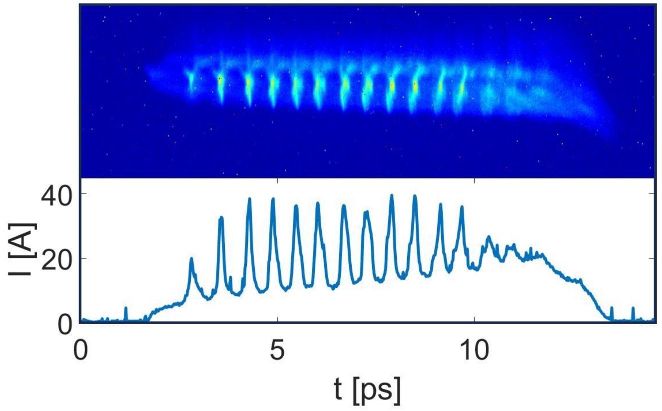


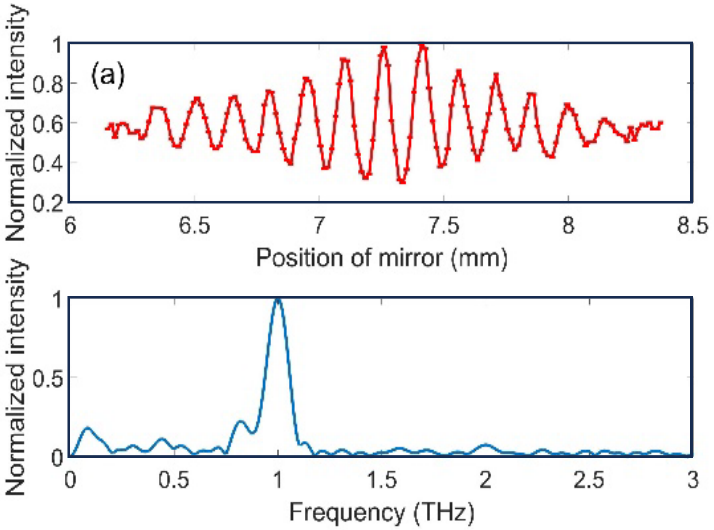
Z Zhang, LX Yan, et al, PRL 116, 184801 (2016)

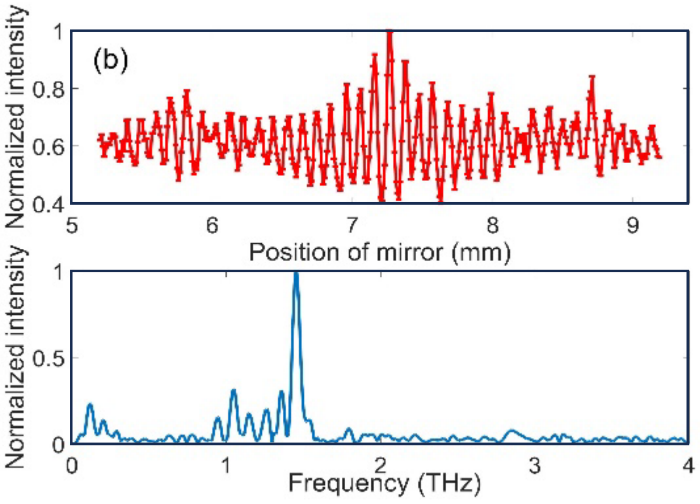
Extending the Tuning Range of NLSCO

- We further optimized the nonlinear space charge oscillation process. The bunching can be tuned between 0.6-2THz.





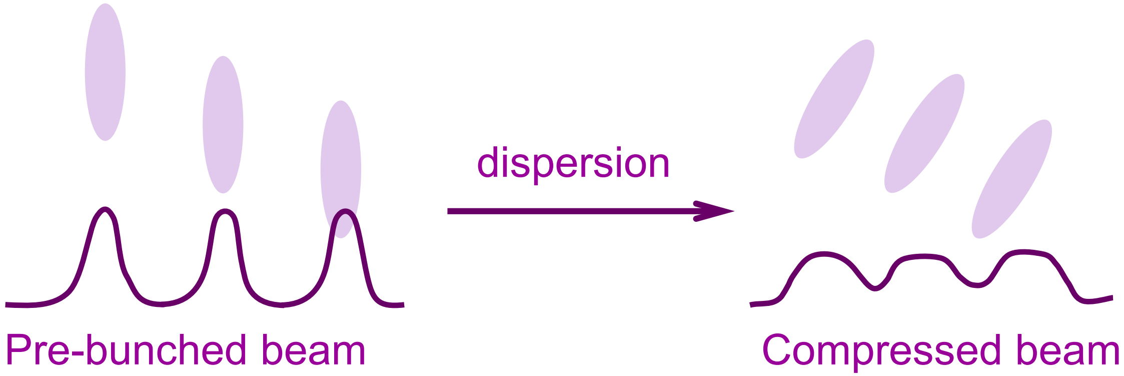




YF Liang, LX Yan, et al, Sci China-Phys Mech Astron (2023)

Nonlinear Space Charge Force for THz Bunch Train

- If a pre-bunched beam is compressed or stretched, its uncorrelated energy spread will result in degradation of bunching:

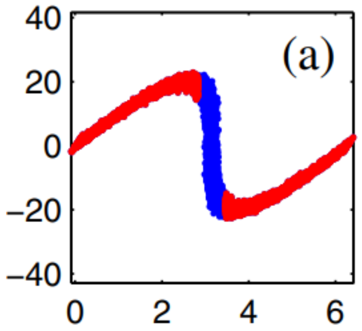


Energy Modulation!

- For sine energy modulated electron beam, the bunching factor it can achieve at the fundamental frequency after dispersion R_{56} is:

$$b_1 = \boxed{J_1(k_0 R_{56} A)}\exp\left(-\frac{1}{2}k_0^2 R_{56}^2 \sigma_\delta^2\right)$$

bunching factor limited by sinusoidal modulation



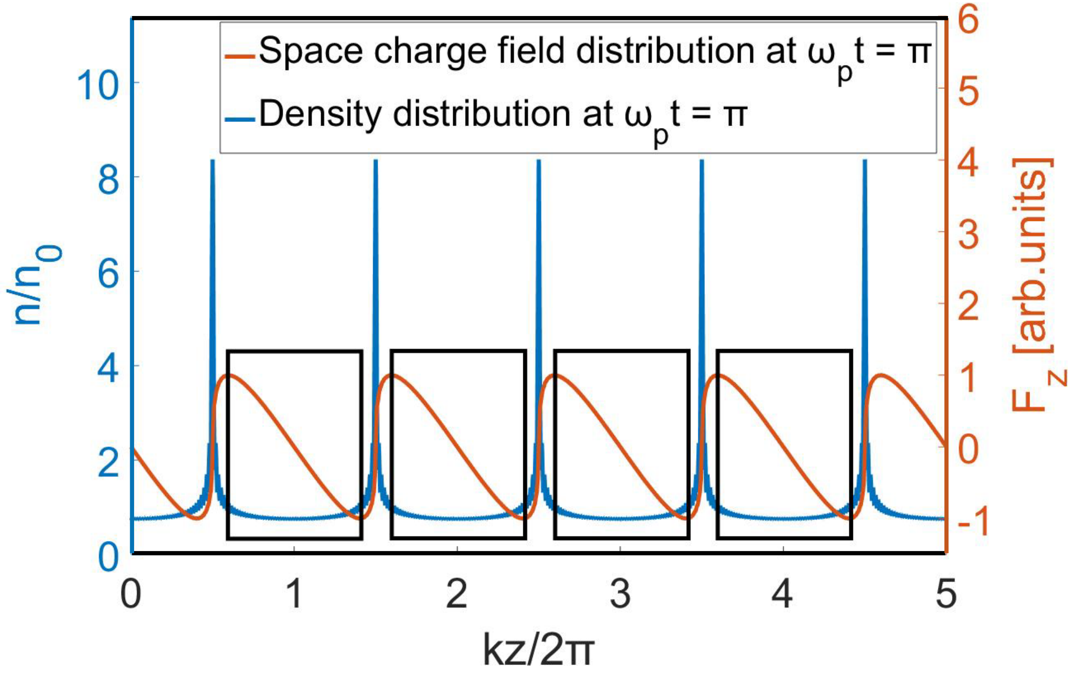
Quasi-linear Modulation!
Ultrashort Micro-bunch!

Nonlinear Space Charge Force for THz Bunch Train

- For NLSCO, after 1/2 plasma oscillation period: $\omega_p t = \pi$

$$n(z,0) = n_0\left(1 - \sum_{m=1}^{\infty}(-1)^{m+1} J_m(4mb_0)\cos(mkz)\right) \qquad \omega_p = \sqrt{\frac{e^2 n_0}{\varepsilon_0 m_0 \gamma^3}}$$

$$F_z(z,0) = \frac{m_e \omega_p{}^2}{k}\sum_{m=1}^{\infty}(-1)^{m+1}\frac{1}{m}J_m(4mb_0)\sin(mkz)$$

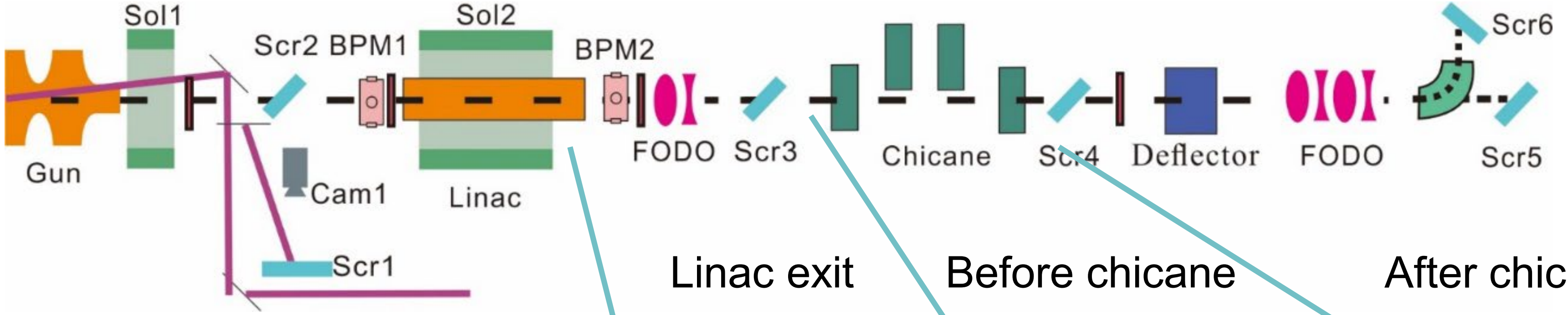


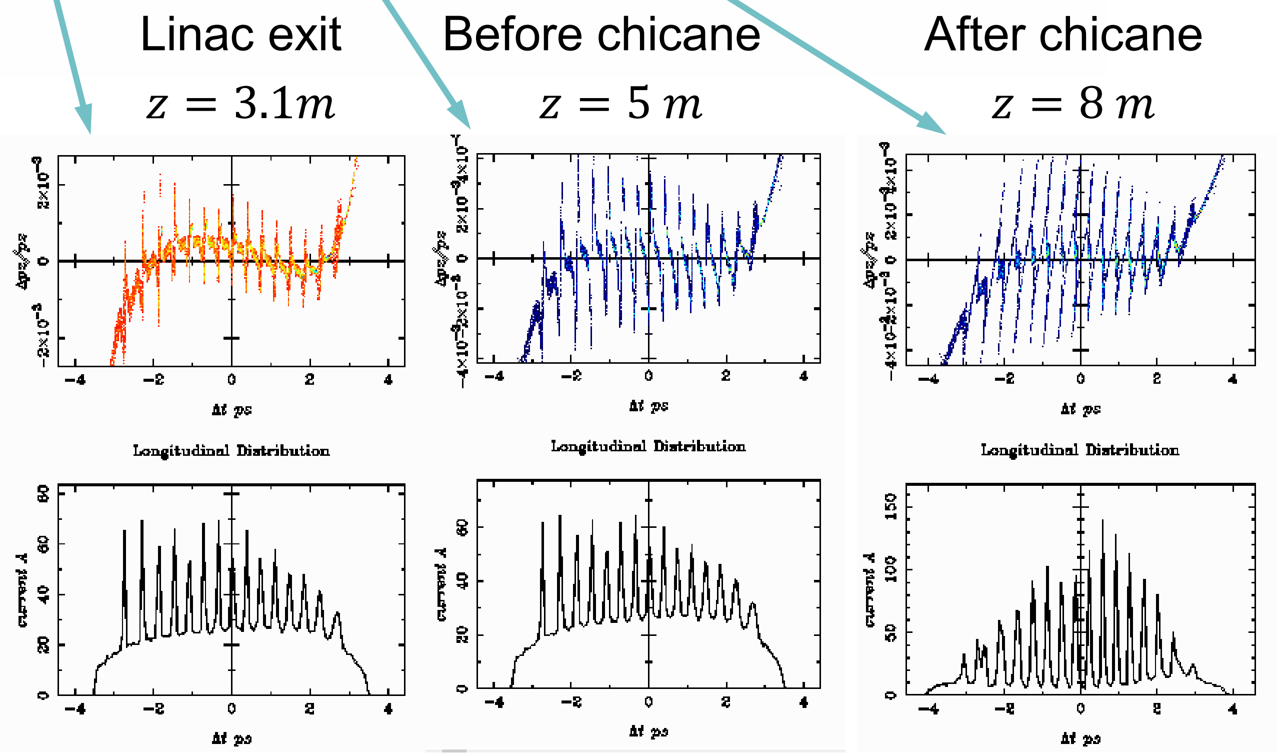
Quasi-linear Modulation
Ultrashort Micro-bunch

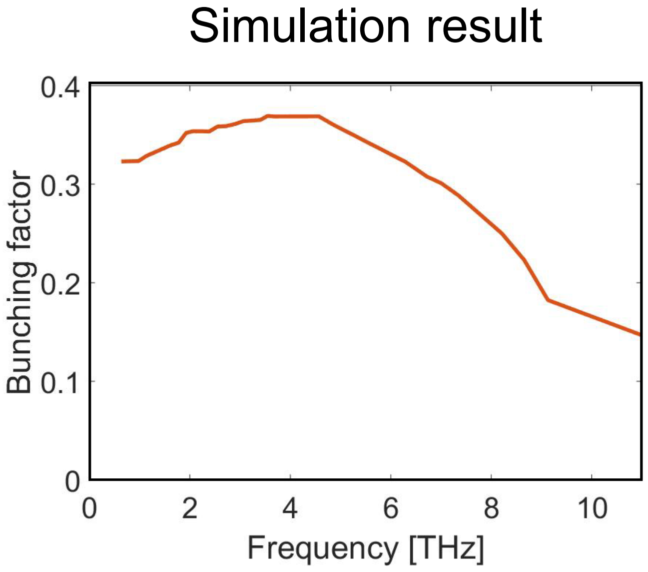
- The quasi-linear space charge force will induce linear energy modulation for the beam outside the peak. After dispersion ultrashort THz bunch trains can be generated.

Nonlinear Space Charge Force for THz Bunch Train

- Simulations confirm this idea for tunable THz bunch train generation with large bunching factor covering 1-10THz by controlling space charge force to modulate the beam energy.

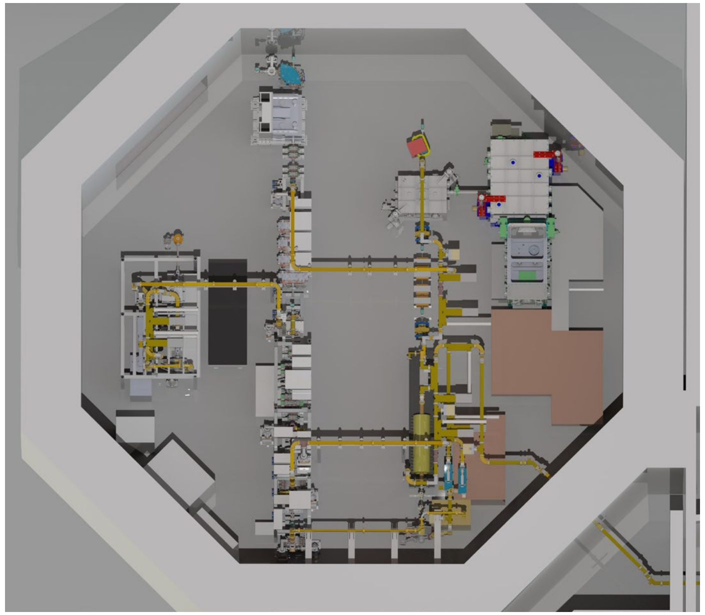






THz Beamline @AccLab of Tsinghua

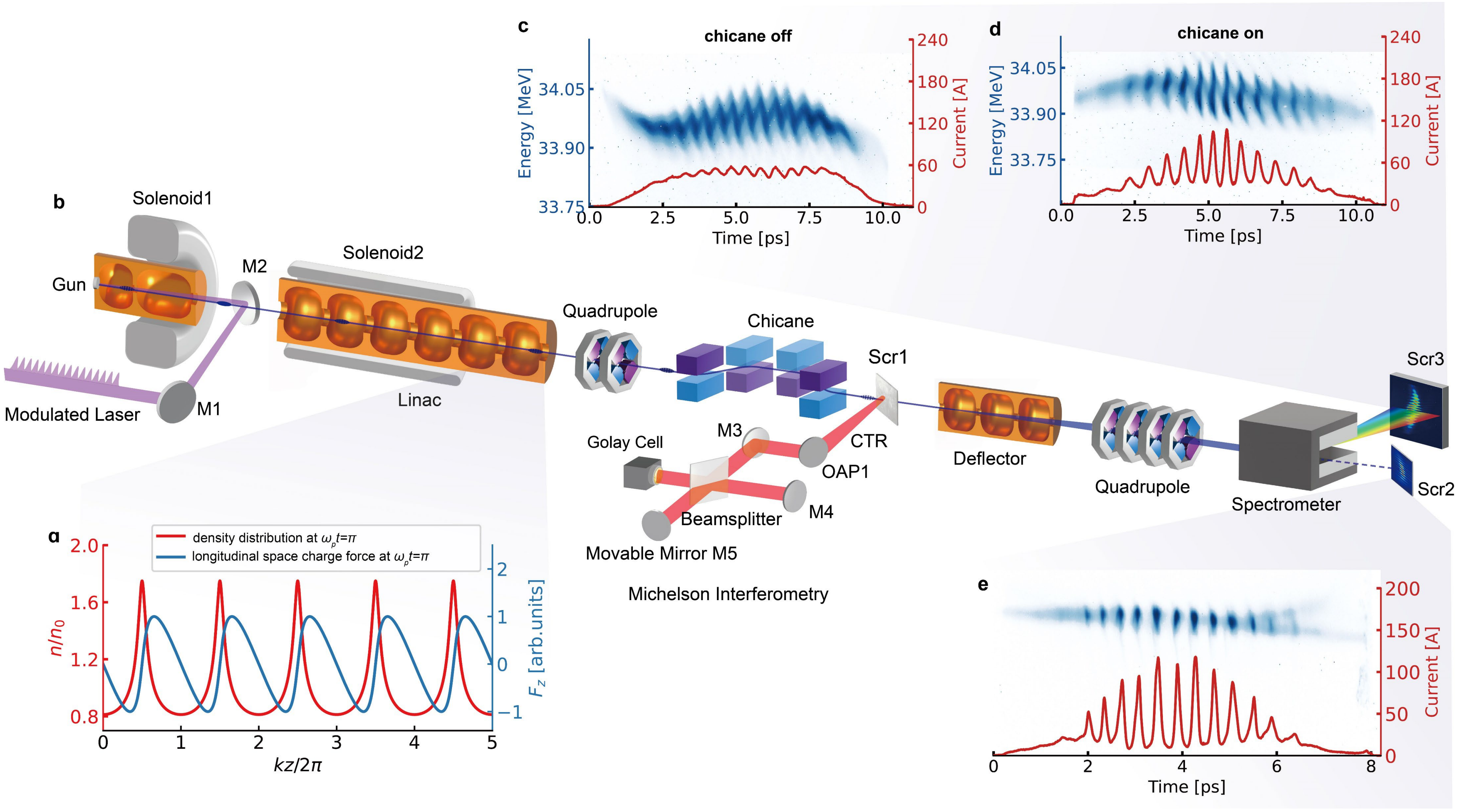
- For novel THz developments and applications, a new beam line has been designed and built up at our lab.
- After commissioning in Aug/2021, PoP experiments on novel THz bunch train generation schemes began.



Parameters	Value
Gradient of electron gun	110MV/m
Bunch charge	0-1000pC
Beam energy at gun exit	5MeV
Beam energy at linac exit	42MeV
Projected energy spread	0.2%
Voltage of deflecting cavity	3MV

Experimental Demonstration of THz Bunch Train

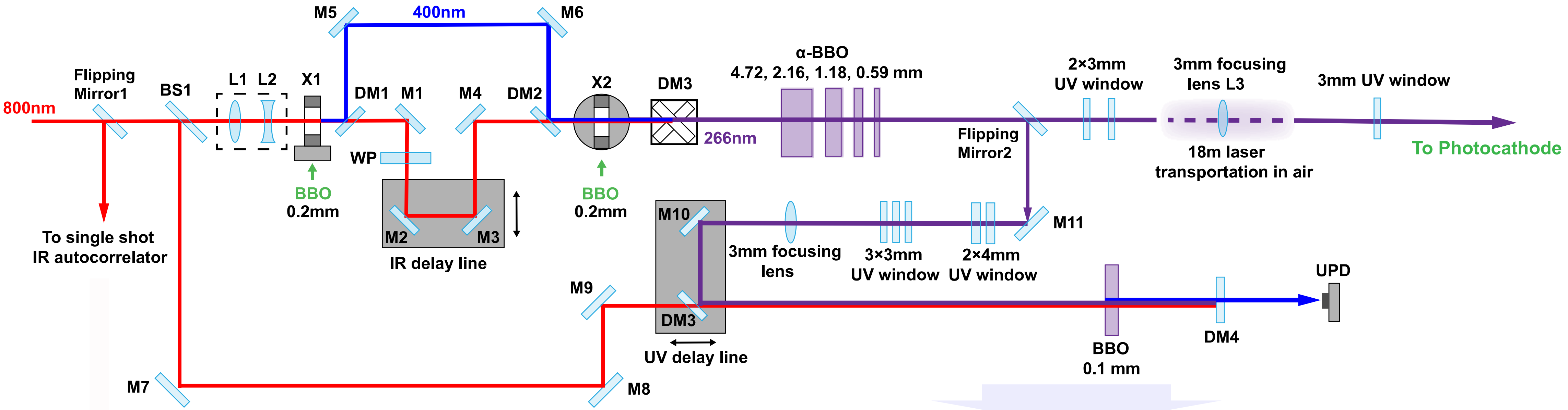
Experimental layout

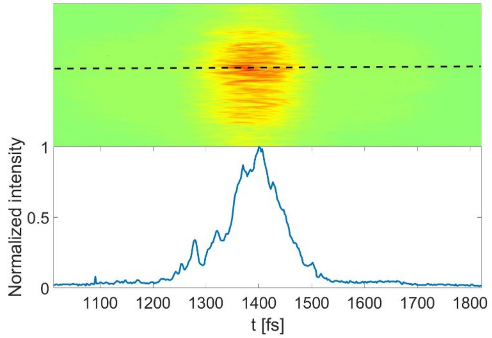


YF Liang, ZY Liu, LX Yan et al, Nature Photonics 17, 259-263(2023)

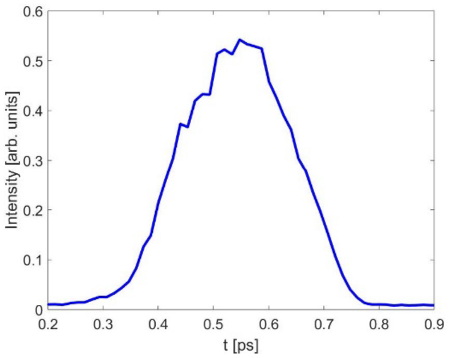
Experimental Demonstration of THz Bunch Train

- **Drive laser system and diagnostics**

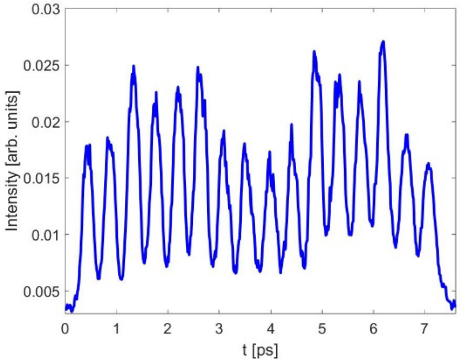




IR laser



UV Before stacking

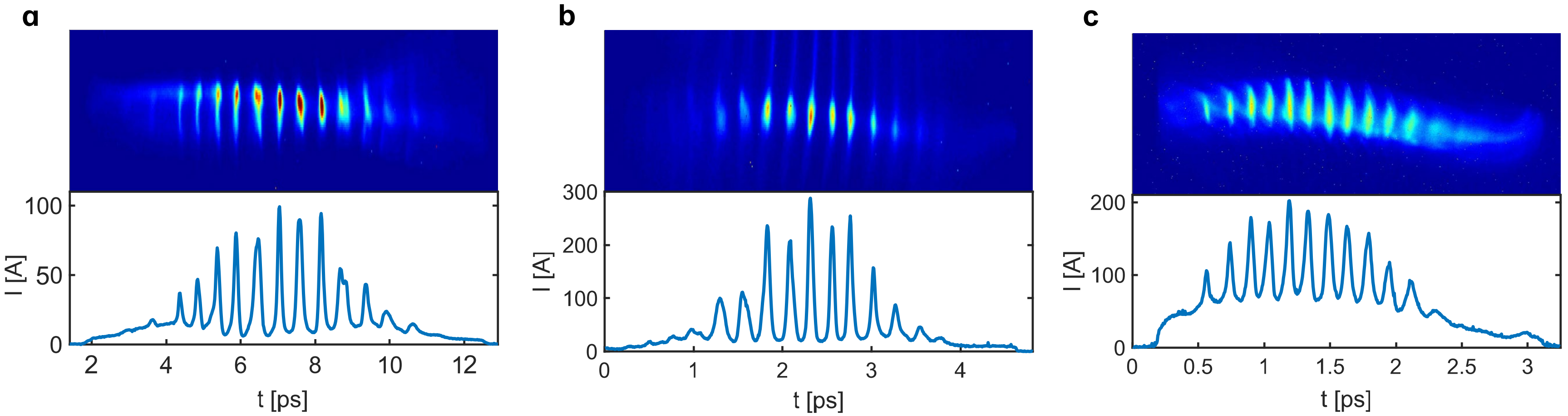


UV After stacking

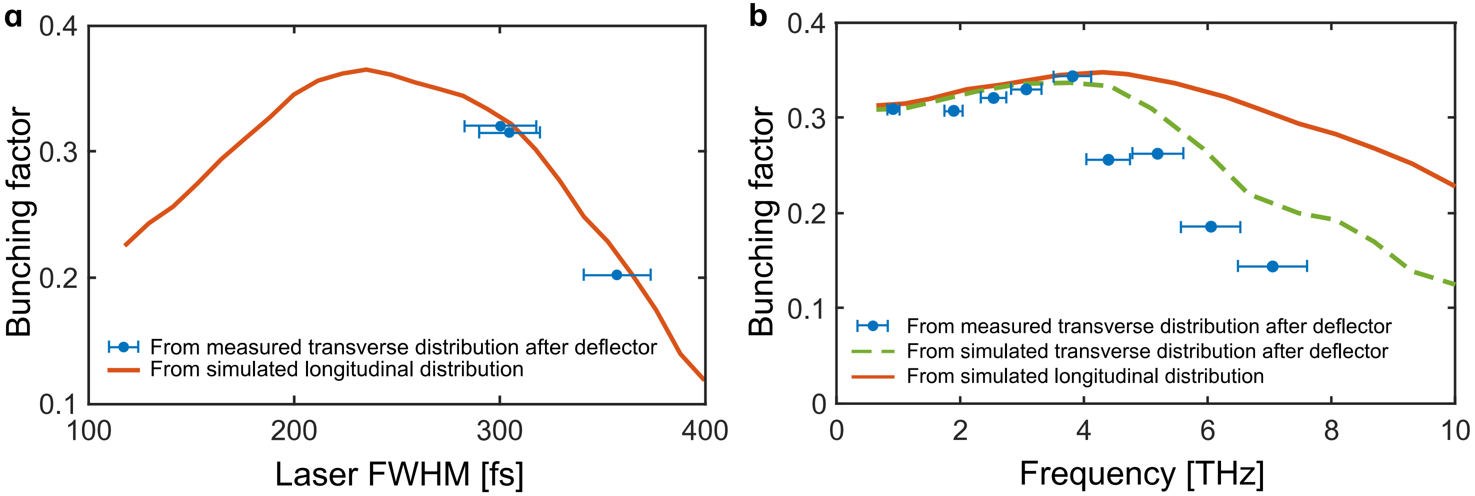
YF Liang, ZY Liu, LX Yan et al, Nature Photonics 17, 259-263(2023)

Experimental Demonstration of THz Bunch Train

- **Measured longitudinal density distribution and projected density profile of the bunch trains**



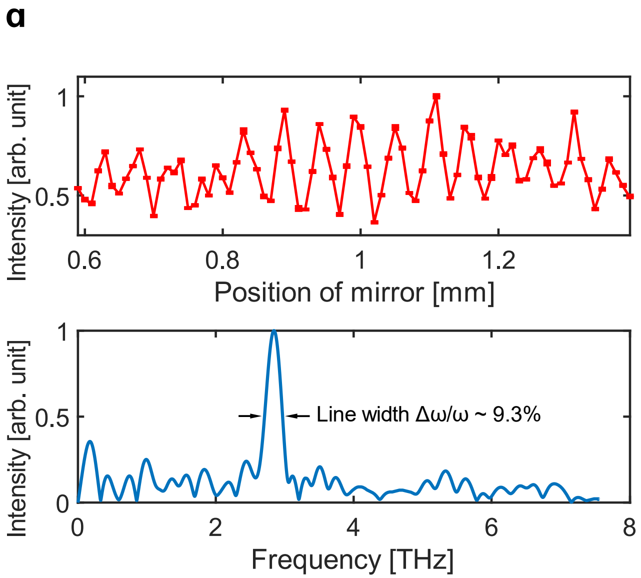
- **Bunching factor measurements**



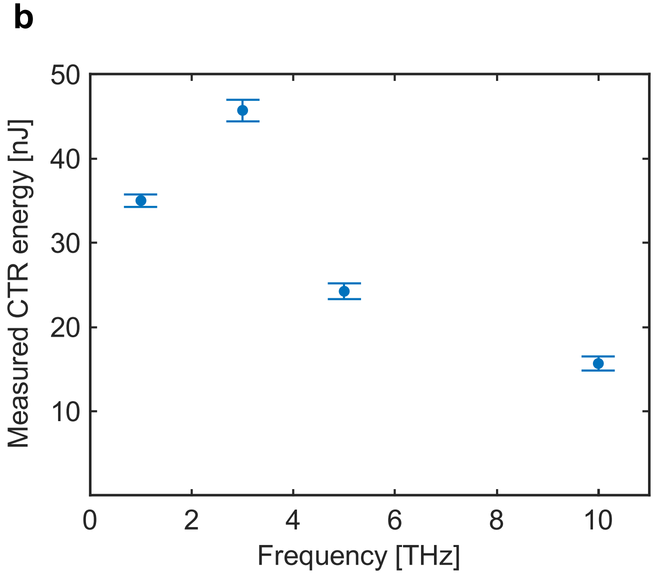
YF Liang, ZY Liu, LX Yan et al, Nature Photonics 17, 259-263(2023)

Experimental Demonstration of THz Bunch Train

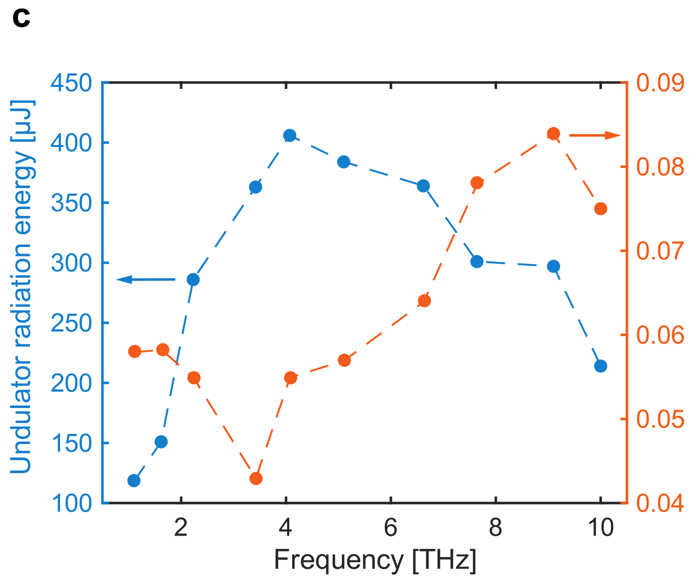
- **Characterization with THz radiation and simulation on THz generation**



Autocorrelation measurements (top) and Fourier transform (bottom) (2.84THz)



Measurements of the THz energy from the CTR.
Four narrow-bandpass filters (1, 2.8, 5.1, 9.8 THz) were inserted before the Golay cell

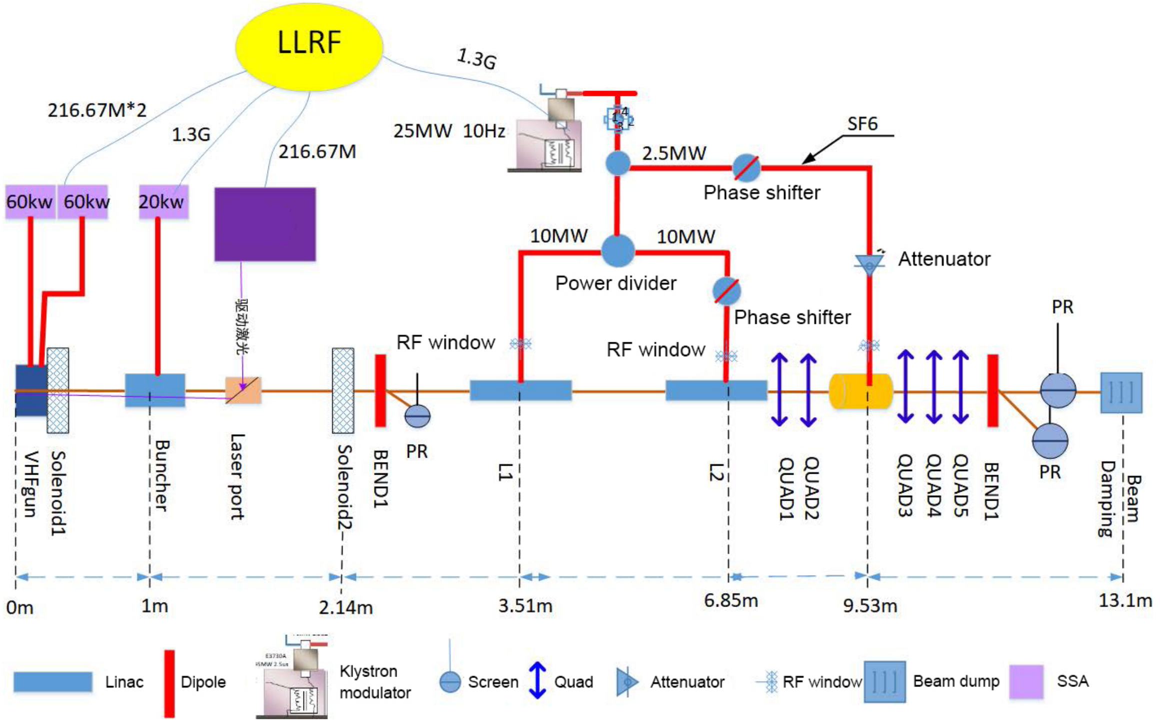


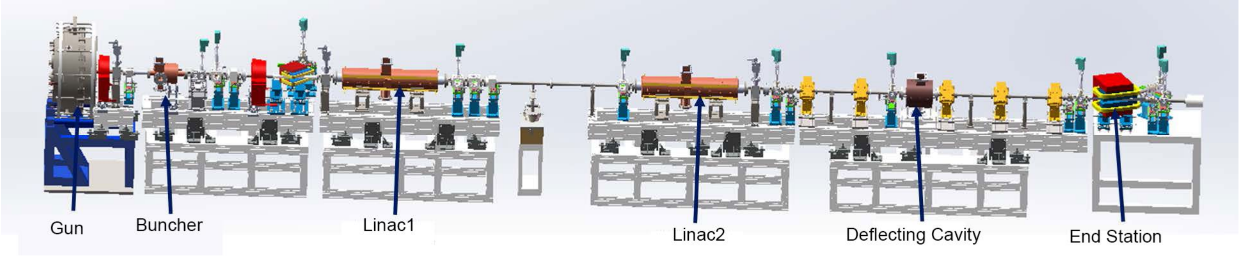
Simulation results of superradiant undulator radiation (1nC beam with 30 undulator periods)

YF Liang, ZY Liu, LX Yan et al, Nature Photonics 17, 259-263(2023)

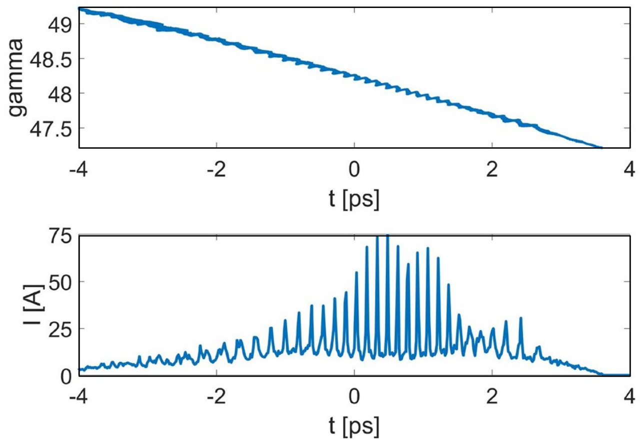
Extending to Higher Repetition Rate

- **High average power THz generation with VHF gun**

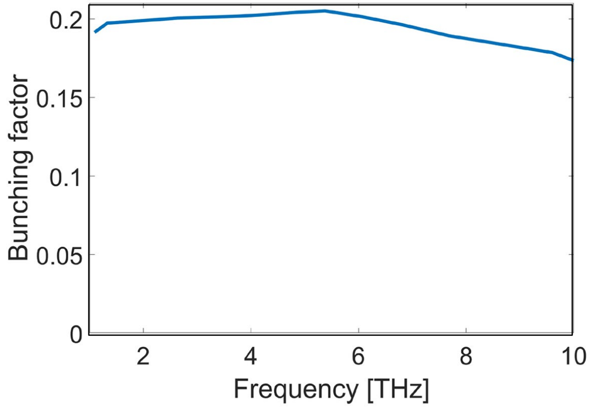




Longitudinal phase space @chicane exit



Bunching factor vs Frequency



VHF Test Facility @Tsinghua University

To be submitted

Concluding Remarks

- The experimental parameters of bunch trains are:

Parameter	Value	Unit
Beam charge	200	pC
Beam energy	27-34	MeV
Bunching tunability	1-10	THz
Measured bunching factor	0.15-0.35	
Measured CTR bandwidth	9.3%	

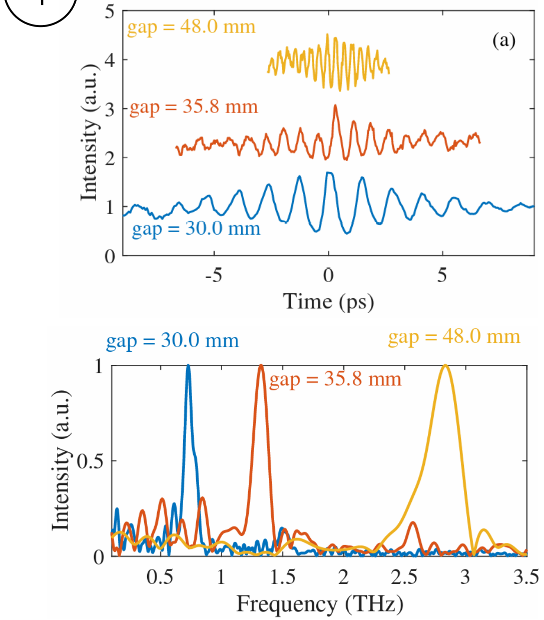
- First experimental demonstration of widely tunable THz source that can cover 1-10 THz. Compared to FEL oscillators, the setup does not need complicated design.

- The proposed scheme can be combined with high repetition rate beamline or burst mode beamline. Further extension to THz FEL oscillators is currently under investigation.

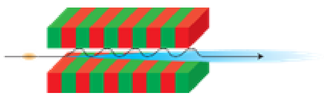
Concluding Remarks

- What can we expect from these electron bunch trains?
  High power THz radiation with tailored properties.

①



Superradiant undulator radiation[1]



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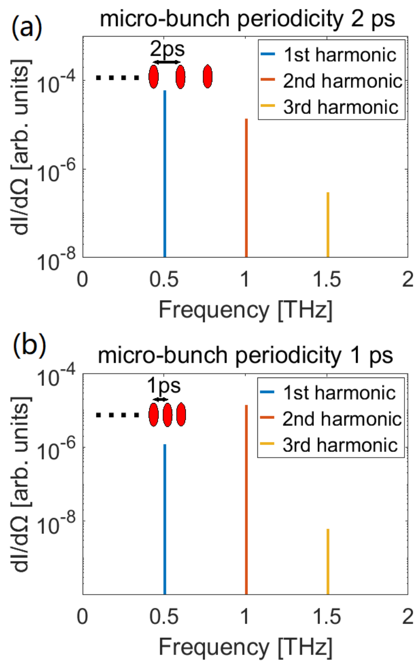
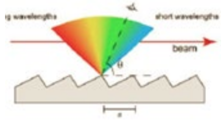


Smith-Purcell radiation[2],
Selective mode excitation[3]



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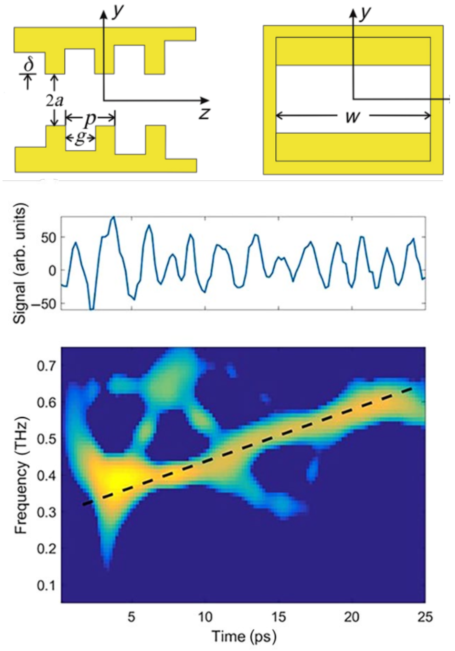
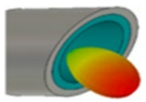


Wakefield radiation[4],
Chirp control[5]



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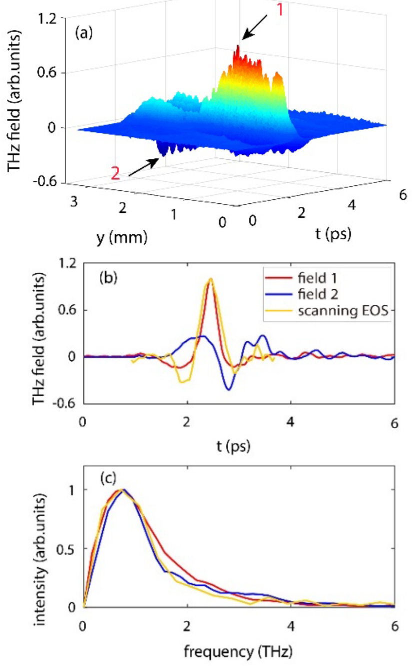
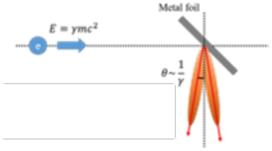


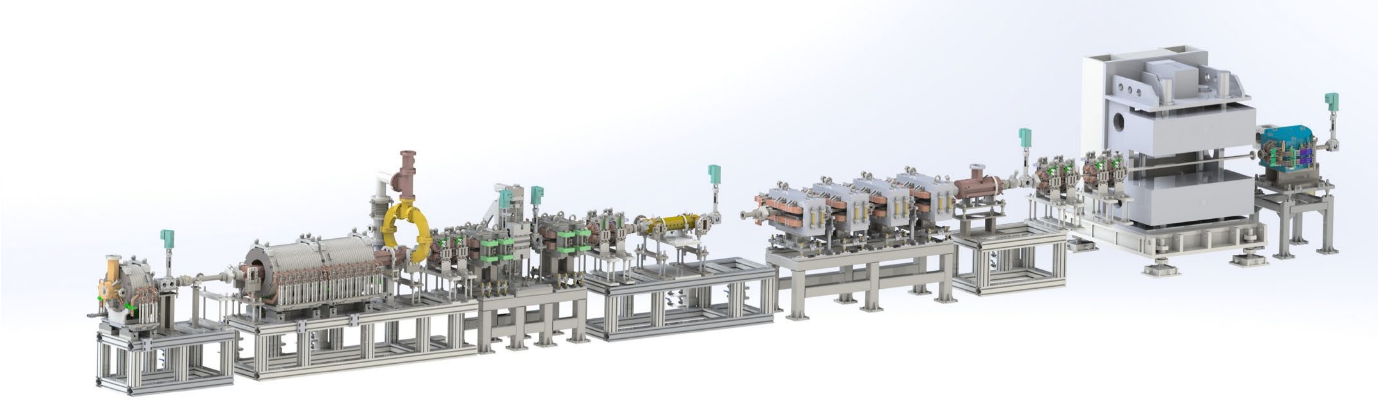
Transition radiation[6]



[1] XL Su, et al, Rev. Sci. Instrum. 89, 013304(2018)
[2] YF Liang et al., APL 112, 053501 (2018).
[3] YF Liang et al., APL, 113， 171104(2018)
[4] D. Wang, et al., RSI,89, 093301 (2018)
[5] YF Liang et al. Physical Review Applied, 2023, 19(5): 054085.
[6] QL Tian, LX Yan, et al, PRAB, 23, 102802(2020)

Summary& Outlook

- Several new schemes to generate THz bunch trains with large bunching factor have been proposed, from which tunable narrow band high power THz can be hopefully developed.
- The PoP exp on generation of THz electron bunch train tunable between 1-10THz with bunching factor up to 0.35 by controlling NLSC forces has been demonstrated, which marks a significant advance in the development of narrow-band THz sources.
- A compact beamline devoted to novel high power coherent THz has been built. After the installation of THz undulator, it can be expected to be a powerful tool for broad scientific and industrial applications.



Acknowledgement

- Colleagues and students:

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- Collaborators: Haixiao Deng, Zhirong Huang, Sergey Antipov

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Q&A