Recent Progress on Linac Based THz Radiation at THU

Lixin Yan

yanlx@mail.tsinghua.edu.cn

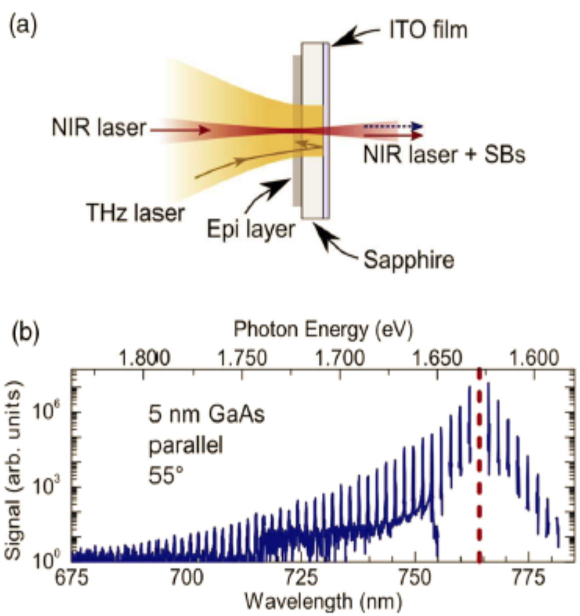
On Behalf of the Accelerator Laboratory of Tsinghua University

Outline

- Motivations
  - ✓ High-peak-current e bunch/trains for THz generation
- Generation of e bunch/trains
  - ✓ Bunch trains(NLSCO, Laser-beam modulation)
- Experiments with e bunch/trains
  - ✓ THz radiation by cTR/cSPR/CUR/cDWR; DWFA
- Summary

Motivations

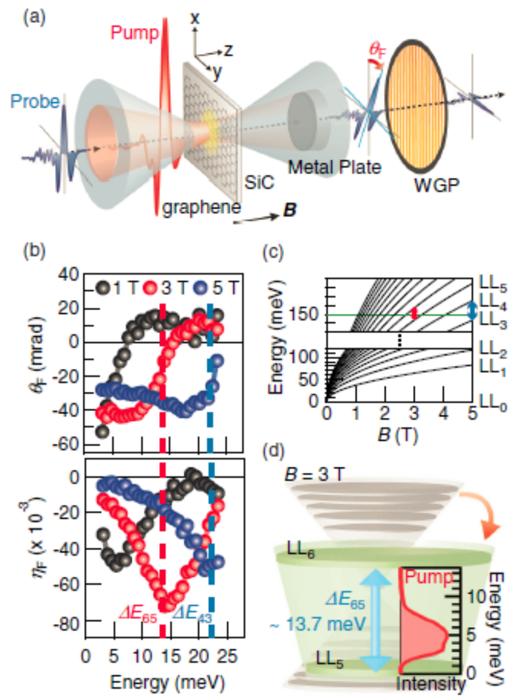
- High power THz radiation finds many important applications in modern science. Accelerator-based coherent THz radiation has great potentials.



$$f_{SB} = f_{NIR} + n f_{THz}$$

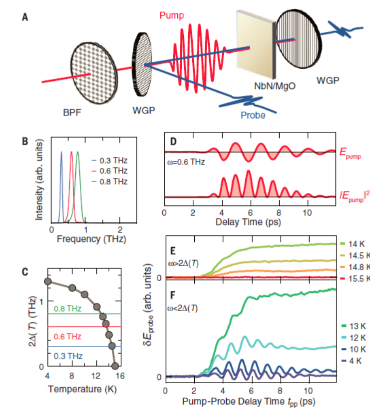
Dynamical birefringence: High-order (90th) sideband generation in **semiconductor**.

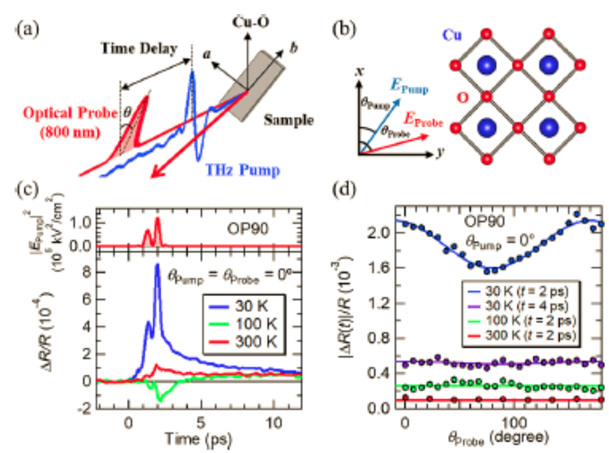
H B Banks, et al, PRX, 7,041042(2017)



Ultrafast THz nonlinear optics of Landau level transitions in a monolayer **graphene**.

G Yumoto, et al, PRL, 120,107401(2018)





Higgs mode in **superconductor** driven by intense THz pulse, pump-probe experiment.

R Matsunaga, et al, Science, 345,6201(2014)
K Katsumi, et al, PRL, 120,117001(2018)

Motivations

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

Radiation power of electron bunch formulated as:

Incoherent Coherent

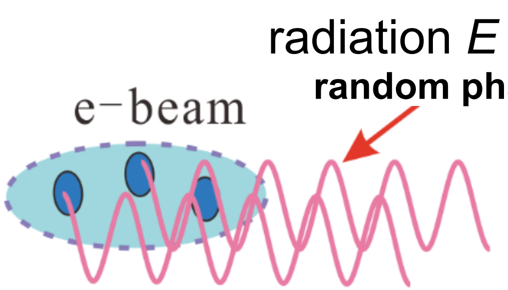
$$P(\omega) = P_1(\omega)\left[N_e + N_e^2 f(\omega)\right]$$

$P_1(\omega)$: the radiated power from a single electron

N_e: number of electrons in a bunch, 100pC (N_e~10^9)

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

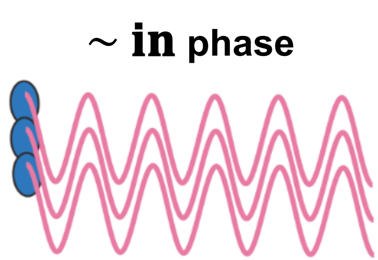
$\sigma \gg \lambda$



Incoherent *radiation for a single bunch*

$P \approx N P_1$

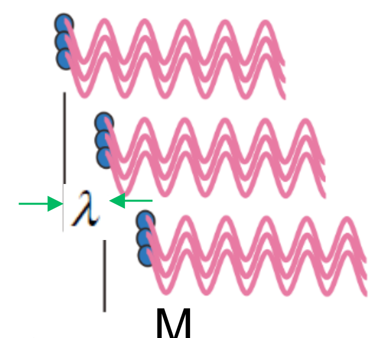
$\sigma \ll \lambda$



Coherent radiation for a single bunch

$P \approx N^2 P_1$

$\sigma \ll \lambda$

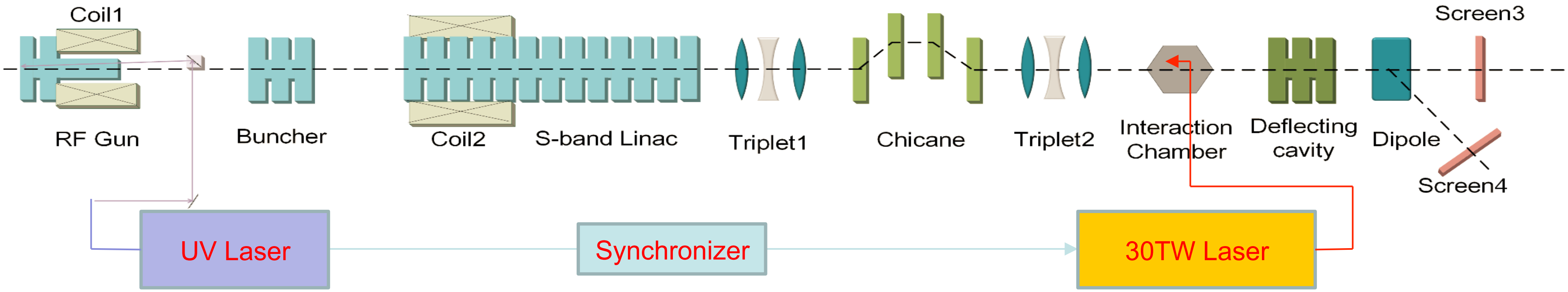


Coherent radiation for bunch train

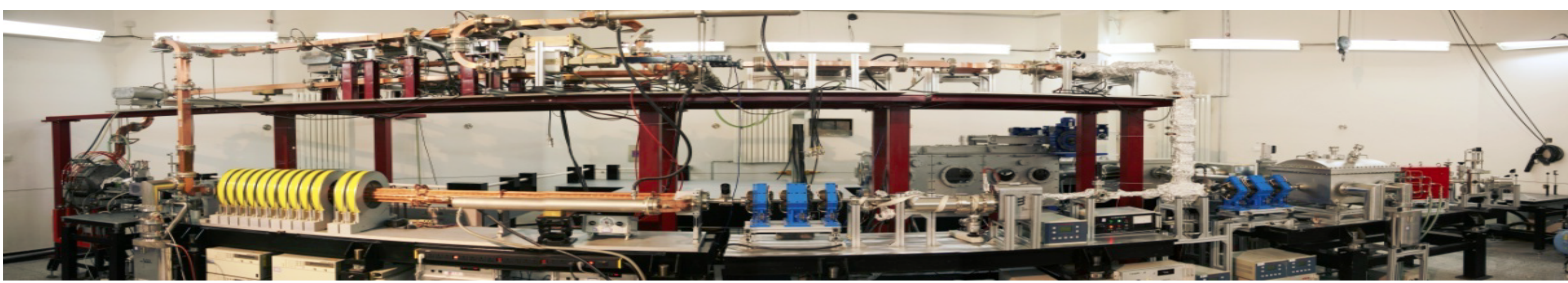
$P_{\omega_0} \approx (MN)^2 P_1(\omega_0)$

Introduction of TTX

- TTX: Tsinghua Thomson scattering X-ray Light Source

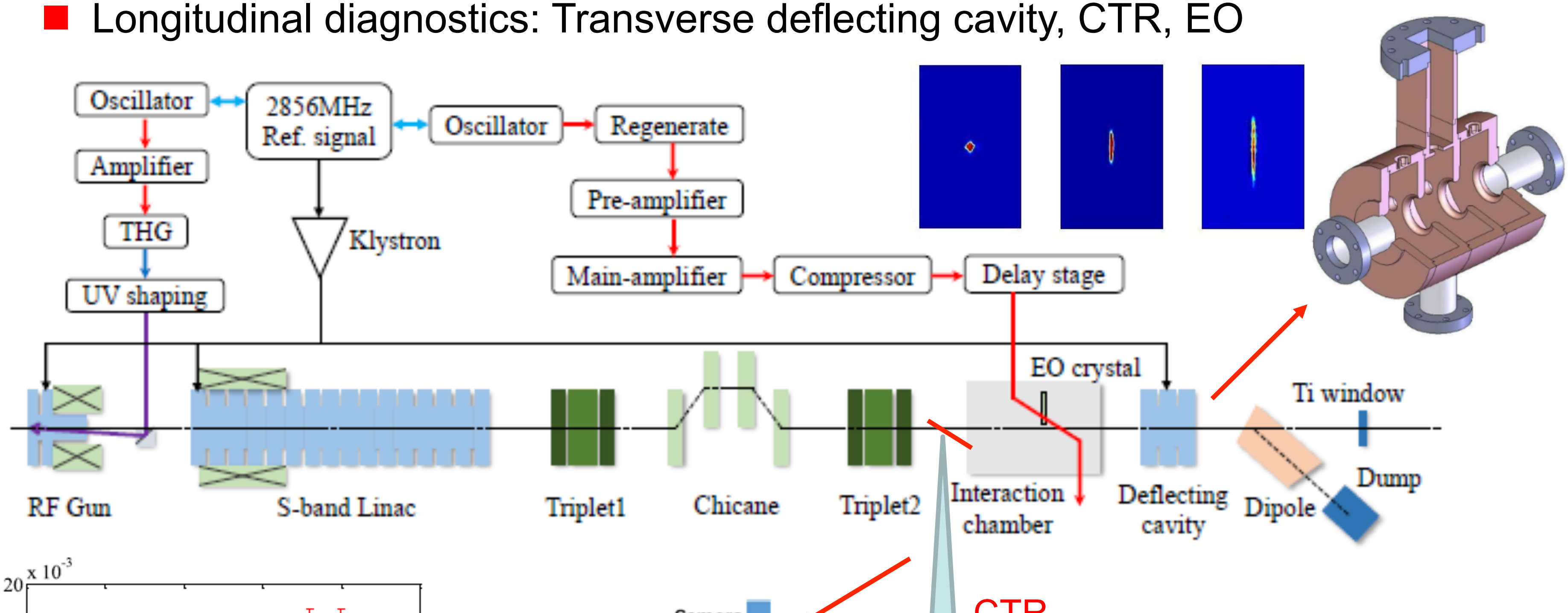


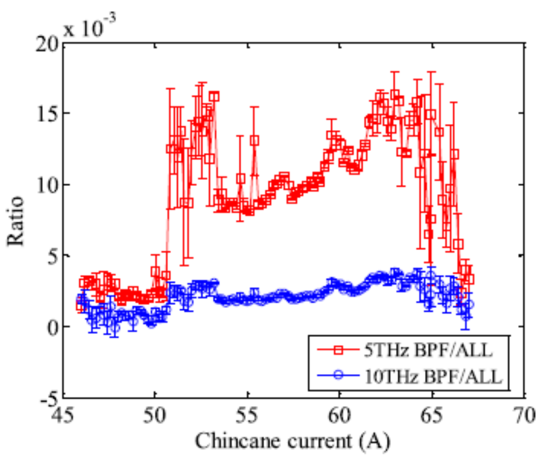
- ✓ 50MeV electron beam line and 30TW laser system:
- ✓ The gun gradient is ~110MV/m and the bunch charge from a few pc up to >1nC;
- ✓ A 4-dipole chicane has been installed after the linac for beam compression.
- ✓ It's able to generate ultra-short (100fs) and high intensity (~10kA) beam with ballistic bunching and magnetic compression.

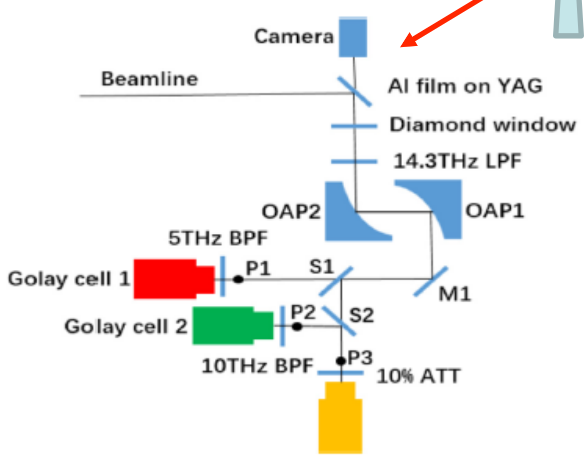


Diagnostics Development

- Longitudinal diagnostics: Transverse deflecting cavity, CTR, EO







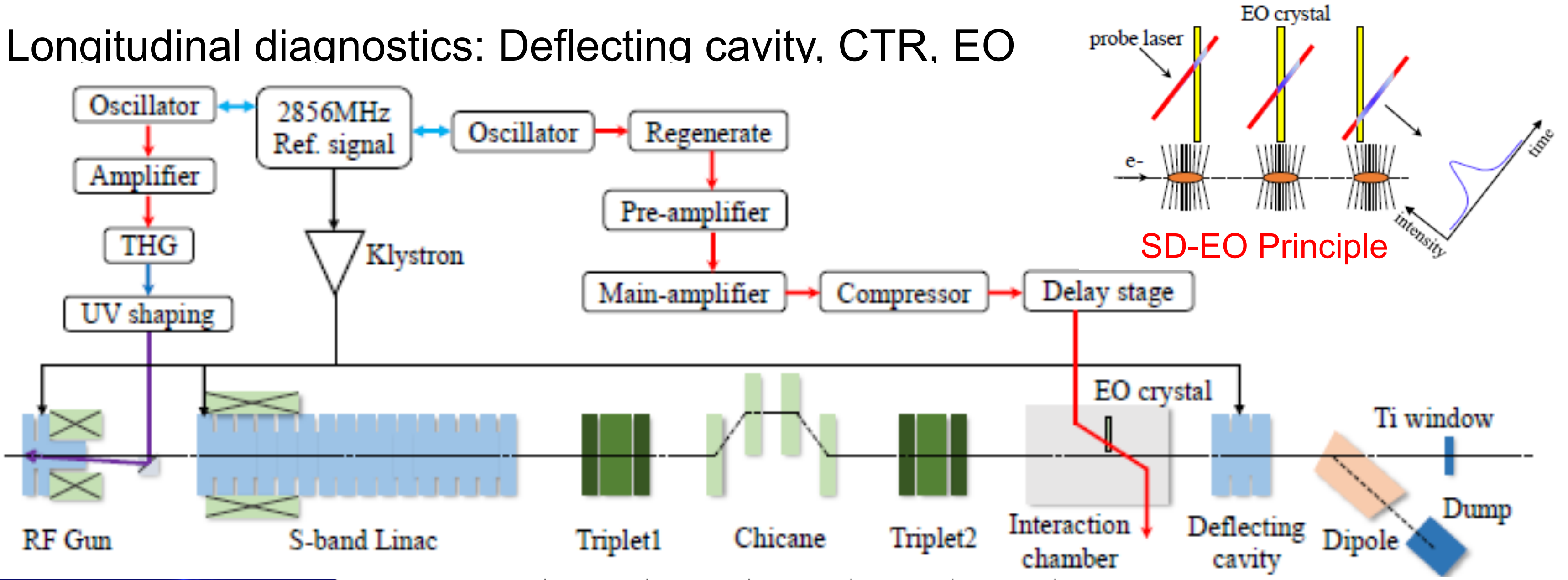
3-cell, S-band, Standing wave, TM110 mode

Deflecting cavity can measure bunch length of 100fs.

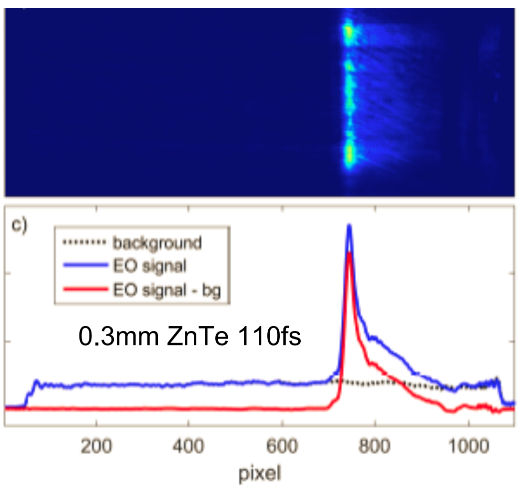
XL Su, LX Yan et al., NIMB 402, 157 (2017)

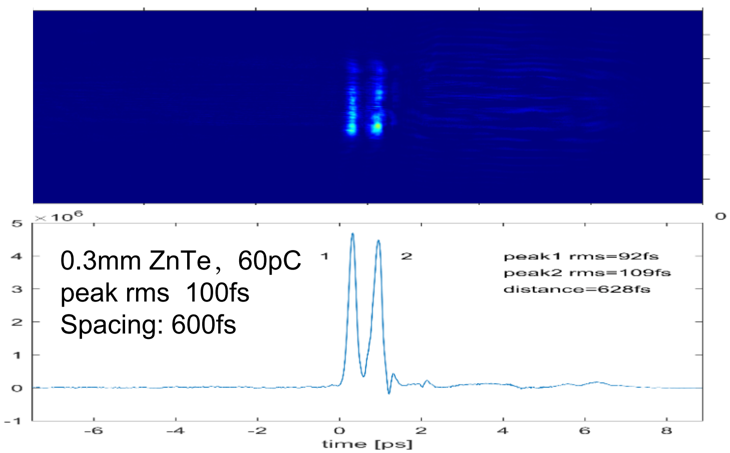
Diagnostics Development

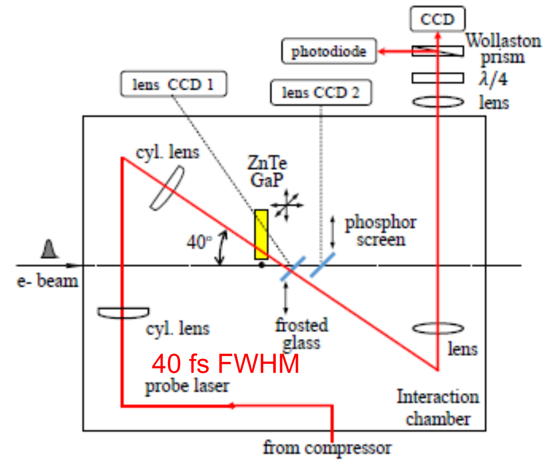
- Longitudinal diagnostics: Deflecting cavity, CTR, EO



SD-EO Principle





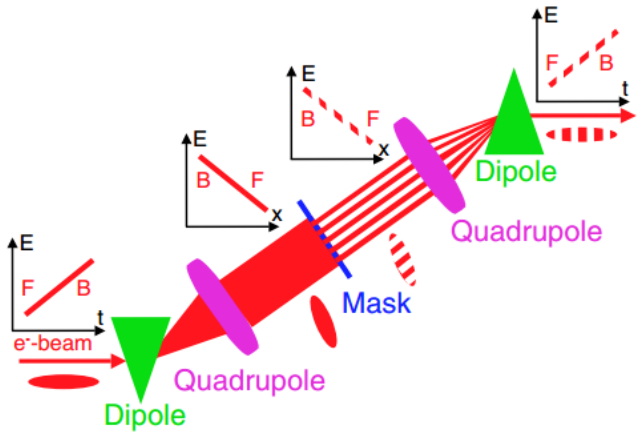


- ✓ EO sampling, single-shot spatial decoding EO (SD-EO)
- ✓ Arrive time of e beam, feedback control of time jitter

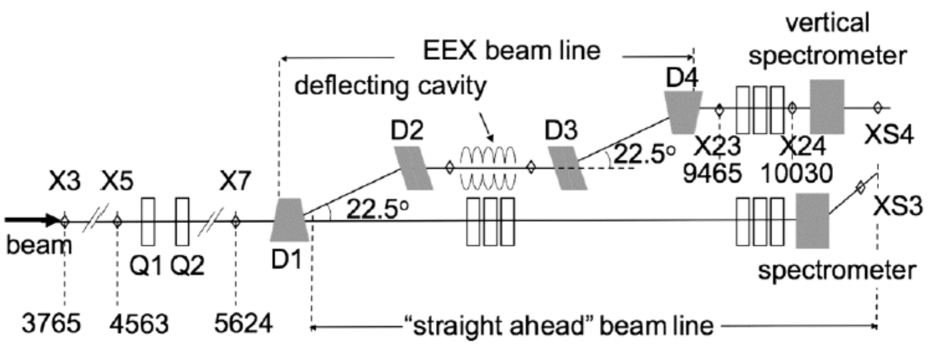
W Wang, et al, NIMA, 834, 183-186(2016)
W Wang, et al, PRAB, 20, 112801(2017)

Bunch train generation methods

Transverse-to-Longitudinal-phase-space-Exchange based method

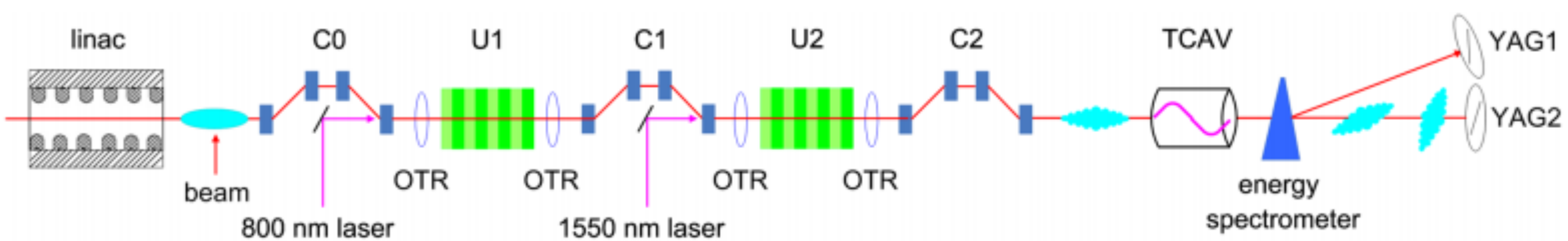


P. Muggli et al., PRL 101, 054801 (2008)



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

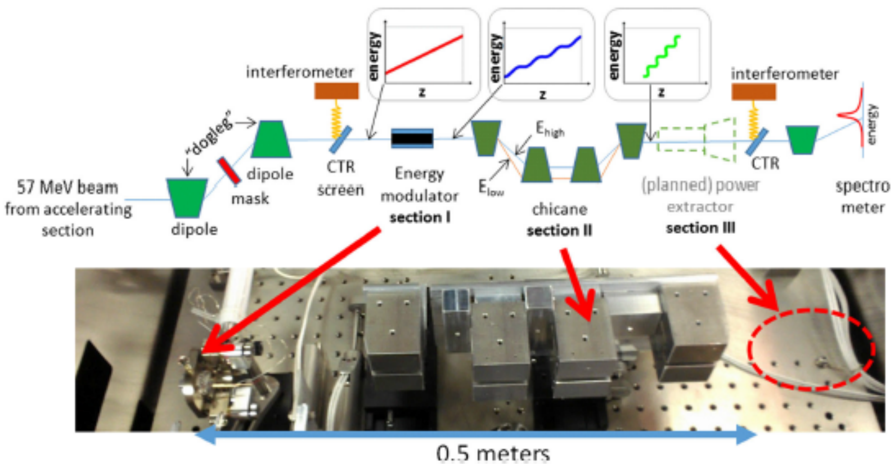
Difference-frequency echo-based THz beam structure generation



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

Bunch train generation methods

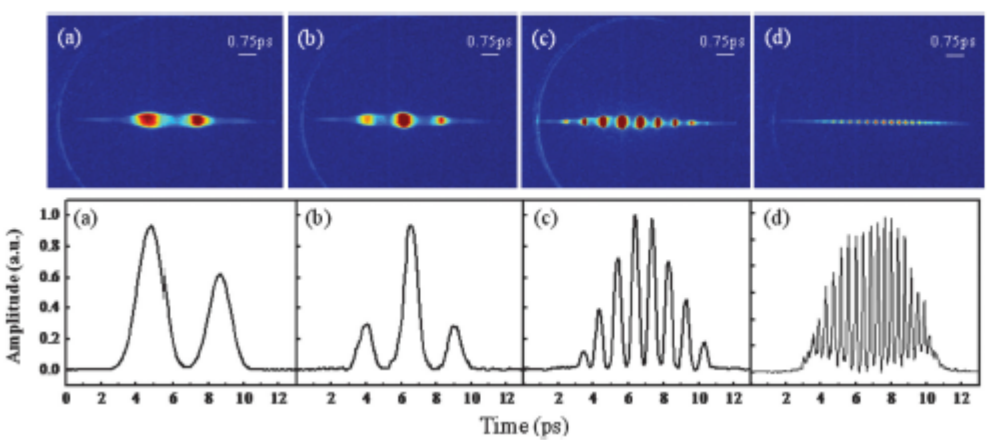
- **Self Wakefield modulation based method**



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

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

- **Direct shaping of drive laser with modulated structure**



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)

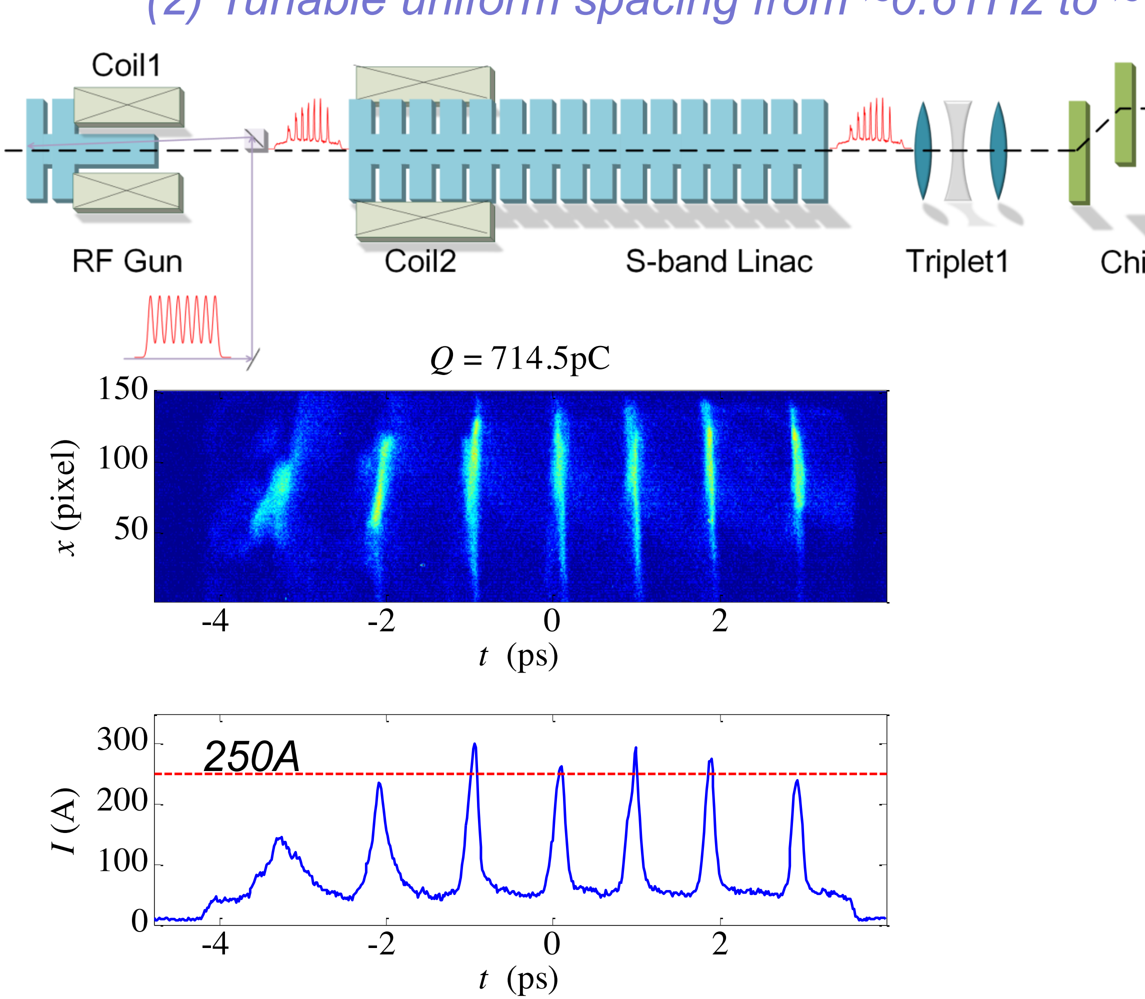
LXYan, et al., IPAC 1st, Kyoto, Japan(2010)

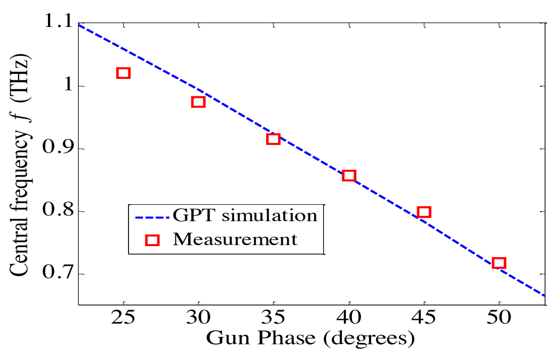
Bunch train generation at THU

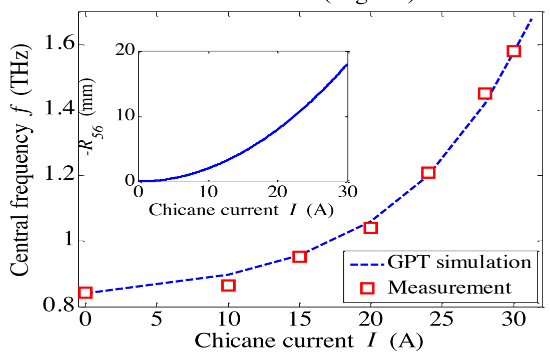
- We take advantage of NLSCO to generate multi-bunch trains with

  (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)

Review on the methods

- 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

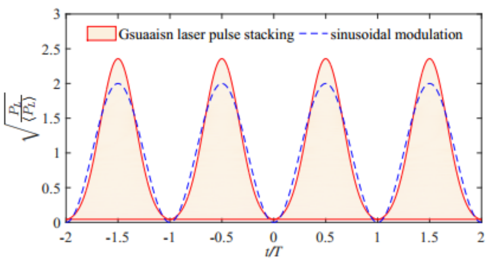
- Compared with others, NLSCO based method can generate bunch trains with considerable larger beam charge, more wider tuning range and larger bunching factor.

A new scheme for bunch train

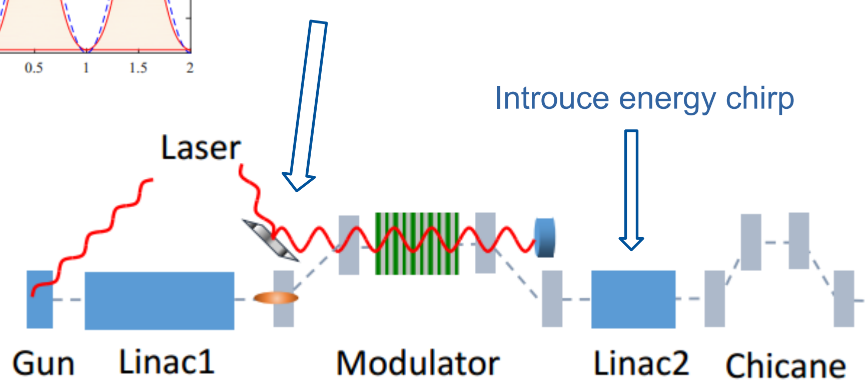
- Limitations of NLSCO: difficult to expand to >2THz; bunching factor<0.2
- Seeking for new schemes to generate bunch trains with more flexibility

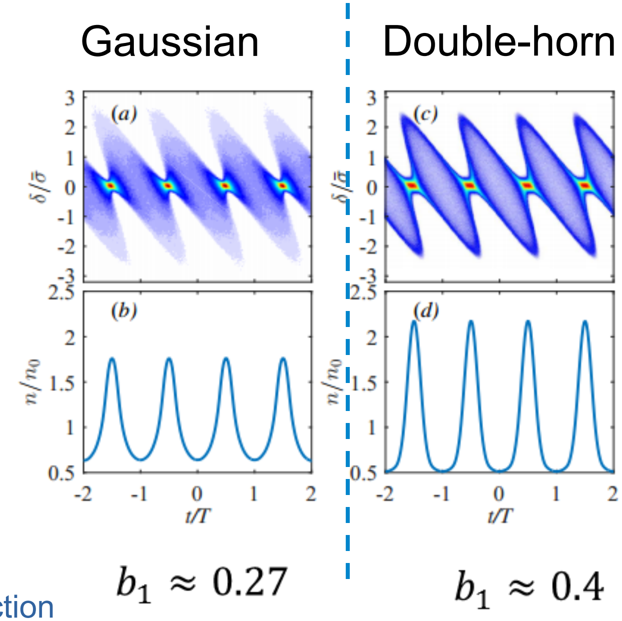
✓ We propose a new method to generate electron bunch train with *wide frequency range* (1~10THz) and *large bunching factor* (~0.4),suitable for *large beam charge*.

✓ The method is based on laser-electron interaction to modulate the slice energy spread.



Deeply modulated laser pulse
With THz structure



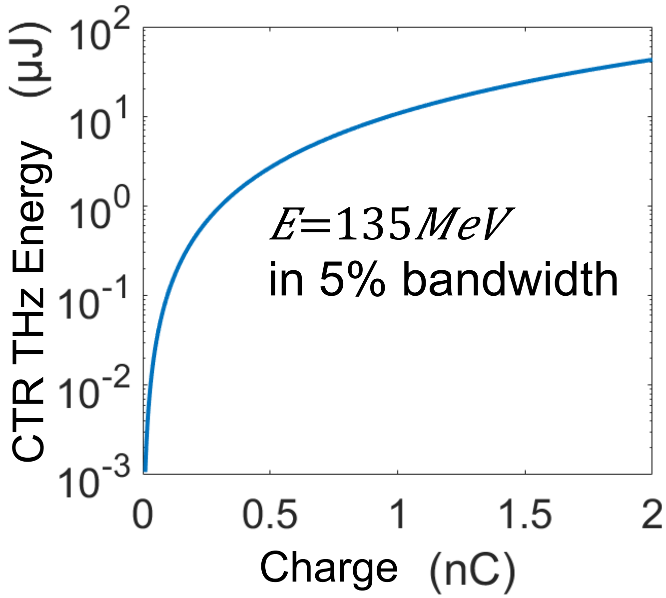


✓ The modulation happens after acceleration, so it is suitable for large beam charge.

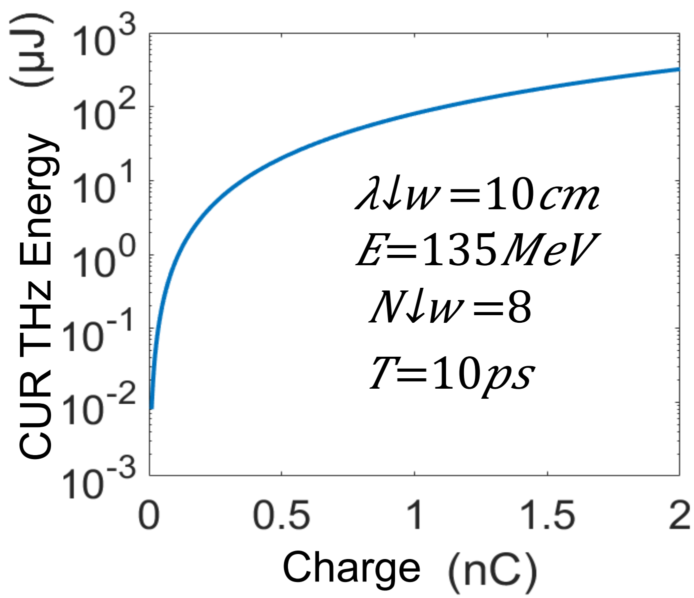
Z Zhang, LX Yan, et al, PRAB, 20, 050701(2017)

High power THz by bunch trains

- By CTR, CUR, et al, tunable high power THz radiation can be generated. Radiation enhancement is expected by increasing beam charge.



Coherent Transition Radiation



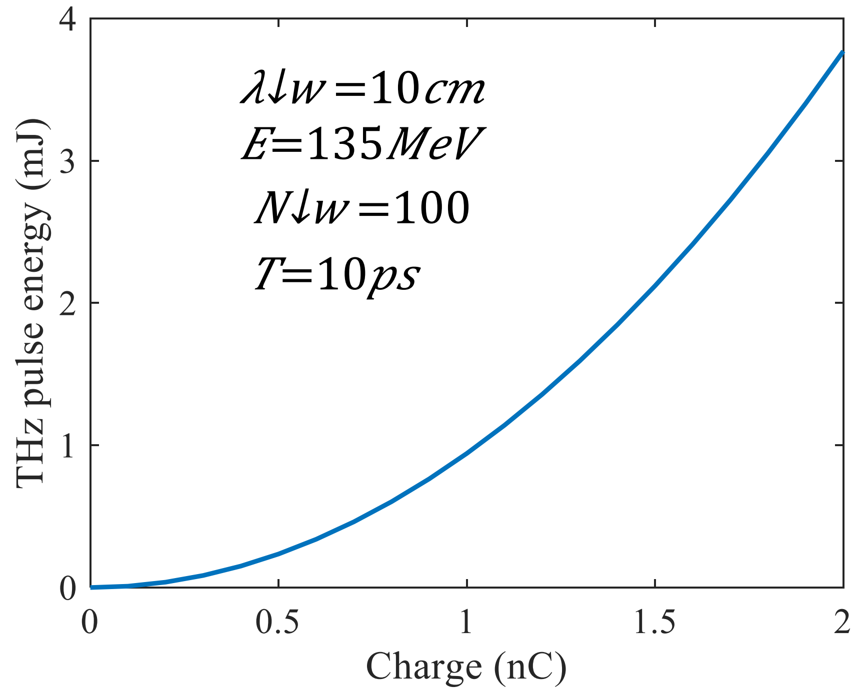
Coherent Undulator Radiation

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

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

High power THz by bunch trains

- mJ level narrow band THz radiation energy (hundreds of MW power) with longer undulater.



Coherent Undulator Radiation

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

Work on 3rd harmonic mode

- e-beam 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 mm) .

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	0.25 m / 10
Laser wavelength	800 nm
Laser RMS spot size	0.5 mm
Laser stacking separation	0.5 ps (2 THz)
Laser peak power	100 MW

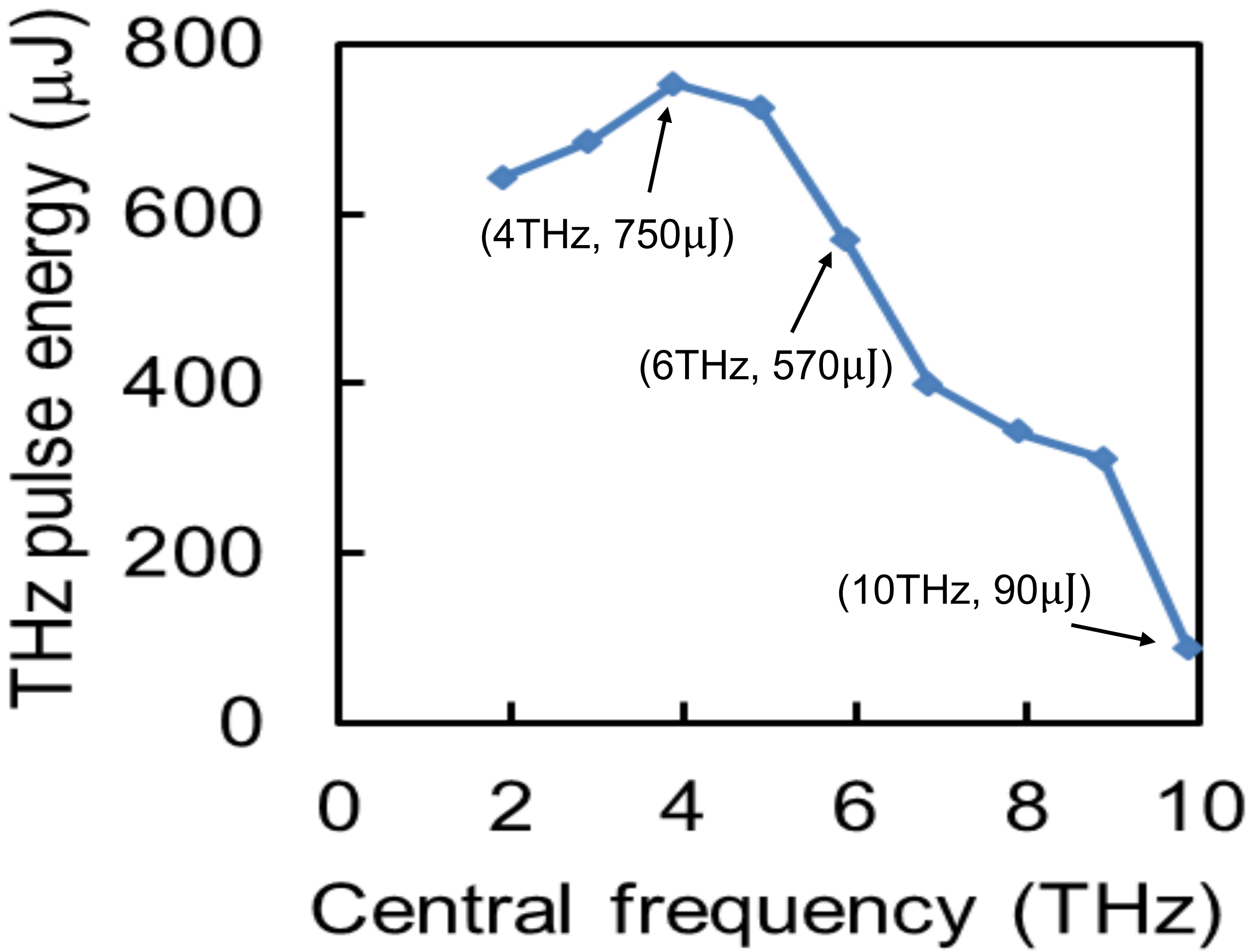
Resonant condition:

$$\lambda_r = \lambda_u (1+K^2/2)/2\gamma^2$$

$$\Rightarrow \quad \lambda_r = 2.4\mu\text{m}$$

THz radiation tunability

- For a helical undulator (radiator) , the radiation energy at different central frequencies can be calculated by Genesis simulations.



$E=50\text{MeV}$

$Q=1\text{nC}$

$I=100\text{A}$

$\lambda_w=10\text{cm}$

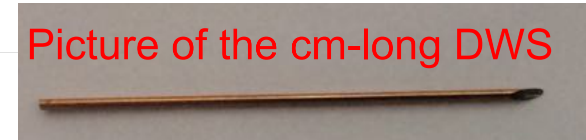
$N_w=30$

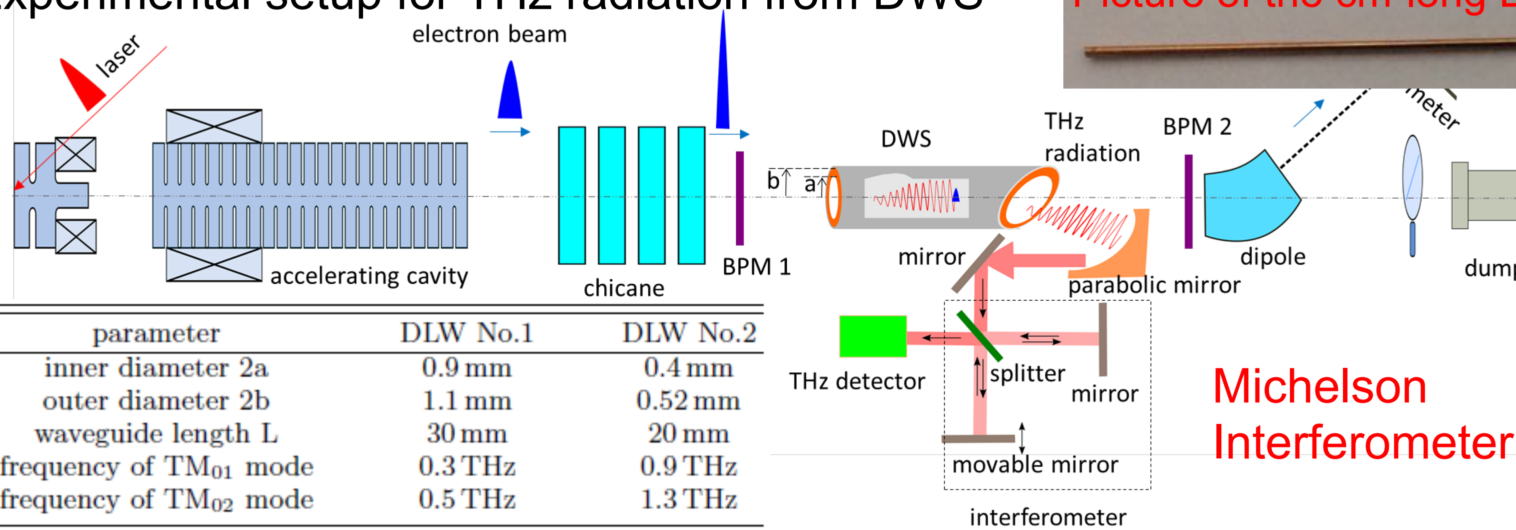
$P_L=100\text{MW}$

Courtesy to Koichi Kan

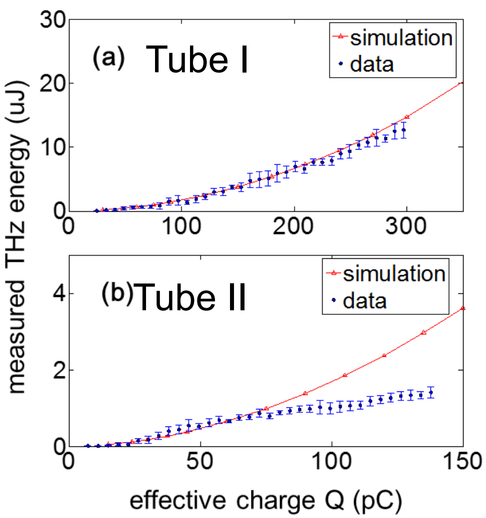
THz radiation from DWS

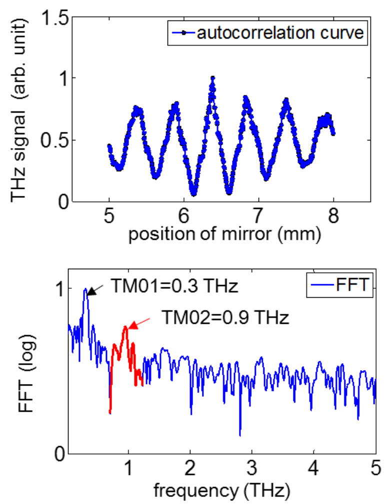
- Experimental setup for THz radiation from DWS



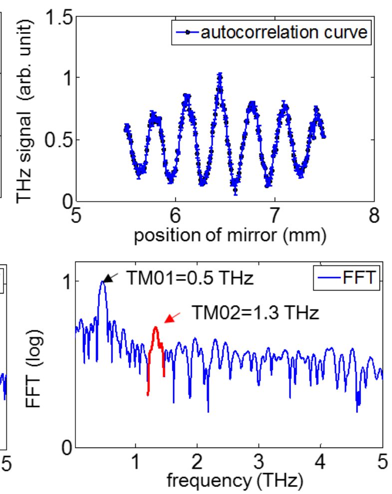


parameter	DLW No.1	DLW No.2
inner diameter 2a	0.9 mm	0.4 mm
outer diameter 2b	1.1 mm	0.52 mm
waveguide length L	30 mm	20 mm
frequency of TM_{01} mode	0.3 THz	0.9 THz
frequency of TM_{02} mode	0.5 THz	1.3 THz





Tube I



Tube II

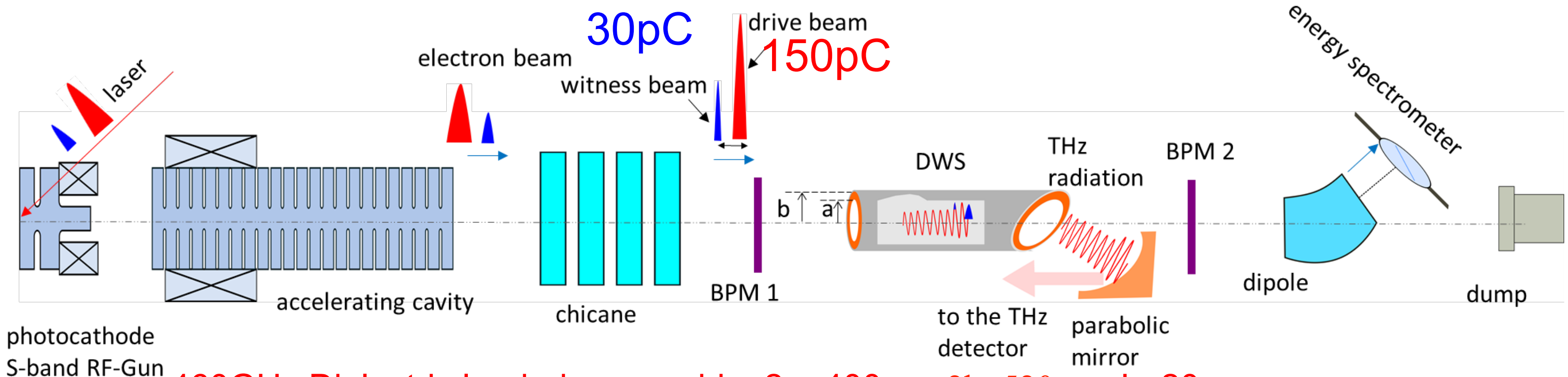
✓Tens of μJ THz pulse energy has been measured with several hundred pC.

✓Second order mode of the THz radiation is clearly seen with short drive beams.

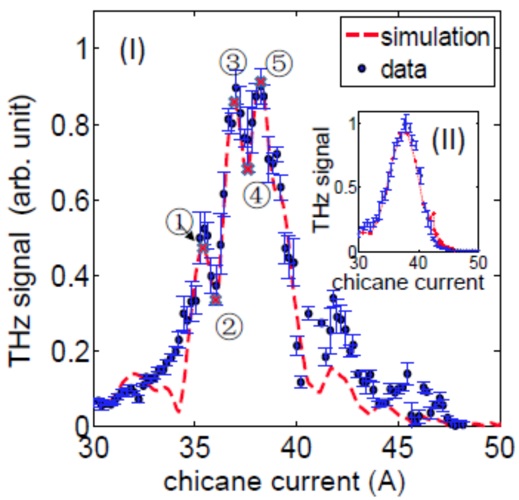
D. Wang, et al., RSI,89, 093301 (2018)

DWS for Wakefield acceleration

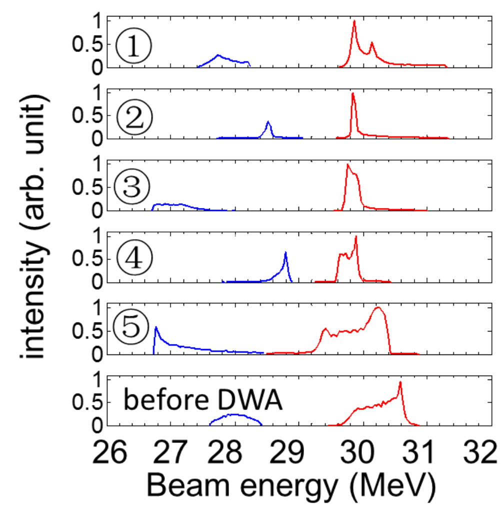
- THz radiation for the study of wakefield acceleration using a double-bunch interaction scheme with DWS. MeV energy gain or loss observed.



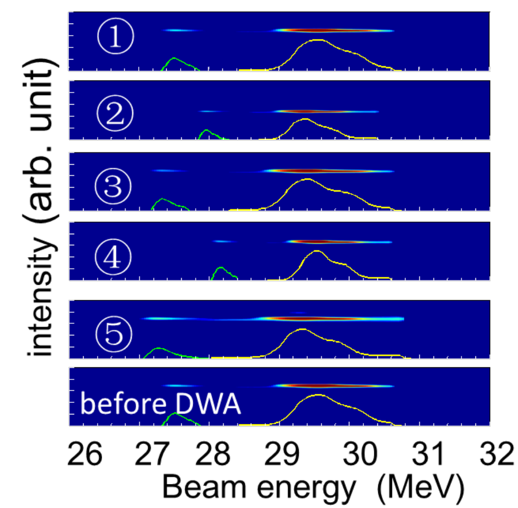
460GHz Dielectric loaded waveguide: 2a=400μm, 2b=520μm, L=20mm



THz from DWS



Simulations from ASTRA

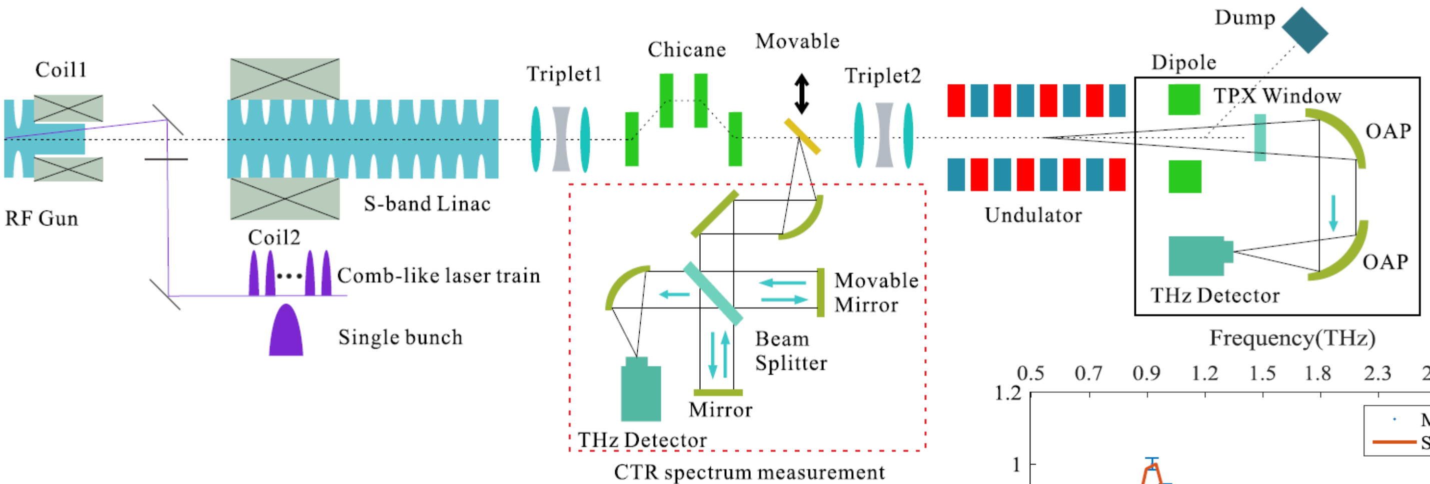


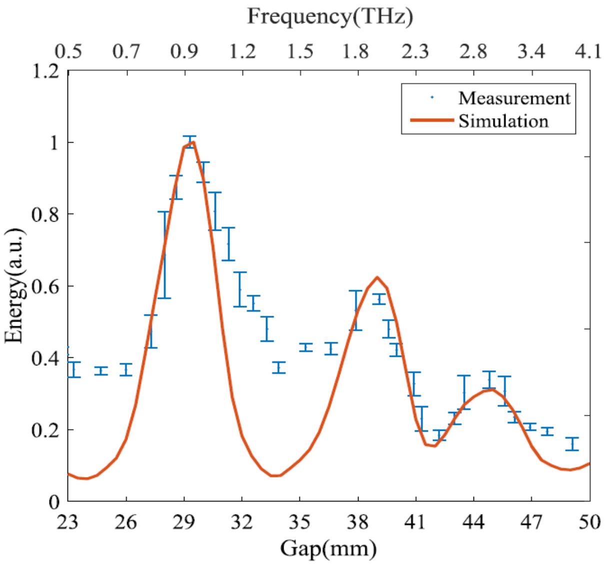
Measurements

D Wang, LX Yan, et al, APL 111, 174102(2017)

THz from Undulator

- Experiments on THz radiation from an eight-period undulator by the electron bunch trains has been conducted at our lab.





Measurement of pre-bunched beams' form factor based on radiation from a gap-tunable undulator

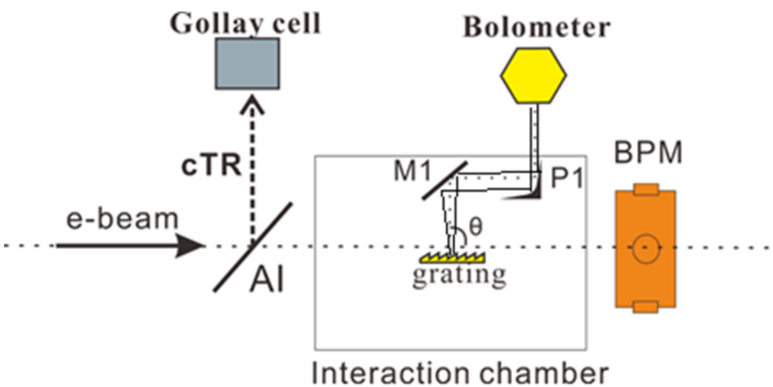
Parameters of the undulator

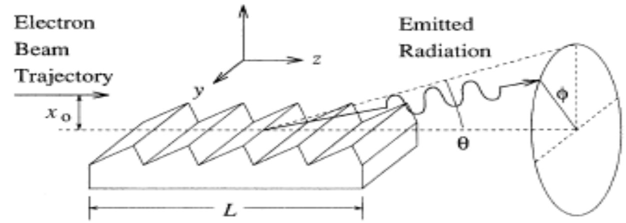
Parameter		Value
Undulator period	λ_u	100 mm
Number of periods	N	8
Magnetic gap range	g	23-75 mm
Peak magnetic field	B	0.99-0.15 T
Undulator parameter	K	9.24-1.39

XL Su, et al, Rev. Sci. Instrum. 89, 013304(2018)

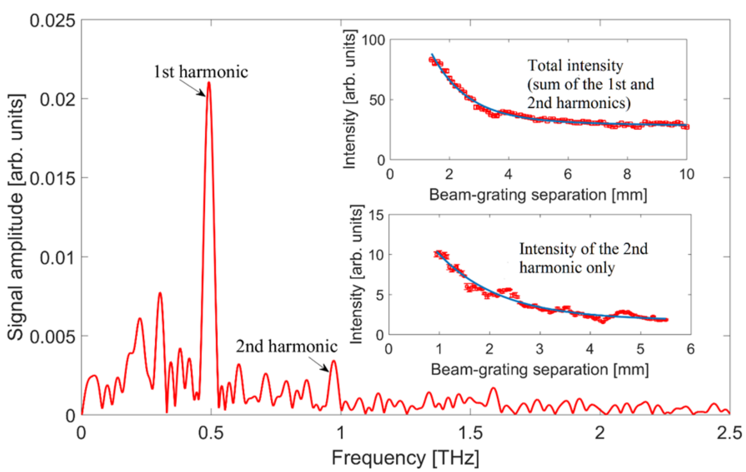
Study on Smith-Purcell effect

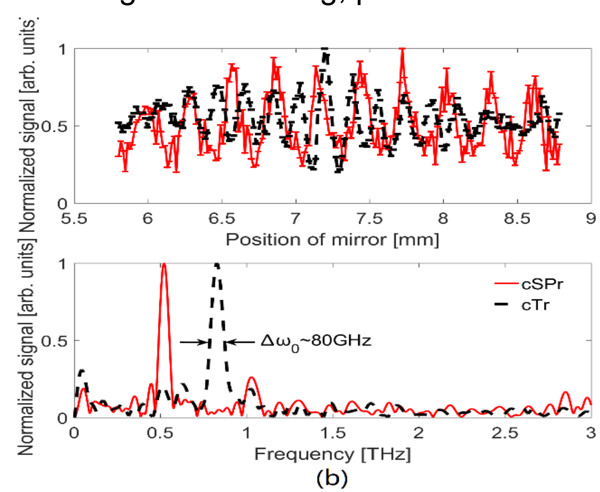
- Manipulation of sub-picosecond beam to study the characteristics of SP effect; Comparison between SP CTR with bunch trains.





Gratings:110mm long, period 0.3/0.6mm



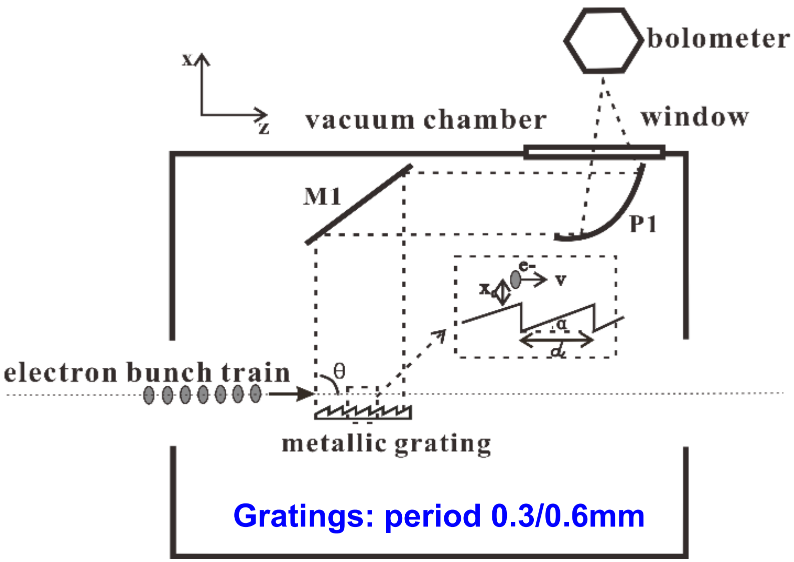


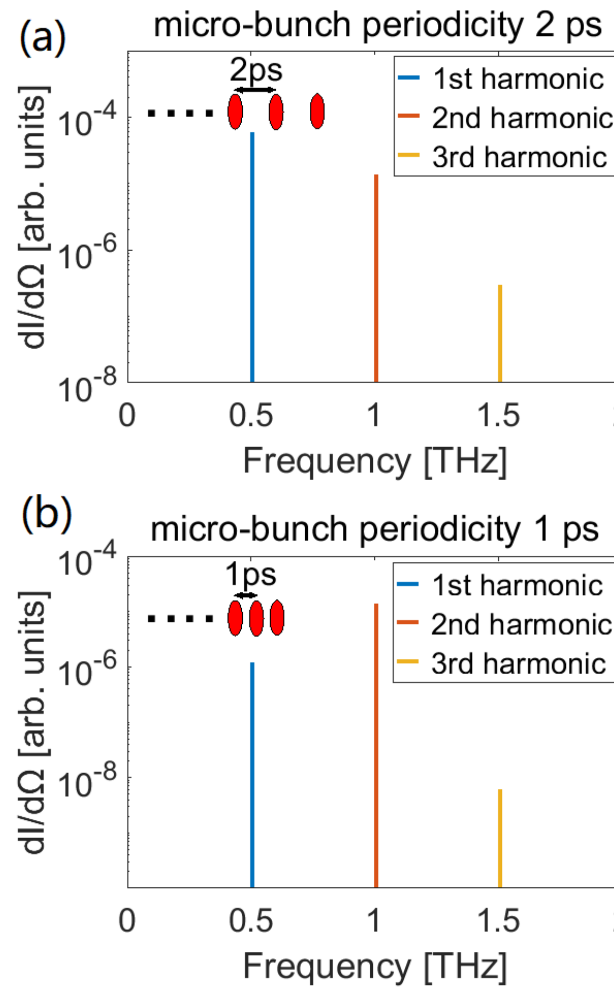
- contrary to CTR, SP spectrum is determined by dispersion relation of the grating and the collection angle, regardless of electron longitudinal structure.

YF Liang et al., APL 112, 053501 (2018)

Selective excitation of cSPR

- To demonstrate the selective excitation and control of coherent SP THz radiation generation.





Both for 0.6mm grating@90° observation angle

✓ Coherent SP radiation by bunch trains

$$\left(\frac{dI}{d\Omega}\right)_{N_b} = \left(\frac{dI}{d\Omega}\right)_1 \left(N_e S_{inc} + N_e^2 S_{coh}\right)\left[\frac{\sin\left(\frac{\pi N_b \lambda_b}{\lambda}\right)}{\sin\left(\frac{\pi\lambda_b}{\lambda}\right)}\right]^2$$

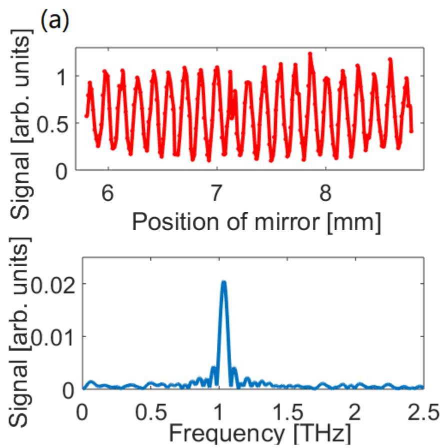
$$\left(\frac{dI}{d\Omega}\right)_1 = 2\pi q^2 \frac{Z}{d^2}\frac{m^2\beta^3}{(1-\beta\cos\theta)^3} R^2 \exp\left(-\frac{2x_0}{\lambda_e}\right)$$

YF Liang et al., APL, in press

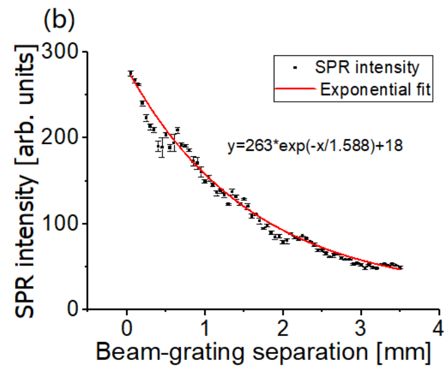
Selective excitation of cSPR

ACCELERATOR LABORATORY of TSINGHUA UNIVERSITY

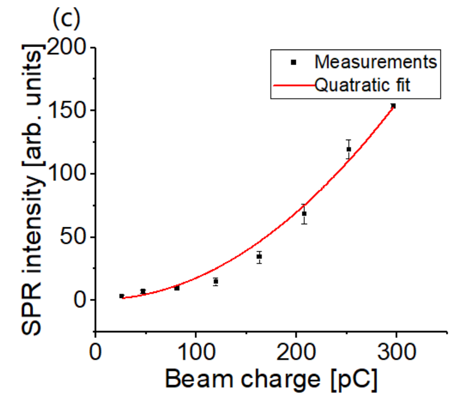
- Experimental and theoretical results agree well in the selective excitation and control of coherent SP THz radiation generation.



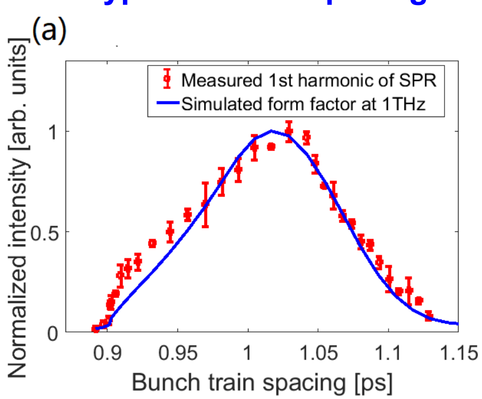
Typical bunch spacing



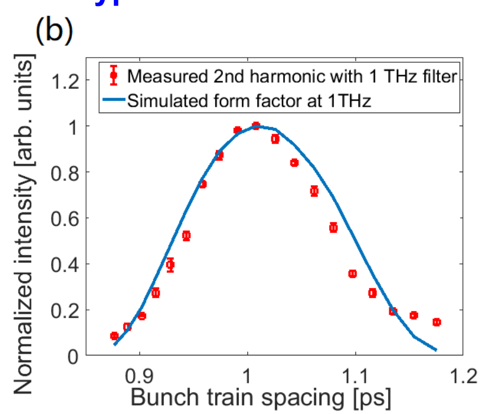
Typical SPR measurement



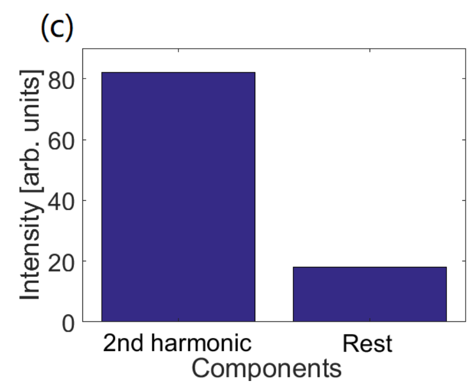
0.6mm-period grating



0.3mm-period grating



0.6mm-period grating



0.6mm-period grating

YF Liang et al., APL, in press

Summary

- At TTX facility, various methods to generate high-peak current electron bunch/trains have been studied for THz source development and advanced beam acceleration.
- After nonlinear longitudinal space charge oscillation, a new scheme based on laser-beam interaction in an undulator was proposed and studied, in which much more flexible bunch trains(periodicity tunable in 1~10THz, bunching factor up to 0.4) would be expected, from which continuously tunable narrow band high power THz can be hopefully developed.
- Using electron bunch/trains, we have performed experiments on THz production based on Coherent Transition Radiation, Undulator radiation, Smith-Purcell radiation and Dielectric Wakefield radiation, and also demonstrated their applications in Dielectric Wakefield Acceleration.

Acknowledgement

- Colleagues and students in THU:

  Yingchao Du, Wenhui Huang, Wei Gai, Chuanxiang Tang, Dan Wang, Zhen Zhang(now@SLAC), Xiaolu Su, Yifan Liang, Dong Wang, Zheng Zhou, Qili Tian, …….

- Collaborators from SLAC:

  Zhirong Huang

- Collaborators from Euclid Techlabs:

  Sergey Antipov

- Collaborators from JAI,Oxford:

  Ivan V. Koloplev, Huibo Zhang, G. Doucas

Thanks for attention!