ACCELERATION OF THE DUAL REPETITION FREQUENCY ELECTRON BEAM AND ITS APPLICATION TO THZ RADIATION GENERATION

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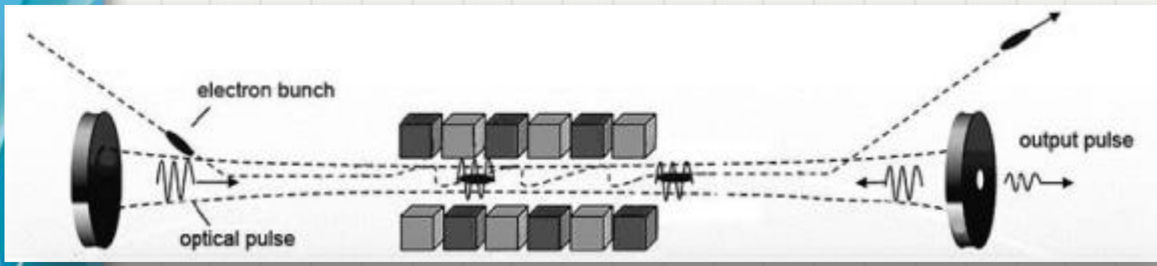
Outline

- Motivation
- Compact pre-bunched generation schemes
- Pre-bunched coherent emission
- Space-charge force suppression
- Multi-micro-bunch concept
- Generation methods and other groups work overview
- LUCX facility
  - List of developments
  - Ti:Sa laser system (FSTB)
  - Laser “Buncher”
  - Multi-micro-bunch, implementation
- 4 – micro-bunch generation, tunability
- Summary, conclusion

Motivation

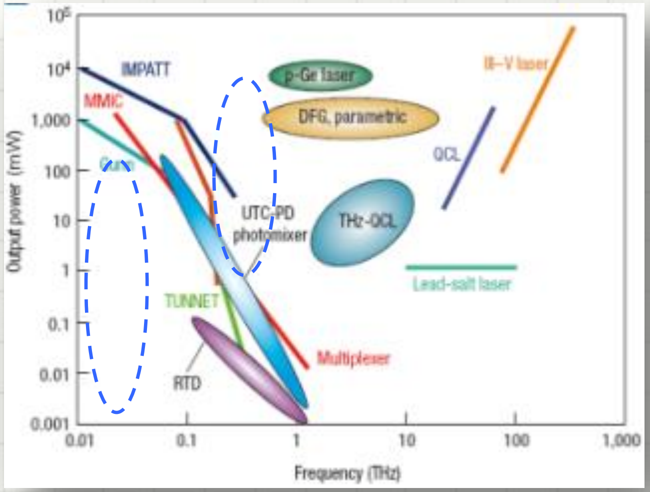
Madey, John, J. Appl. Phys. 42, 1906 (1971)
Madey, John, US Patent 38 22 410,1974



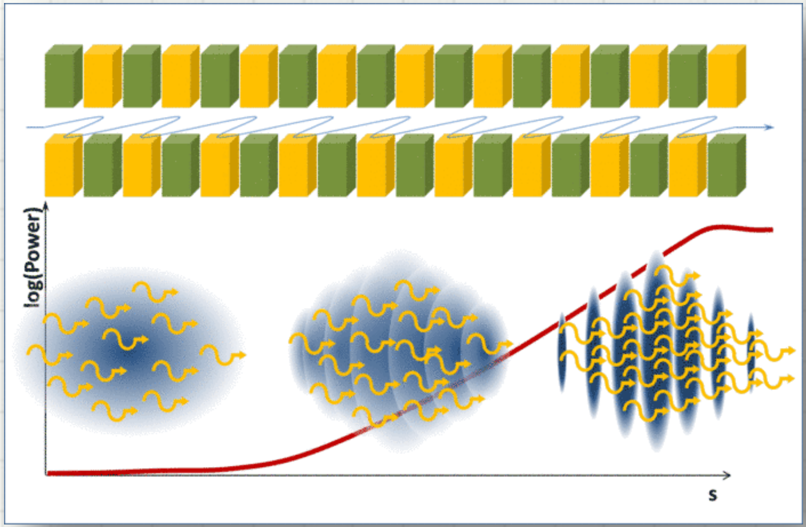
Wavelength of FEL radiation:

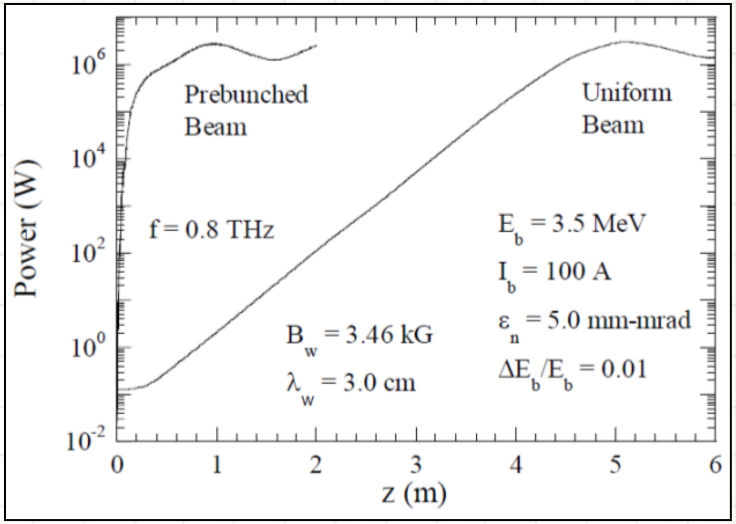
$$\lambda(cm^{-1}) = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

λ_w – period of undulator (cm)
$\gamma=E/E_0$ – relativistic factor
$K=0.93\ B_0\ \lambda_w$
B – magnetic field in undulator (T)



Pre-bunched injection: “Super-radiant” emission & Spectra manipulation

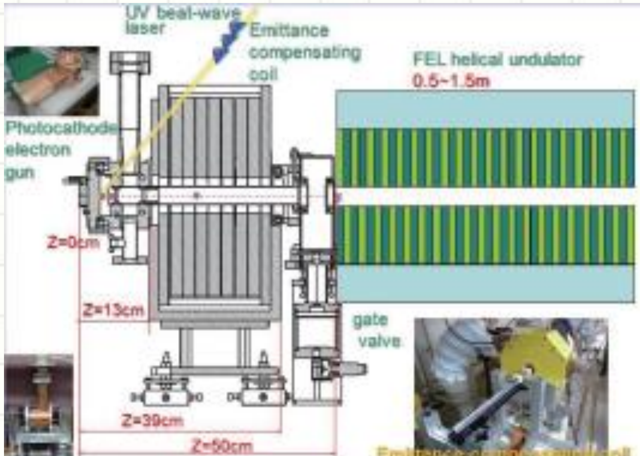


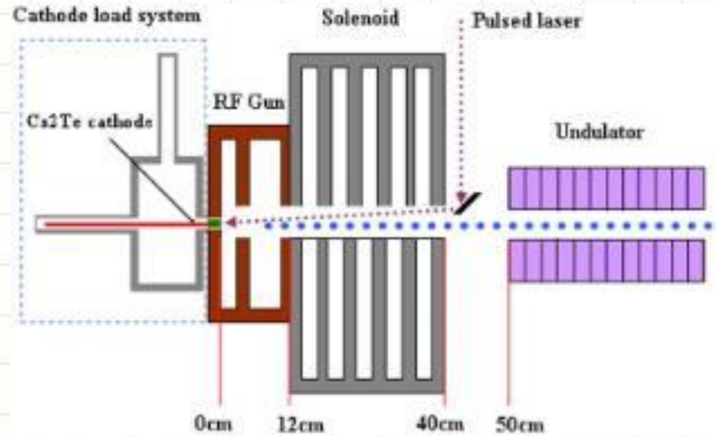


Compact pre-bunched generation schemes

Prof. Y.-C. Huang, National Tsinghua University, Hsinchu, Taiwan

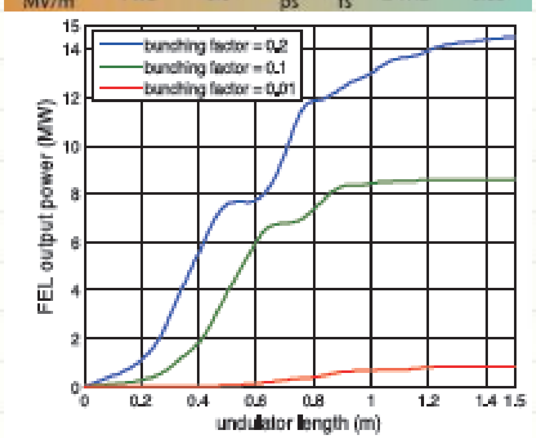
Shengguang Liu, Yen-Chieh Huang, NIM A 637 (2011) S172–S176

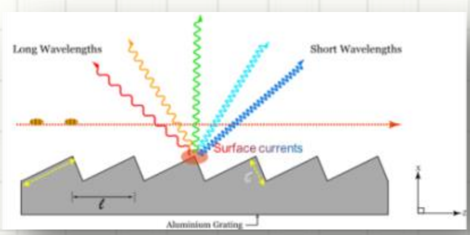


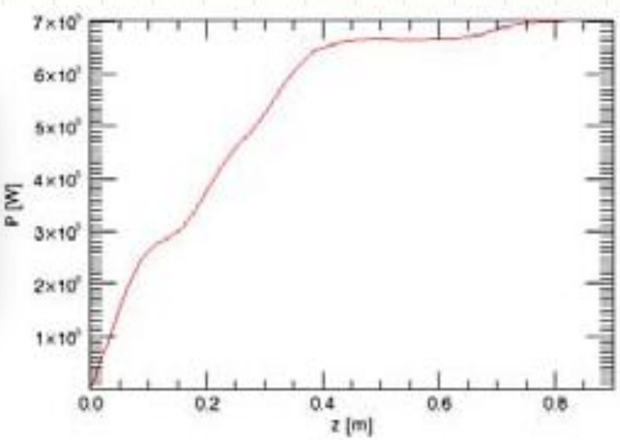


peak gradient	Charges	rms beam radius (mm)	σ_u	σ_μ	micro-pulse rate	Bunching factor @ 2 THz
120 MV/m	1 nC	0.6	4.25 ps	50 fs	2 THz	0.85

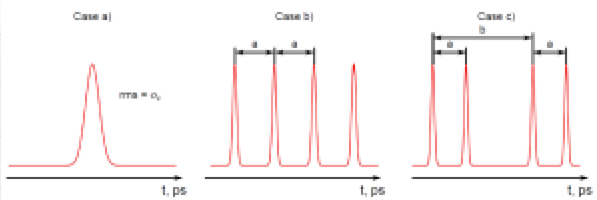
@2THz (150 um), time spacing between laser pulses is 500fs. 16-pulse train of 50fs. Pulse train charge more than200pC, photocathode Q.E. 1%. Peak power at megawatt(MW) level, 0.1 mJ







Pre-bunched coherent emission

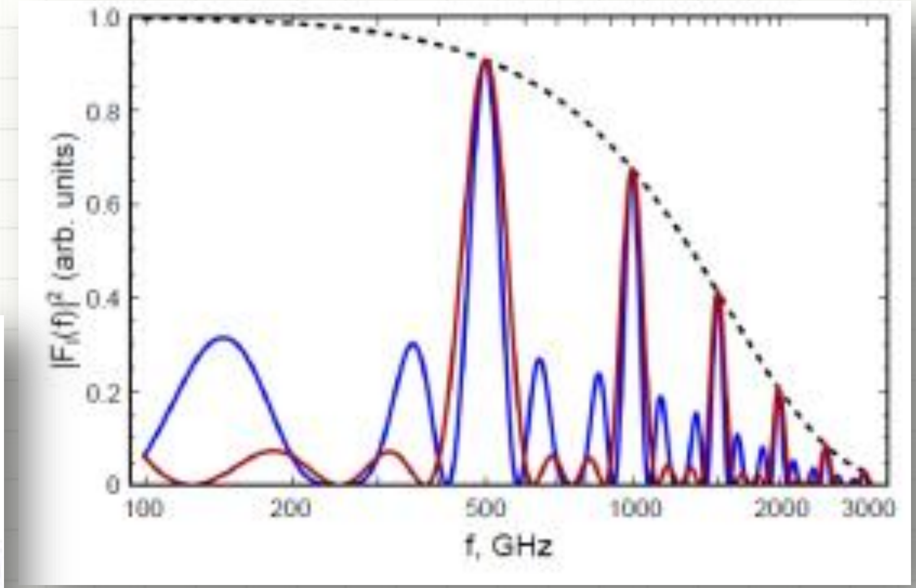


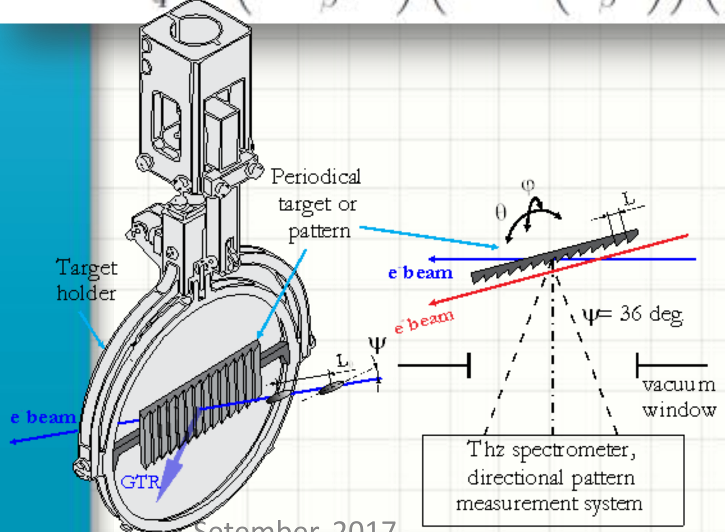
$$\frac{d^2W^s_{tot}}{d\omega d\Omega} = \frac{d^2W_{sing}}{d\omega d\Omega} N_e(1+(N_e-1)\,|\,f_l(\omega)\,|^2)$$

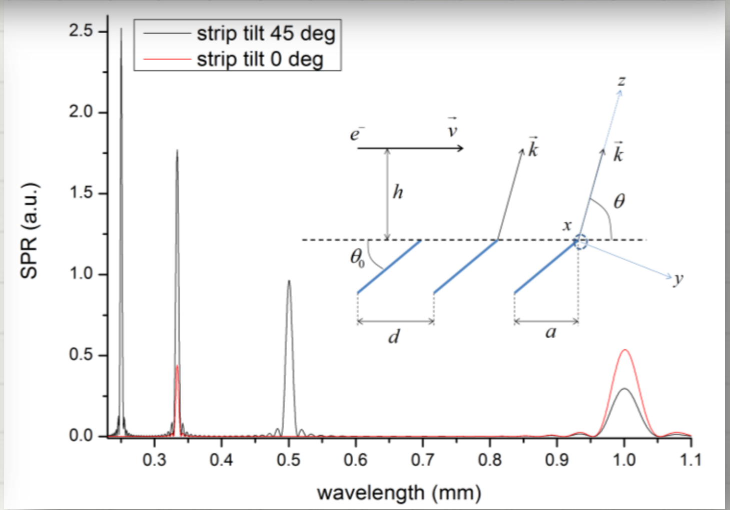
$$|F_l^a(f)|^2 = \exp\left(-\frac{4\pi^2 f^2\sigma_z^2}{\beta^2}\right)$$

$$|F_l^b(f)|^2 = \frac{1}{N_b^2}\exp\left(-\frac{4\pi^2 f^2\sigma_z^2}{\beta^2}\right)\frac{\sin^2\left(N_b\frac{\pi f}{\nu_m}\right)}{\sin^2\left(\frac{\pi f}{\nu_m}\right)}$$

$$|F_l^c(f)|^2 = \frac{1}{4}\exp\left(-\frac{4\pi^2 f^2\sigma_z^2}{\beta^2}\right)\left(1+\cos\left(\frac{2\pi a f}{\beta}\right)\right)\left(1+\cos\left(\frac{2\pi b f}{\beta}\right)\right)$$







Space-charge force suppression

I. Serafini, et.al. NIMA 387 (1997) 305-314

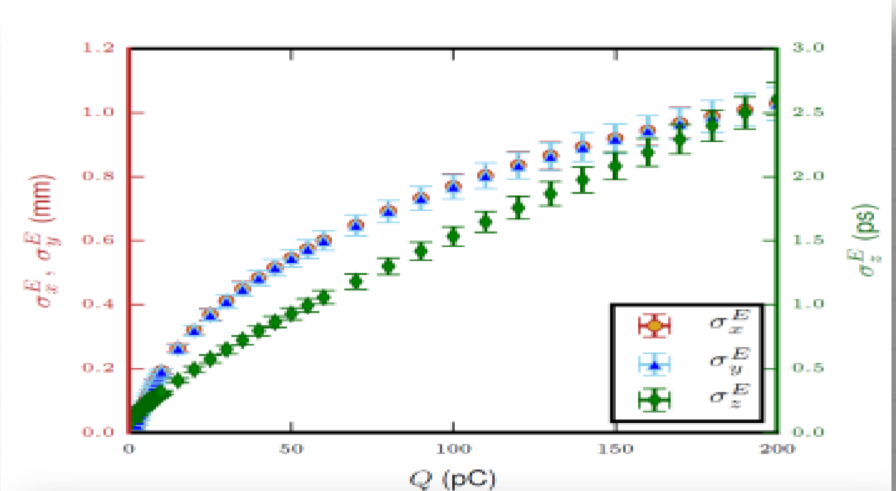
$$\Delta L_{sc} = \frac{4Qc}{I_A \gamma'^2 R^2} f(A, \gamma_f) \qquad (6)$$

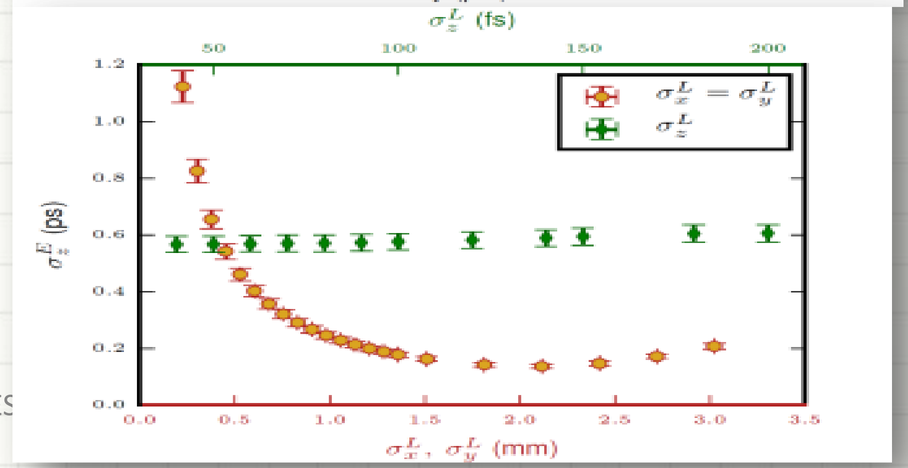
where I_A is the Alfven current, Q the bunch charge, and

$$f(A, \gamma_f) = \left\{ A(1 - 1/\gamma_f) + \sqrt{1 + A^2/\gamma_f^2} + (1 - A)\log\left[\frac{\gamma_f}{1 + \gamma_f}\right] + A[\operatorname{arc\,sinh}[A] - \operatorname{arc\,sinh}[A/\gamma_f]] - \log[2](A - 1) - \sqrt{1 + A^2} \times \left(1 + \log\left[\frac{A^2(1 + \gamma_f)}{A^2 - \gamma_f + \sqrt{1 + A^2}\sqrt{1 + A^2/\gamma_f^2}}\right]\right) \right\}$$

ASTRA simulation, LUCX RF gun

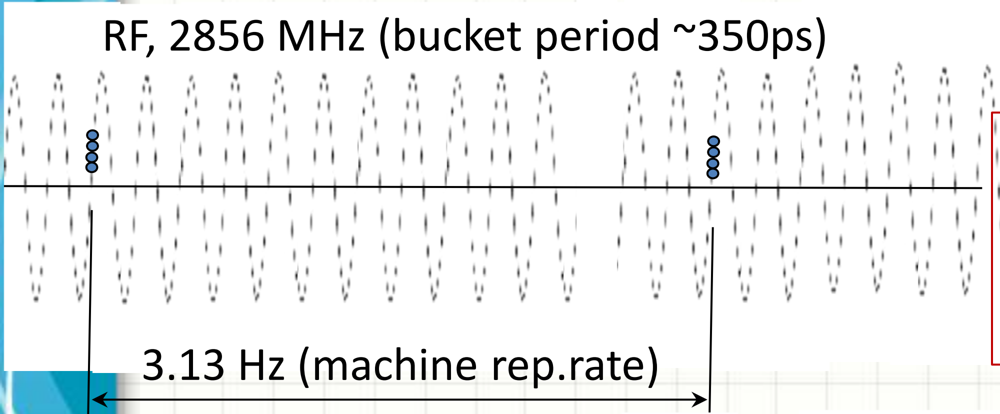
M. Shevelev, A. Aryshev, Y. Honda, N. Terunuma, J. Urakawa, Influence of space charge effect in femtosecond electron bunch on coherent transition radiation spectrum, Nucl. Instrum. Methods Phys. Res., Sec. B 402, 134 (2017).





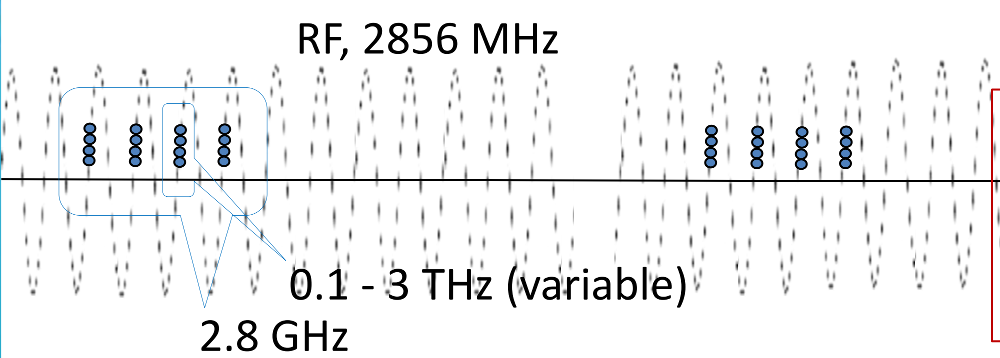
- Acceleration gradient, up -> limited by discharge
- Charge, down -> limited by detector's sensitivity
- UV spot size, up -> limited by off-axis dynamics
- UV Pulse length, !!! -> limited by THG
- Multi-bunch -> limited only by beam-loading

Multi-micro-bunch, concept



4 micro-bunches
1 multi-bunch (1 RF bucket)

- Number of filled RF buckets depends only on FH laser energy budget
- Non-sequential RF bucket filling is possible
- **Number of micro-bunches/rf bucket ?**

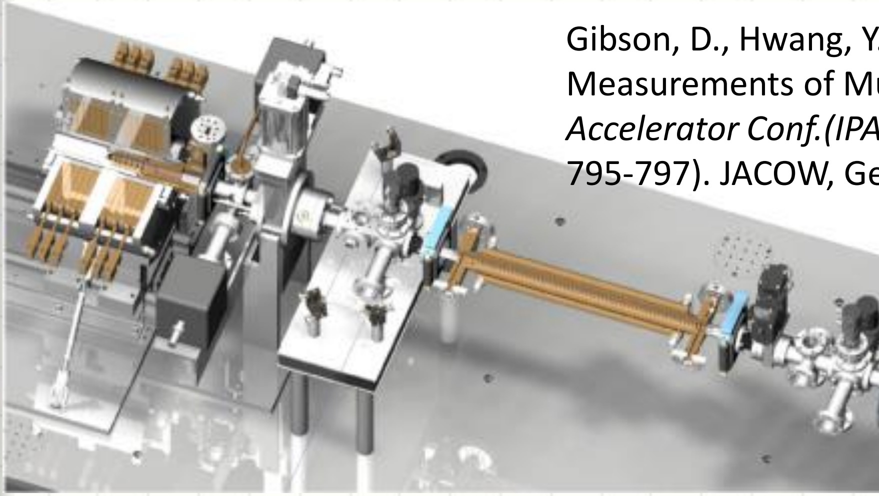


4 micro-bunches
4 multi-bunch (4 RF buckets)

- DAQ sees this micro-train as a single event (no trigger modification is required)
- Micro-bunch spacing can be changed simultaneously in all buckets

- One of the typical S-band accelerator parameters:
  - Multi-bunch rep.rate (from the RF gun laser oscillator) ~ 357MHz (every 9th RF bucket)
  - RF pulse width ~ 4 us => max 1400 bunches (roughly) – filling time etc. ~ 1250 bunches
- Applying 8-times pulse split -> 10000 bunches/4 us !!!
- Effects on: X-ray Compton, Fiber laser oscillators implementation, total radiated power.

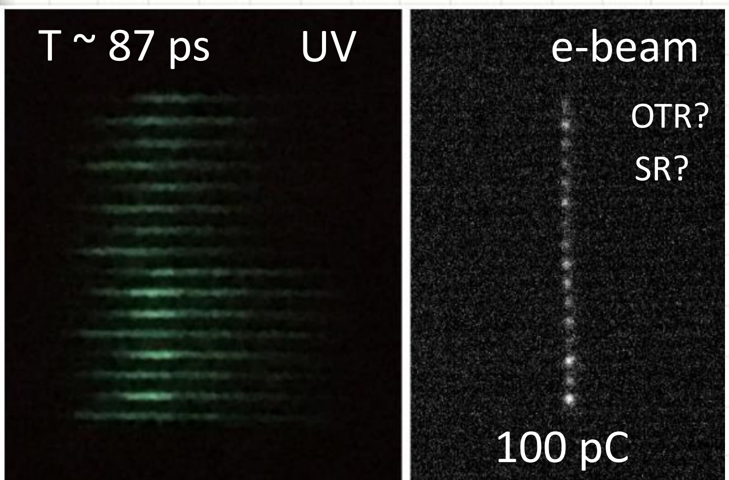
LLNL: linac-driven, laser-based Compton scattering gamma-ray source



Gibson, D., Hwang, Y. and Marsh, R., 2017, May. Initial Performance Measurements of Multi-GHz Electron Bunch Trains. In *8th Int. Particle Accelerator Conf.(IPAC'17), Copenhagen, Denmark, 14â 19 May, 2017* (pp. 795-797). JACOW, Geneva, Switzerland.

R.A. Marsh et al., “Modeling and Design of an X-Band RF Photoinjector”, Phys. Rev. ST Accel. Beams, vol. 15, p. 102001, 2012.

Frequency	11.424 GHz
Unloaded quality factor	7055
First cell length	0.59 cell
Coupler type	Dual feed racetrack
Iris shape	Elliptical, 1.8 major/minor
Mode separation	25 MHz
Cathode material	Oxygen-free high conductivity
Cathode peak field	200 MV/m
Final kinetic energy	7 MeV



RF Gun laser

Wavelength	263.25 nm
Energy	50 μJ
Transverse σ	0.55 mm
Transverse hard edge	0.46 mm
Temporal rise/fall	250 fs
Temporal FWHM	2 ps

Interference-related methods

Neumann, J. G., Fiorito, R. B., O'Shea, P. G., Loos, H., Sheehy, B., Shen, Y., & Wu, Z. (2009), Terahertz laser modulation of electron beams. Journal of Applied Physics, 105(5), 053304.

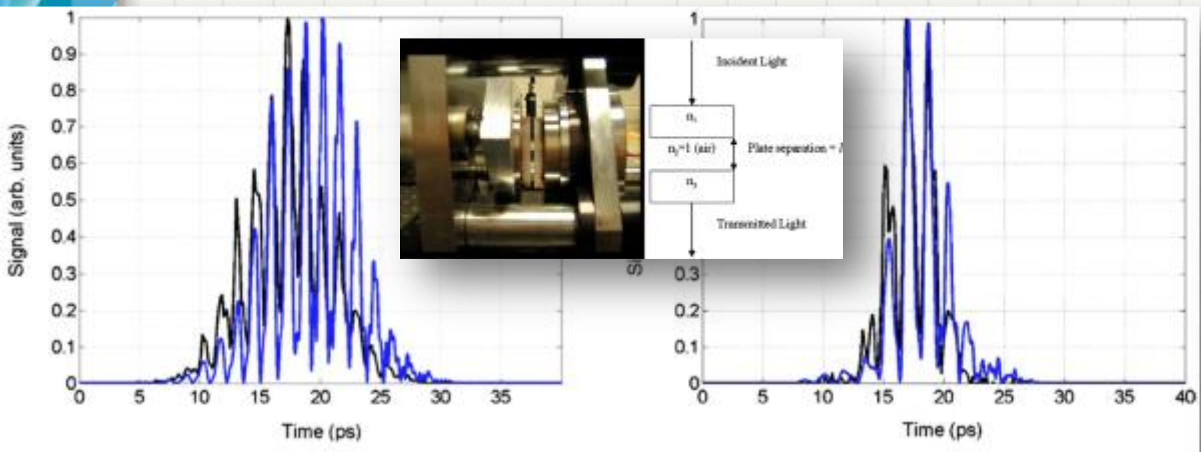


FIG. 7. (Color online) Cross-correlation measurement of modulated laser intensity (blue) compared with theory (black) for a cavity spacing of 260 μm (left) and 207 μm (right).

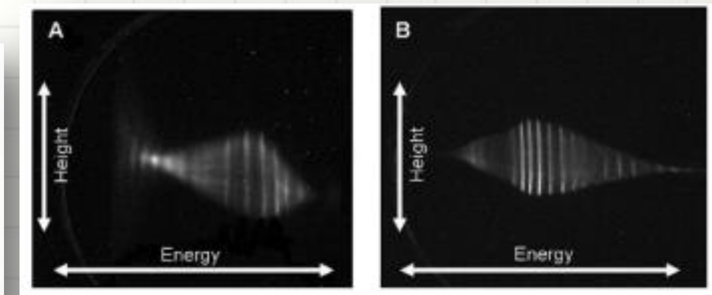
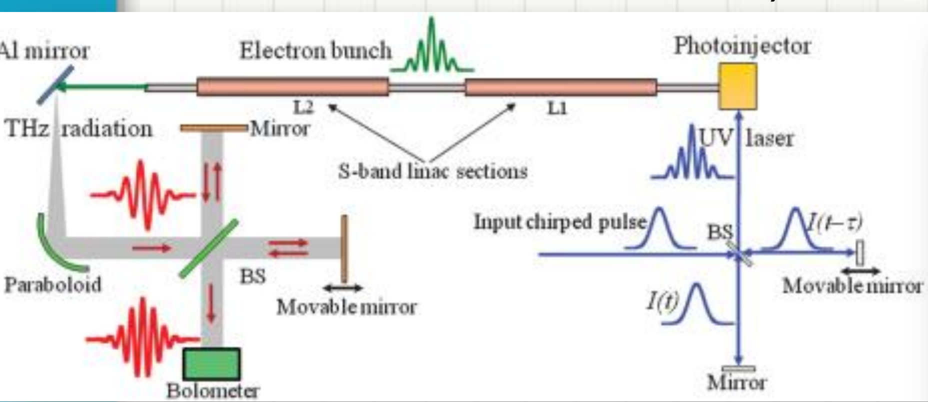
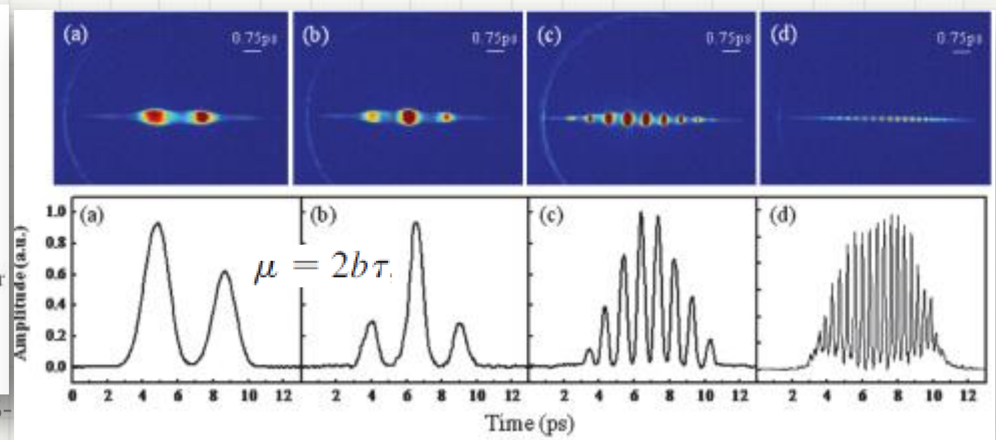


FIG. 9. (Left) rf zero-phase measurement of initially unmodulated compressed electron beam; (right) rf zero-phase measurement of deeply modulated uncompressed electron beam.

$$I(t,\tau) = |E(t) + E(t+\tau)|^2 = I(t) + I(t+\tau) + 2\sqrt{I(t)I(t+\tau)}\cos(\omega_0\tau + b\tau^2 + 2b\tau t)$$

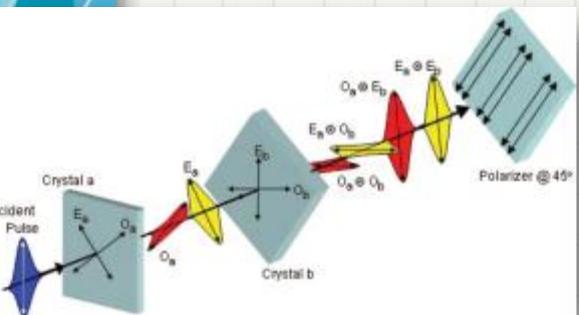
Shen, Y., Yang, X., Carr, G. L., Hidaka, Y., Murphy, J. B., & Wang, X. (2011). Tunable few-cycle and multicycle coherent terahertz radiation from relativistic electrons. *Physical review letters*, *107*(20), 204801.

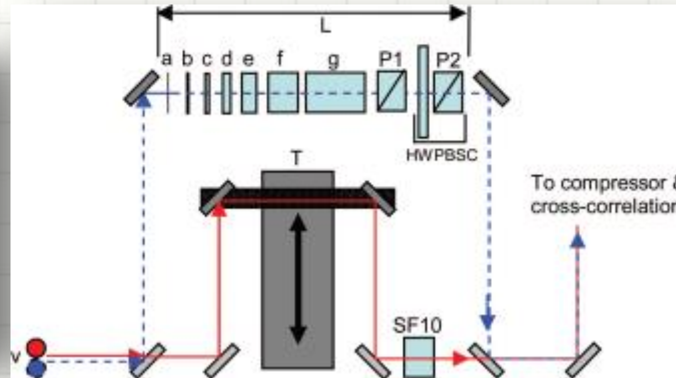




Birefringent crystal array

Dromey, B., Zepf, M., Landreman, M., O'keeffe, K., Robinson, T., & Hooker, S. M. (2007). Generation of a train of ultrashort pulses from a compact birefringent crystal array. *Applied optics*, *46*(22), 5142-5146.





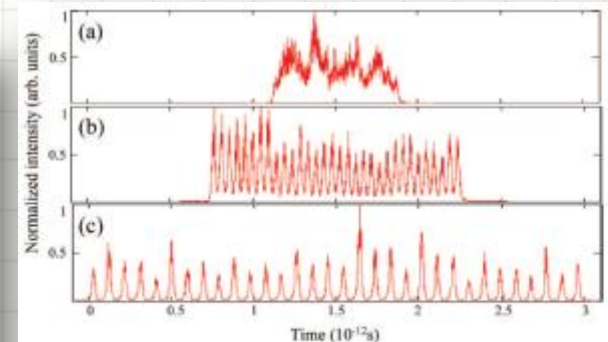


Fig. 5. (Color online) Cross correlation traces of the pulse train with the probe beam pulse performed on the Oxford 125 fs pulse duration Ti:sapphire laser. The following crystal configurations were used: (a) first five crystals in, sixth and seventh crystal out, 32 pulses with minimum separation; (b) first and last crystal out, crystals two through six in, 32 pulses with two times minimum separation; (c) first and second crystal out, crystals three through seven in, 32 pulses with four times minimum separation.

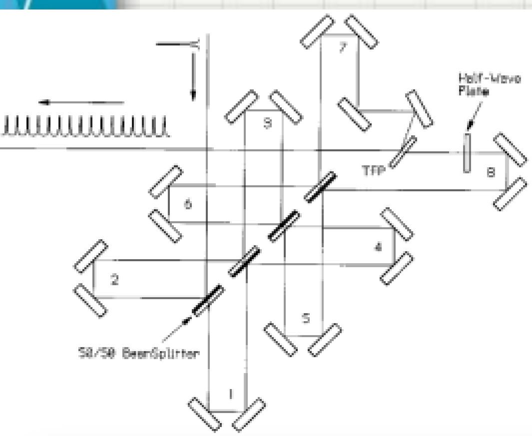
$$\Delta t = x\left(\frac{1}{V_o} - \frac{1}{V_e}\right)$$

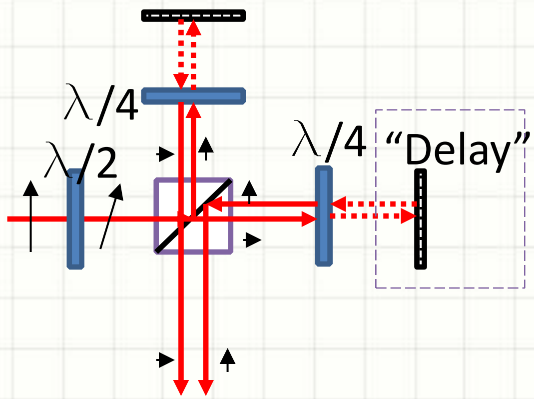
Giorgianni, F., Anania, M.P., Bellaveglia, M., Biagioni, A., Chiadroni, E., Cianchi, A., Daniele, M., Del Franco, M., Di Giovenale, D., Di Pirro, G. and Ferrario, M., 2016. Tailoring of highly intense THz radiation through high brightness electron beams longitudinal manipulation. *Applied Sciences*, *6*(2), p.56.

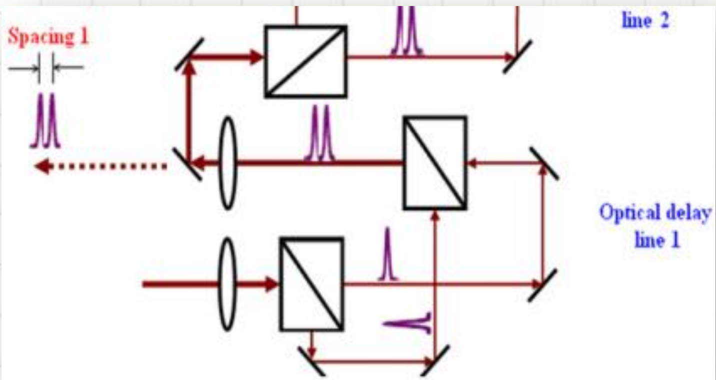
Yan, L., Du, Q., Du, Y., Hua, J., Huang, W. and Tang, C., 2011. UV pulse shaping for the photocathode RF gun. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *637*(1), pp.S127-S129.

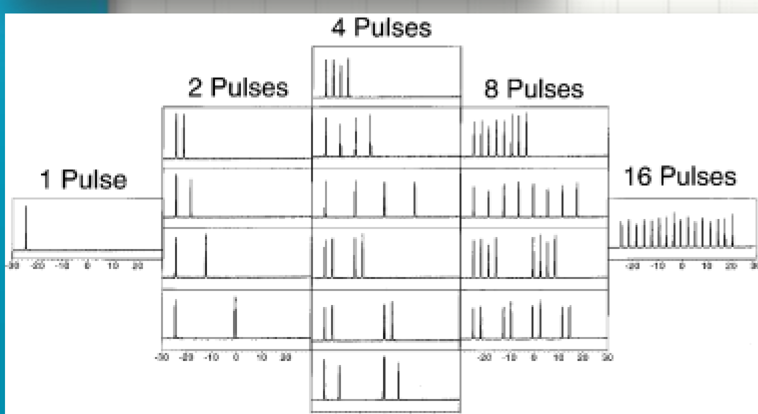
Pulse splitter

- C.W. Siders et al., “Efficient High-Energy Pulse-Train Generation using a 2n-Pulse Michelson Interferometer”, Appl. Opt., vol. 37, p. 5302, 1998.
- Liu, S. and Huang, Y.C., 2011. Generation of pre-bunched electron beams in photocathode RF gun for THz-FEL superradiation. *NIMA*, *637*(1), pp.S172-S176.



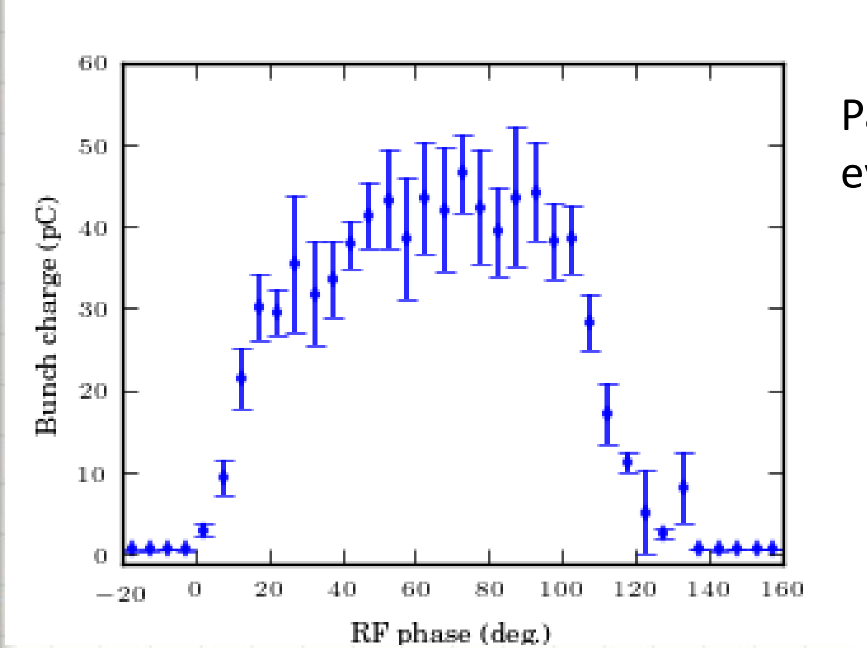






- These approaches give alternative polarizations within the train.
- What is leading to at least 50% loses on downstream polarization-sensitive laser components (Amplifiers, Compressors, HHG, etc.)

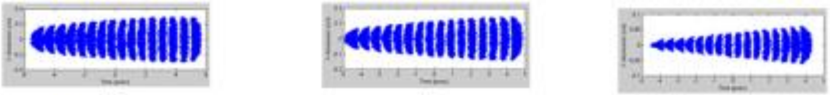
Number of micro-bunches/RF bucket ?

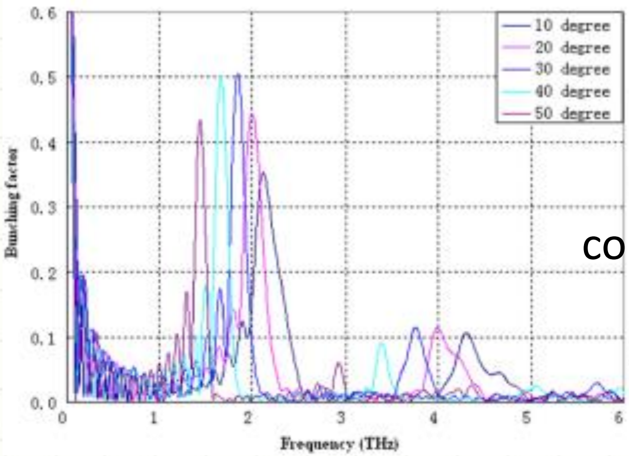


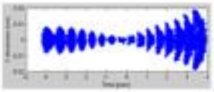
Parameters that will be naturally different for every micro-bunch:

- Charge (pow(N,2) dependence)
- E, dE (Linear dependence)
- Sigma_z (exponential dependence)
- Sigma_x,y (depends on radiation type)

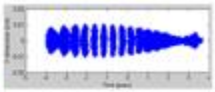
16 micro-bunch ASTRA simulation

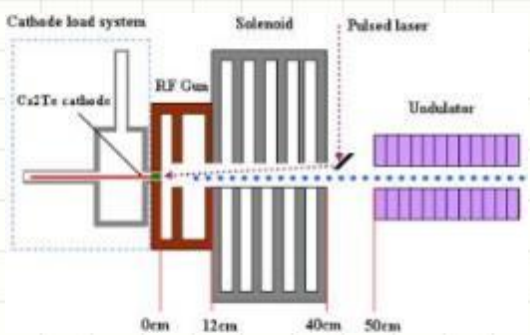






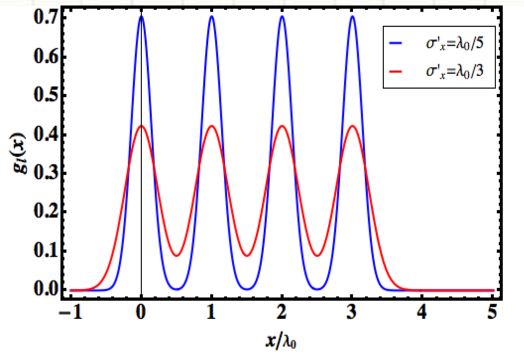
courtesy S. Liu

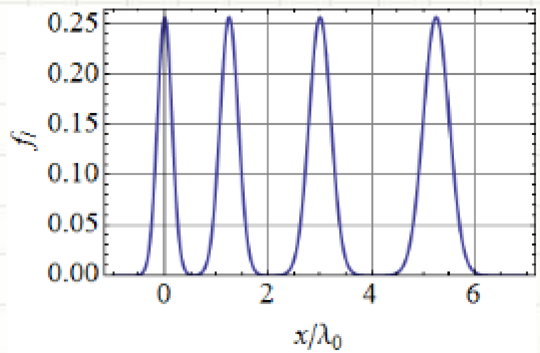


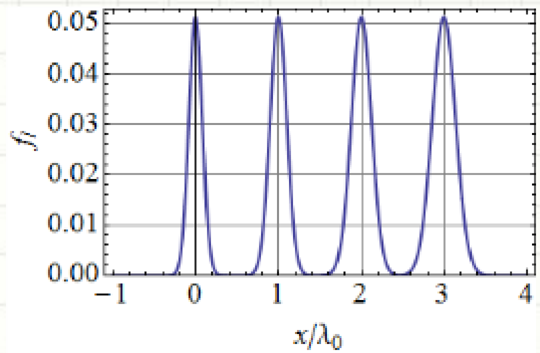


Number of micro-bunches/RF bucket (work in progress)

$$f_l(x) = A\sum_{s=0}^{N_b-1}\exp\left[-\frac{(x-s\lambda_s)^2}{\sigma_s^2}\right], \qquad \int_{-\infty}^{+\infty} dx f_l(x) = 1, \qquad A = \left(\sqrt{\pi}\sum_{s=0}^{N_b-1}\sigma_s\right)^{-1}.$$







$$F = NF_{inc} + N(N-1)F_{coh},$$

$$F_{inc} = \int_V d^3r \left|e^{-i\mathbf{q}(\mathbf{r}-\mathbf{r}_0)}\right|^2 P(\mathbf{r}),$$

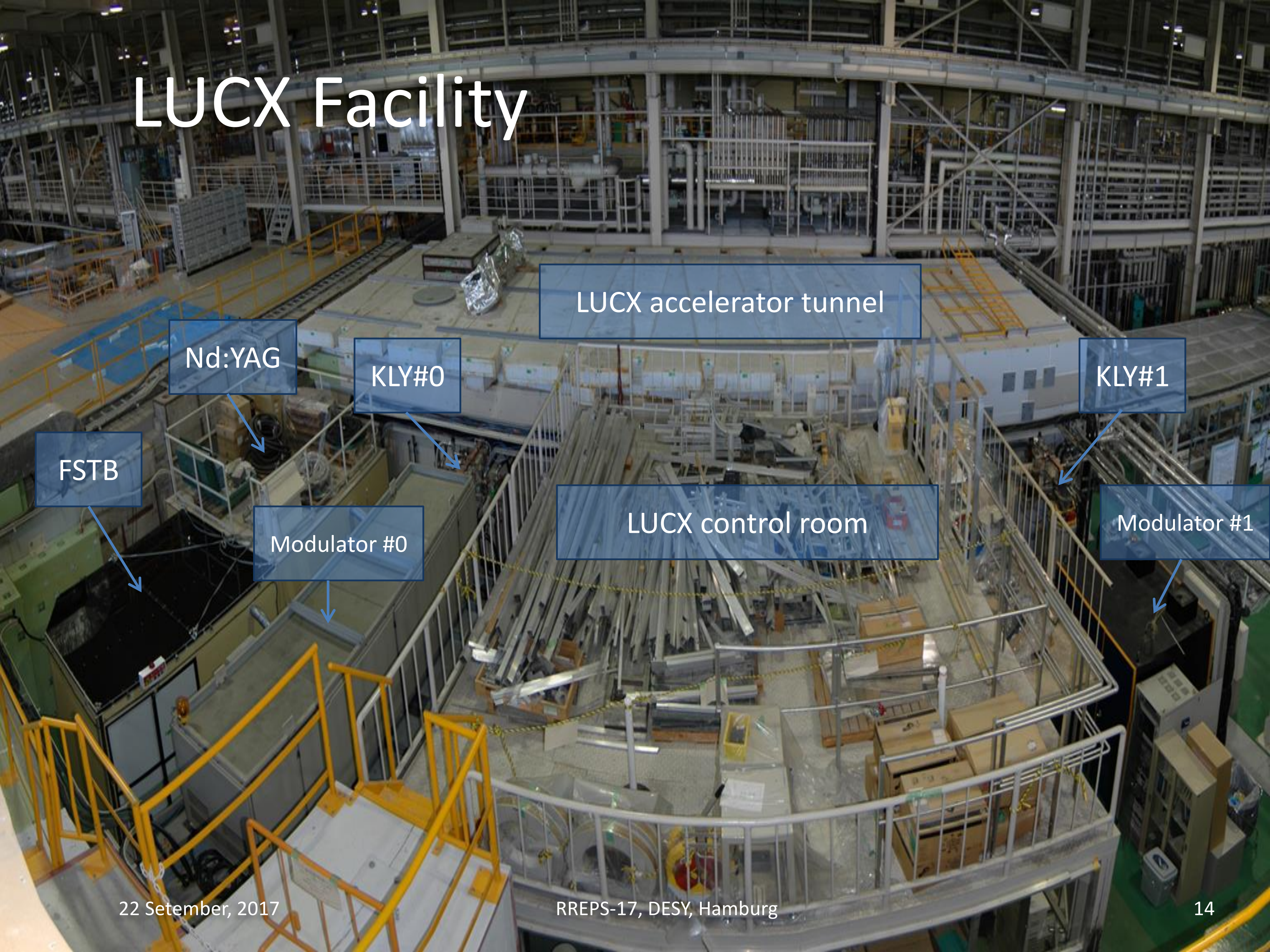
$$F_{coh} = \left|\int_V d^3r e^{-i\mathbf{q}(\mathbf{r}-\mathbf{r}_0)} P(\mathbf{r})\right|^2,$$

- Amplitudes (charge)
- Function on phase

$$F_{coh\,l} = \left|\frac{\sum_{s=0}^{N_b-1}\sigma_s e^{-\frac{\omega}{c\beta}\left(\frac{\sigma_s^2}{4}\frac{\omega}{c\beta}+is\lambda_s\right)}}{\sum_{s=0}^{N_b-1}\sigma_s}\right|^2.$$

$$F_l = \exp\left[-\frac{\sigma_x^2\xi^2}{2}\right]\frac{1}{N_b^2}\frac{\sin^2(N_b\lambda_0\xi/2)}{\sin^2(\lambda_0\xi/2)}, \quad \xi = \omega/v.$$

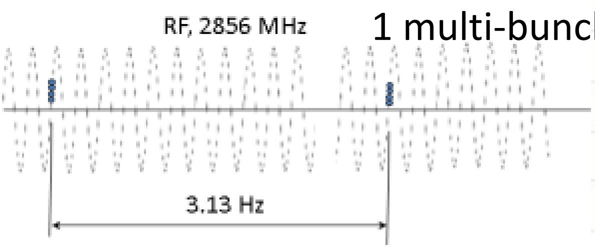
LUCX Facility

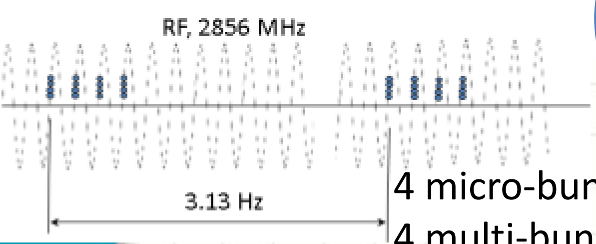


List of developments

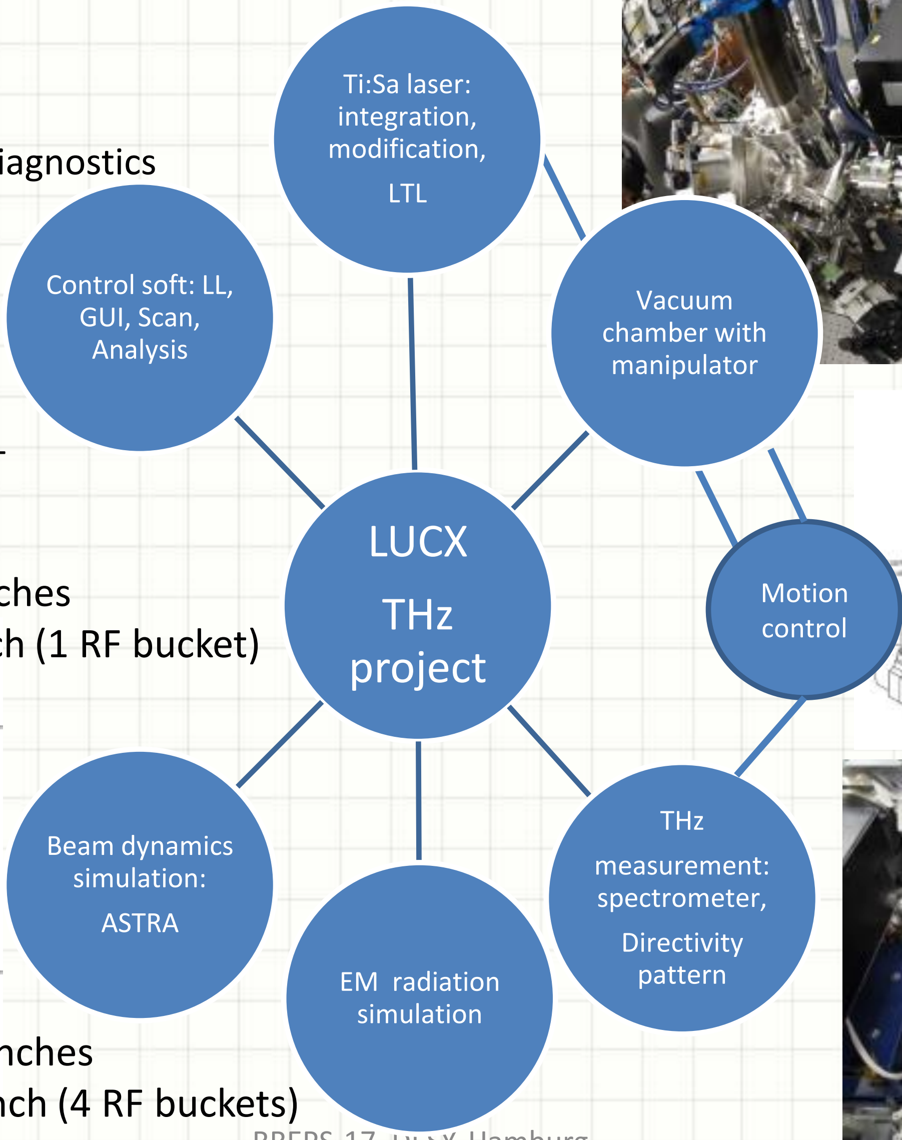
- Pre-bunched fs e-beam generation
  - fs e-beam longitudinal diagnostics
  - Cathode response time
  - Space-charge limitation
- THz radiation generation
  - Simulation and experi-mental validation
  - Tuning procedure + diag-nostics
- THz experiments

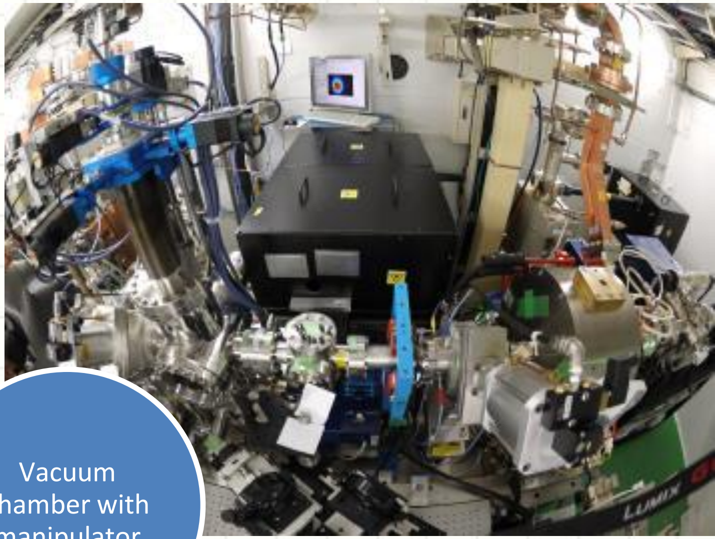
4 micro-bunches
1 multi-bunch (1 RF bucket)

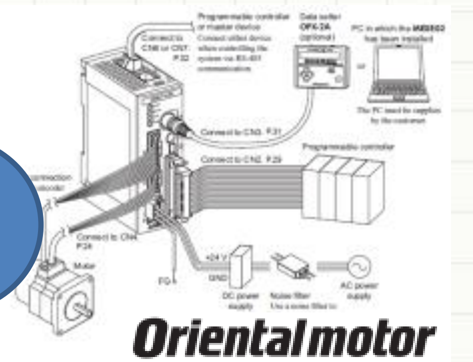




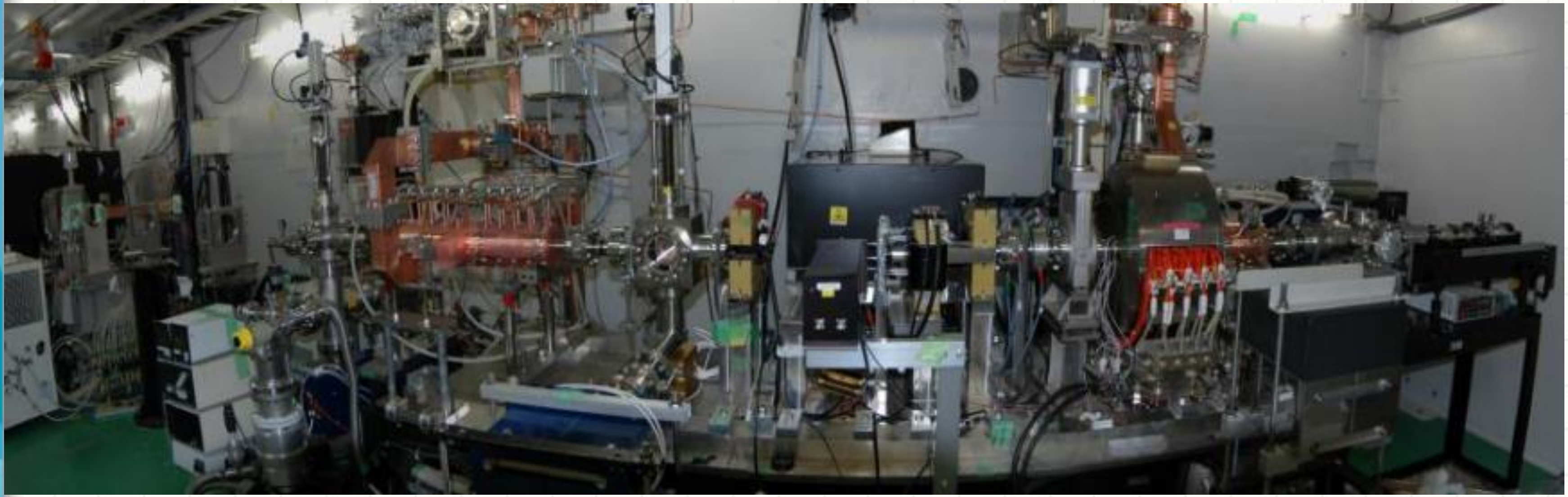
4 micro-bunches
4 multi-bunch (4 RF buckets)







LUCX beamline and operation modes



“Femtosecond mode”	“Picosecond mode”
• Ti:Sa laser • e-bunch rms length ~100fs • e-bunch charge < 100pC • Single bunch train, Micro-bunching 4-16 (4 is confirmed) • Typical Rep. rate 3.13 Hz • Experiments: THz program	• Q-switch Nd:YAG laser • e-bunch rms length ~10ps • e-bunch charge < 0.5 nC • Multi-bunch train 2- few 10^3 • Max Rep. rate 12.5 Hz • Experiments: Compton, CDR

Laser pulse divider, current prototype

General scheme

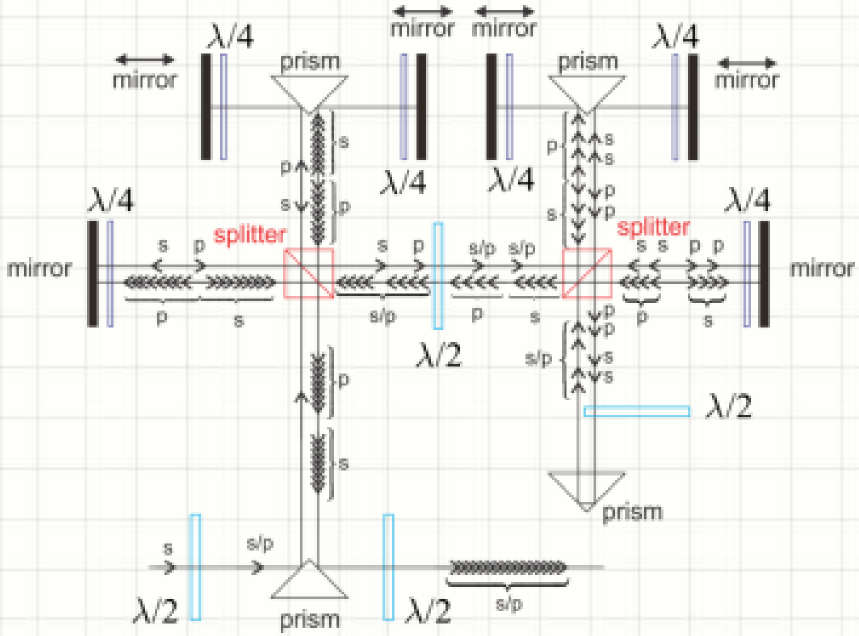
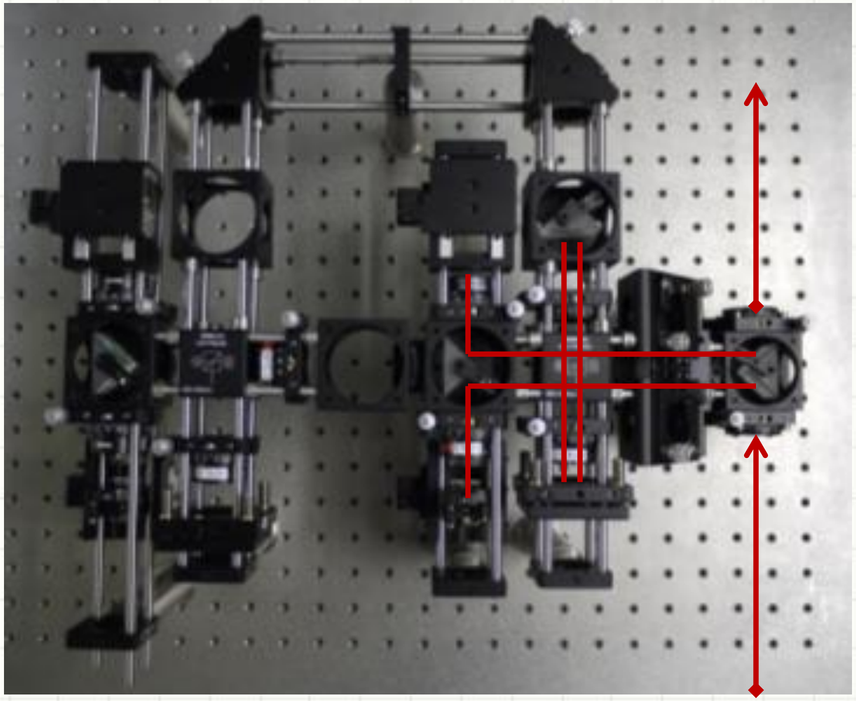
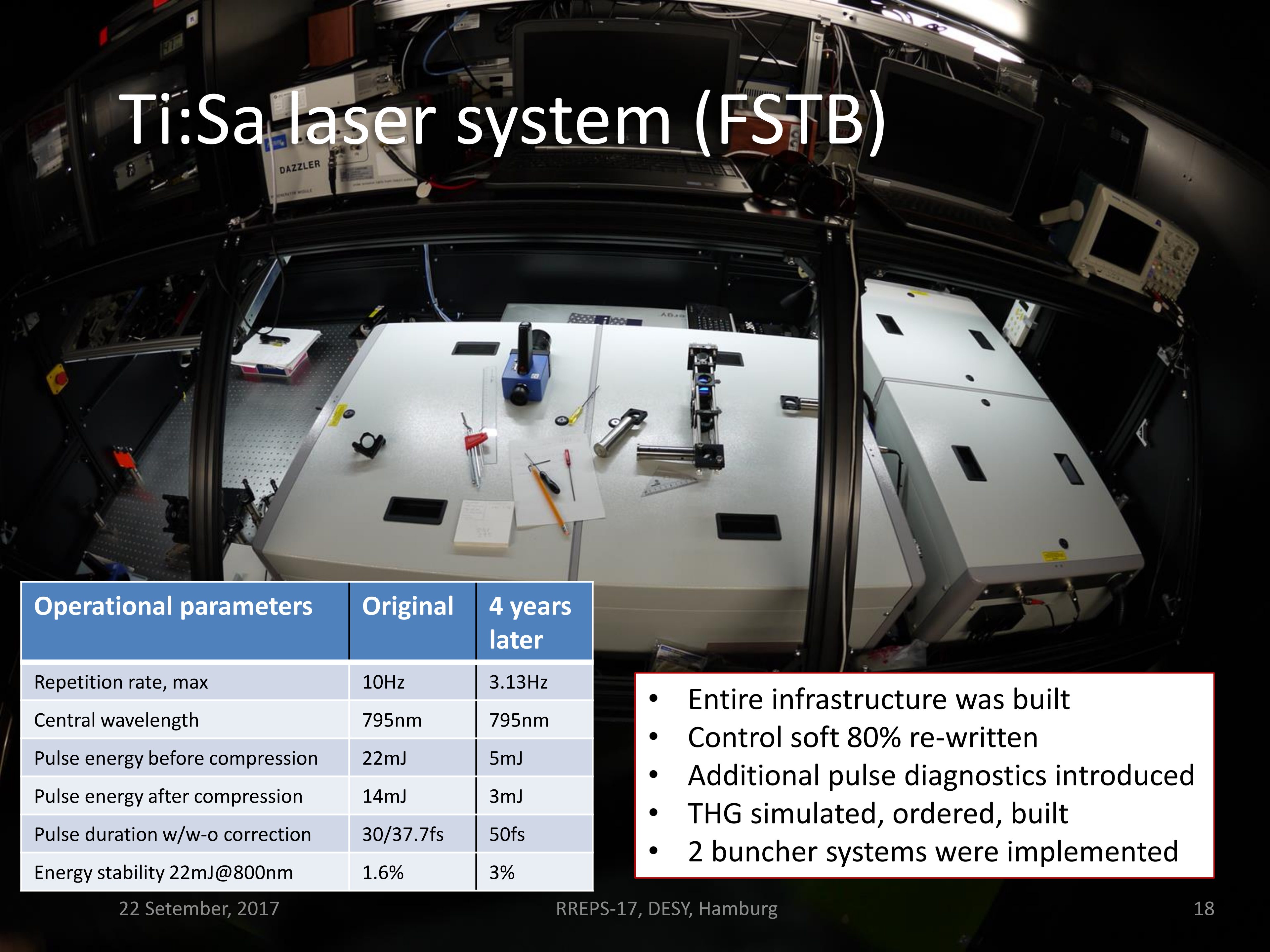


Photo of pre-assembled system



- All bits were delivered in September 2014.
- Assembled and tested (laser side only) in Nov.-Dec. 2014
- Tested (e-beam generation) in Jan. – Feb. 2015

Ti:Sa laser system (FSTB)

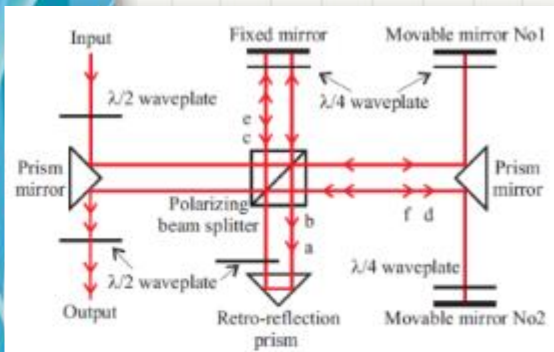


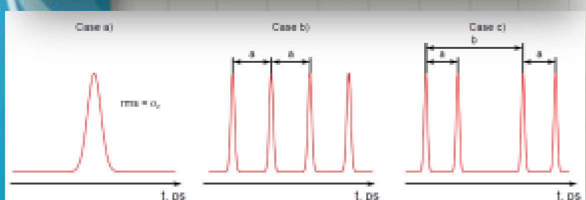
Operational parameters	Original	4 years later
Repetition rate, max	10Hz	3.13Hz
Central wavelength	795nm	795nm
Pulse energy before compression	22mJ	5mJ
Pulse energy after compression	14mJ	3mJ
Pulse duration w/w-o correction	30/37.7fs	50fs
Energy stability 22mJ@800nm	1.6%	3%

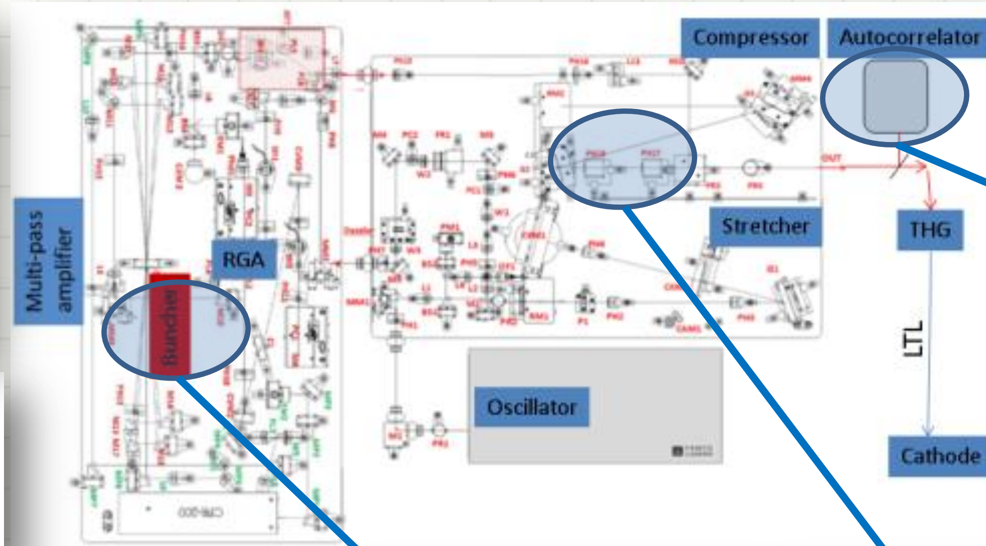
- Entire infrastructure was built
- Control soft 80% re-written
- Additional pulse diagnostics introduced
- THG simulated, ordered, built
- 2 buncher systems were implemented

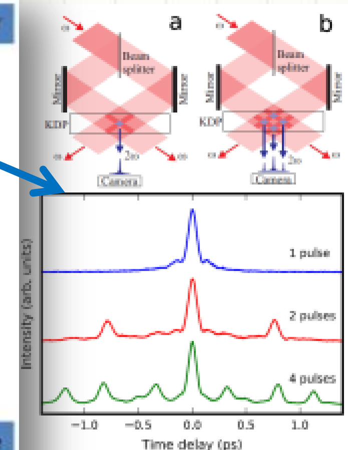
Multi-micro-bunch, implementation

Present condition: 4x4 pulses, ~50 fs each, converted to 266nm, 10uJ

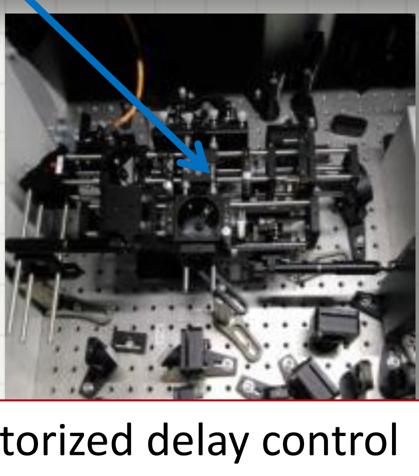








- **Total splitting efficiency ~20%**
- New design with total 10-20% loses is possible.
- Beam expander was removed.
- Multi-pass Amp, Compressor, THG, LTL re-tuned.
- Micro-bunch
  - Separation: +/- 5 ps
  - Stability: < 20 fs (lower than meas. resolution)
- Multi-bunch
  - Separation: 350ps +/- 30 ps



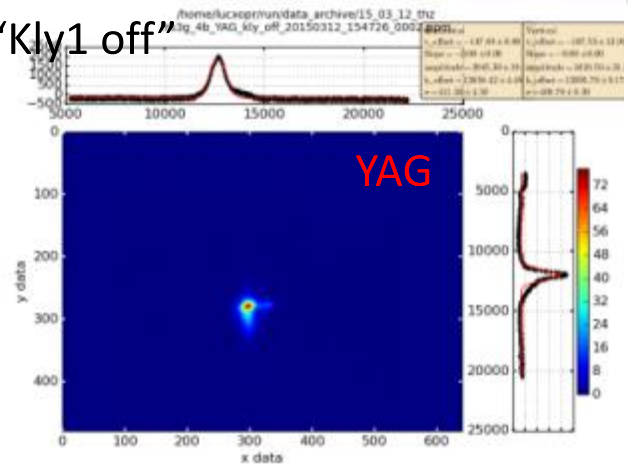
Motorized delay control

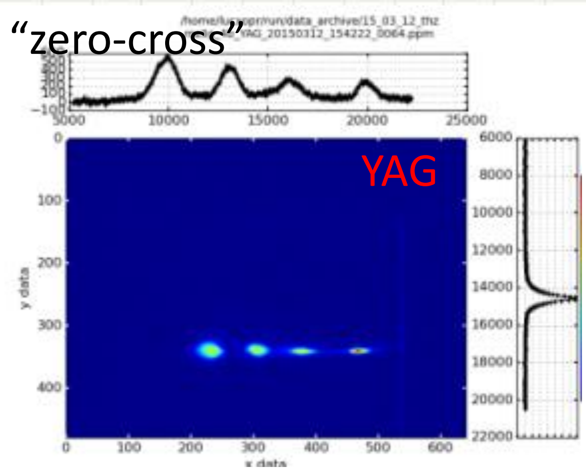
Manual delay control

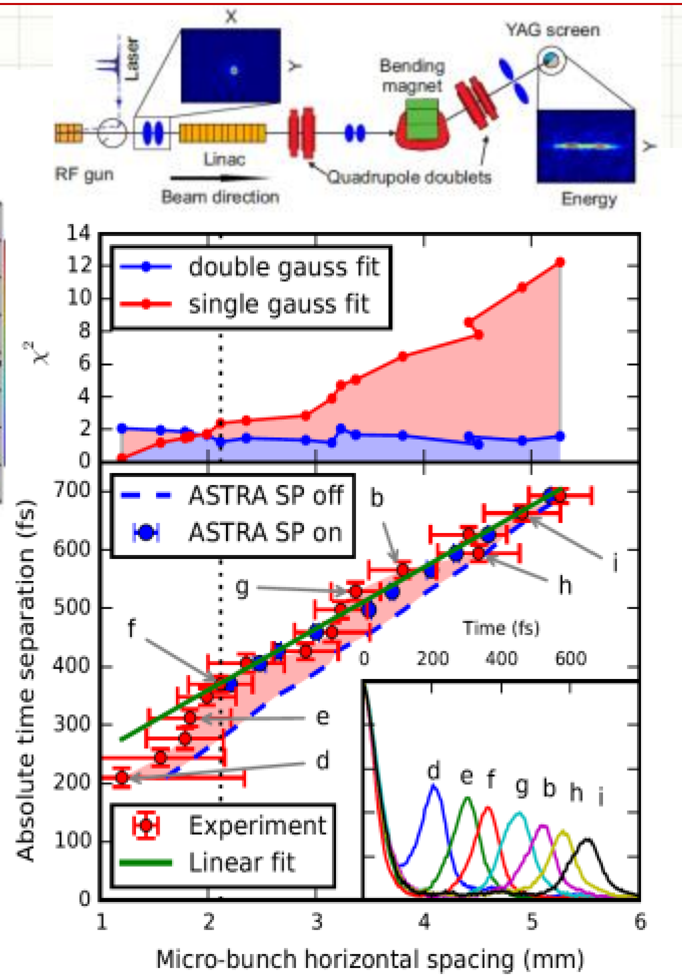
4-micro bunch generation

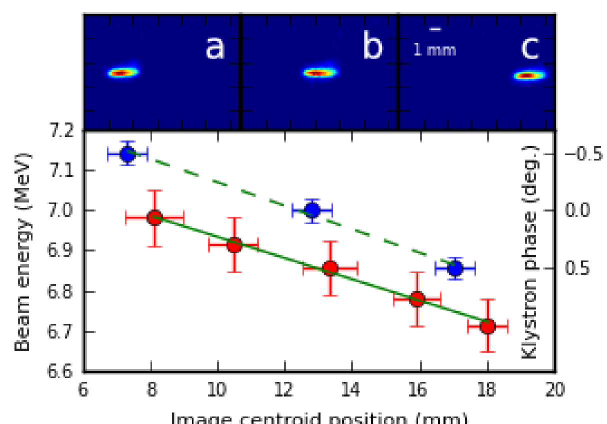
A. Aryshev, M. Shevelev, Y. Honda, N. Terunuma, J. Urakawa, Femtosecond response time measurements of a Cs2Te photocathode, Appl. Phys. Lett. 111, 033508 (2017).

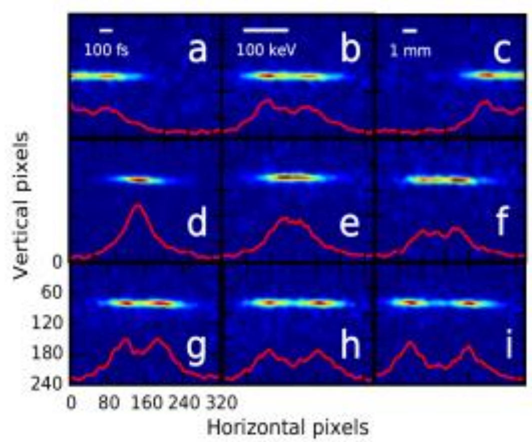
Measured Cs2Te photocathode peak-to-peak response time **369.48 ± 27 fs**.











Tunability

Accepted Paper

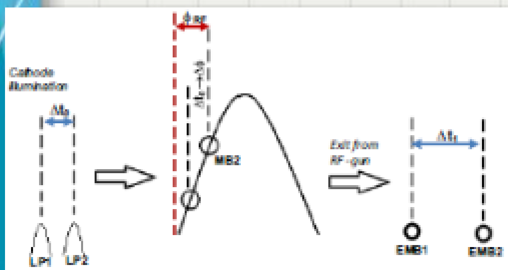
Generation of a femtosecond electron microbunch train from a photocathode using twofold Michelson interferometer

Phys. Rev. Accel. Beams

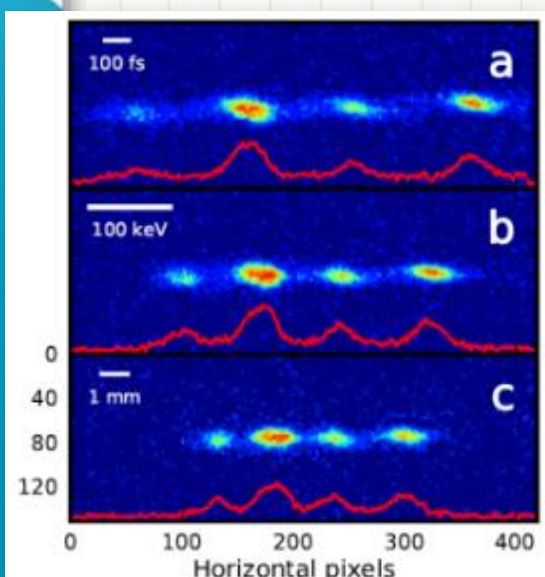
M. Shevelev, A. Aryshev, N. Terunuma, and J. Urakawa

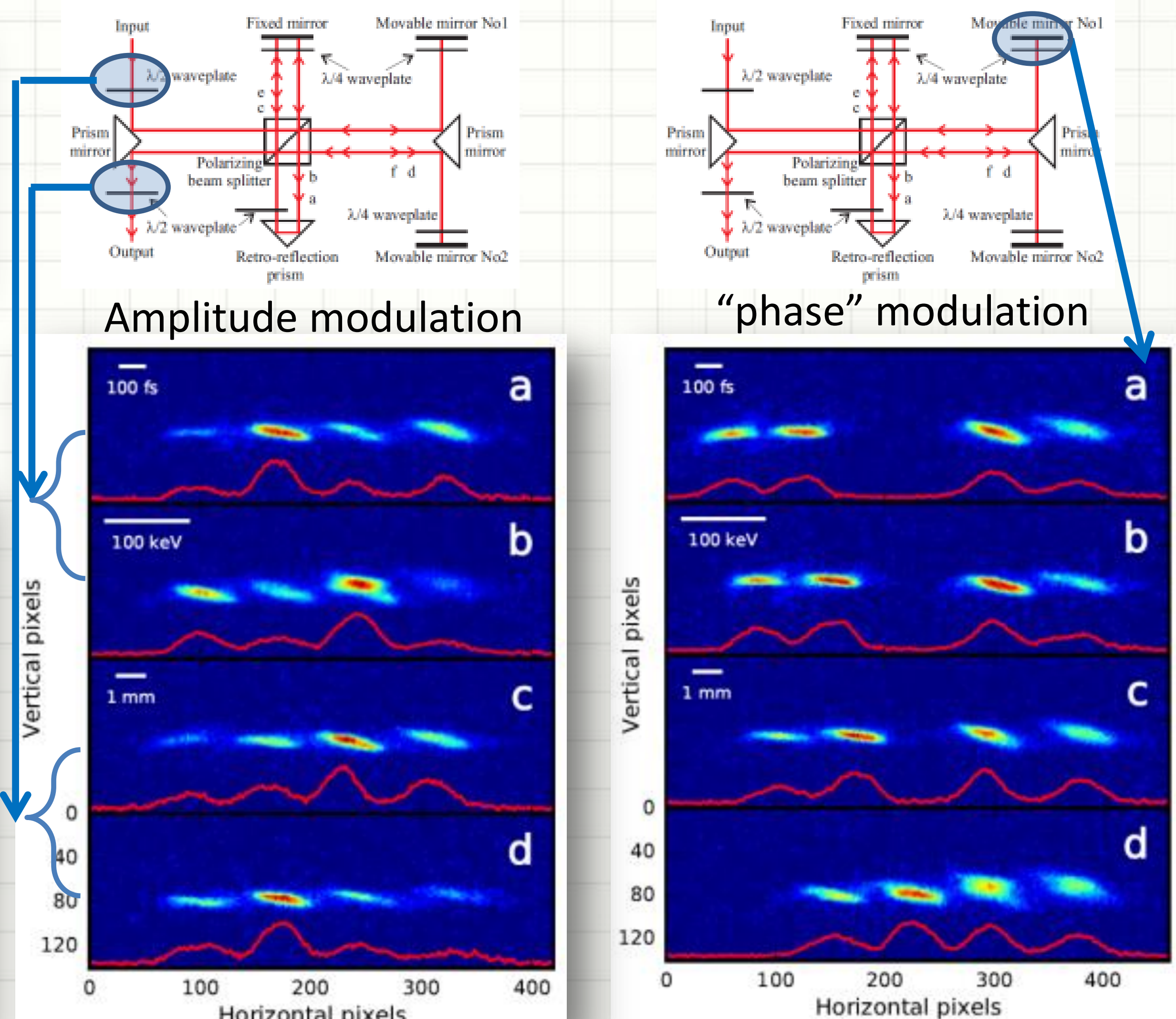
Accepted 14 September 2017

“phase” modulation



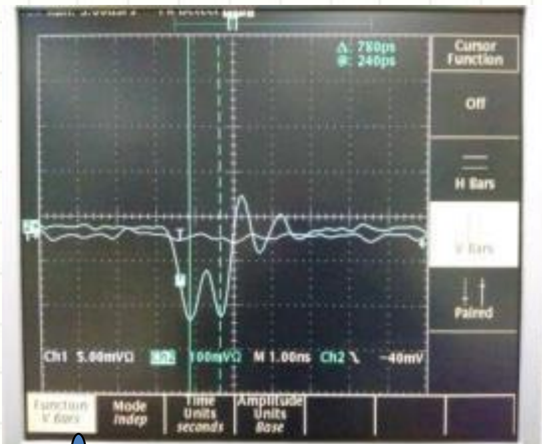
$$\Delta t = \Delta\phi/\omega_{rf}$$



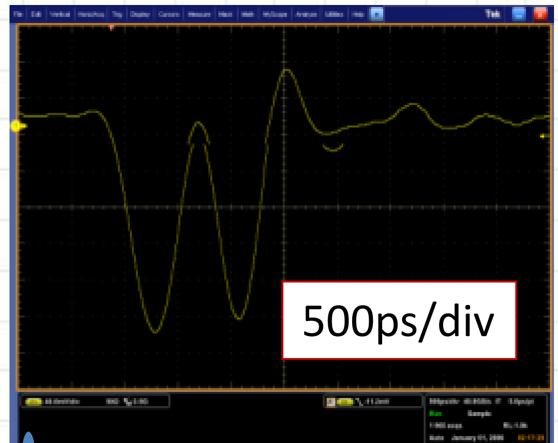


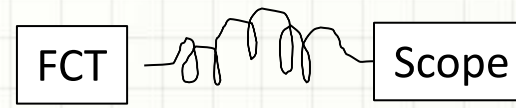
4-multi bunch generation

Tek TDC 684B, 1GHz, 5Gs/s



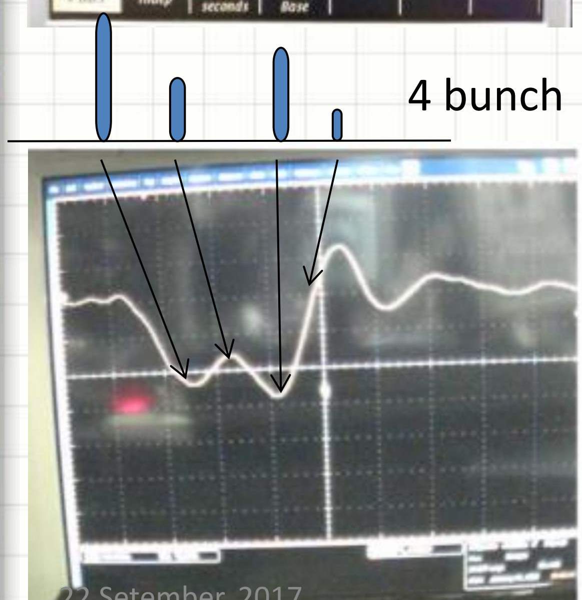
Tek DPO 7354, 5GHz, 40Gs/s

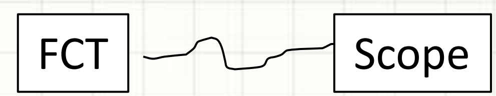




30m RF cable

Every second bucket (~700ps





1m RF cable

Multi-micro-bunch, conclusion

Micro-bunch operation mode

- Beam parameters
  - E = ~ 8.0 MeV
  - Ne = 400 pC/e^- (total, max)
  - Nmicro-bunches = 1,2,4
  - Nmulti-bunches = 1
  - Rep.Rate = 3.13 Hz
  - Sigma_z < 500 um (for 20 pC/bunch)
  - Sigma_x,y < 700 um

Multi-micro-bunch operation mode

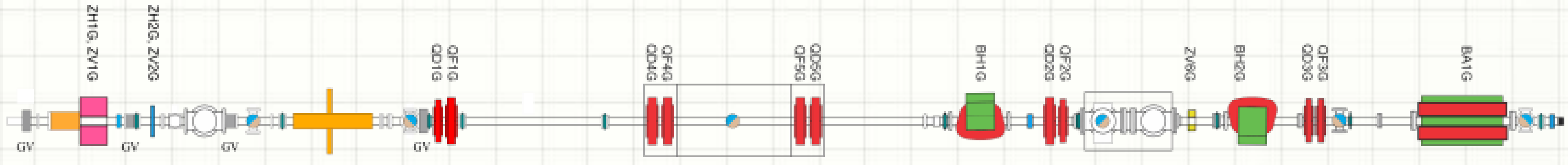
- Beam parameters
  - E = ~ 8.0 MeV
  - Ne = 50 nC/e^- (total, max)
  - Nmicro-bunches = 1,2,4
  - Nmulti-bunches = 1,2,4
  - Rep.Rate = 3.13 Hz
  - Sigma_z < 500 um
  - Sigma_x,y < 700 um

Near future plans and prospects

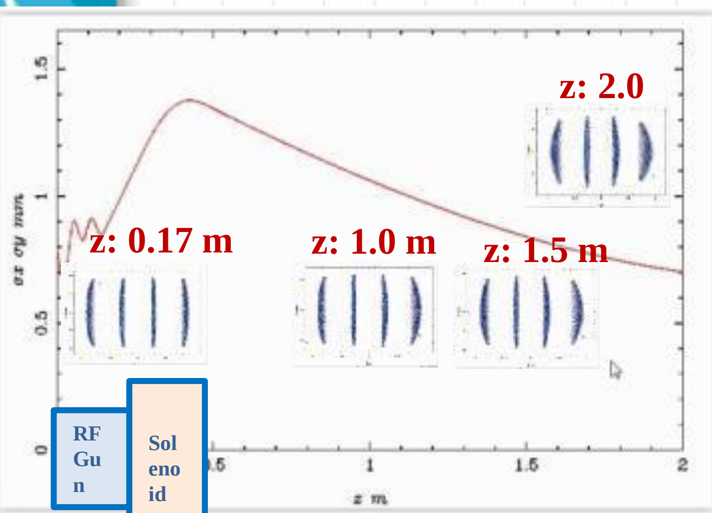
- Quantitatively conclude the effective number of micro-bunches.
- Improve micro-multi-bunch generation
  - Increase number of multi-bunches (2856MHz) up to 16.
  - Increase number of micro-bunches (0.5 – 1 THz) up to 16.
- Continue fs beam dynamics studies
  - ASTRA simulation – measured beam parameters.
  - Transverse beam (projected and **intrinsic**) emittance.
- Continue collaboration experiments

Thank you for your attention

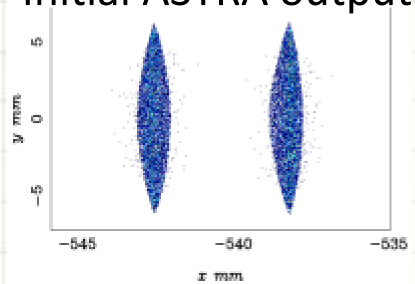
ASTRA simulation



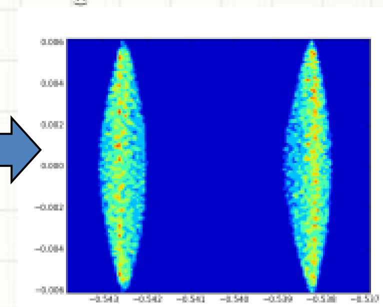
Calculation parameters: $\tau_g^l = 100$ fs, $\sigma_g^l = 450\ \mu$m, $Q = 25$ pC,
MaxB= 0.225 T (solenoid field), MaxE= 77 MV/m, $z = 1.31$ m.



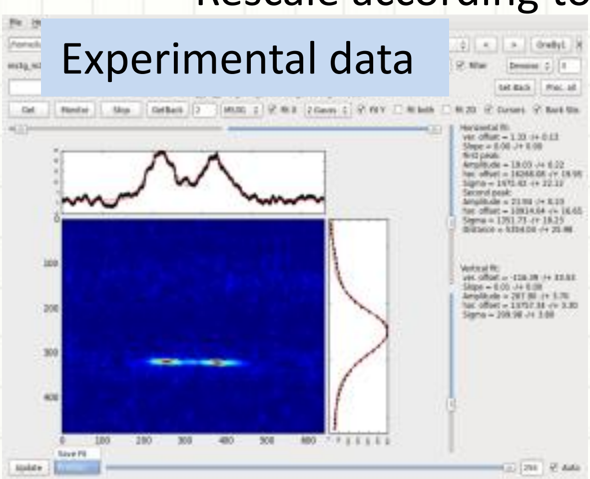
Initial ASTRA output XY plot

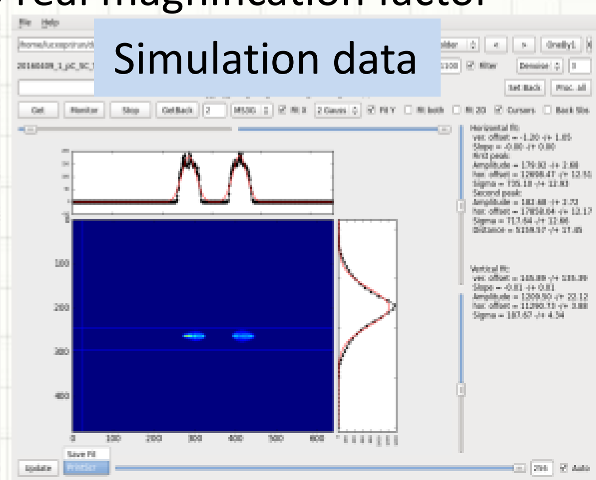


2D re-binning (effectively histogram)



Rescale according to real magnification factor





Beam Size minimum: 0.70 mm at 2 m
Normalized Emittance: 0.68 π-mm-mrad

THz FELs

Tan P, *et al. Sci. China Inf. Sci.* January 2012 Vol. 55 No. 1

Table 1 Demonstrated THz FELs (2010)

Location (Name)	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	
Frascati (FEL-CAT)	760	15–20	1.8	5	16	2.5	0.75	RF, O
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA, O
Novosibirsk (RTM)	120–230	70	12	10	2x33	12	0.71	ERL, O
KAERI (THz FEL)	100–1200	20	4.5–6.7	0.5	80	2.5	1.0–1.6	MA, O
Osaka (ISIR, SASE)	70–220	20–30	11	1000	32	6	1.5	RF, S
Himeji (LEENA)	65–75	10	5.4	10	50	1.6	0.5	RF, O
UCSB (FIR FEL)	60	25000	6	2	150	2	0.1	EA, O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF, O
Osake (ISIR)	32–150	20–30	13–19	50	32	6	1.5	RF, O
Osaka (FELI4)	18–40	10	33	40	30	8	1.3–1.7	RF, O
Dresden U100-FELBE)	18–280	1–25	18–34	15	38	10	0.5–2.7	RF, O, K
Nieuwegein (FELIX)	3–250	1	50	50	38	6.5	1.8	RF, O
Orsay (CLIO)	3–150	10	8–50	100	38	5	1.4	RF, O

RF–radio-frequency linear accelerator; ERL–energy recovery linear accelerator; MA–microtron accelerator; EA–electrostatic accelerator; O–FEL oscillator; K–FEL klystron.

Table 2 Proposed FIR FELs (2010)

Location (Name)	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	
Tokyo (FIR-FEL)	300–1000	5	10	30	25	7	1.5–3.4	RF, O
Nijmegen (THz-FEL)	100–1500	3	10–15	50	40	11	0.5–3.3	RF, O
India (CUTE-FEL)	50–100	1000	10–15	20	50	5	0.57	RF, O
Novosibirsk (RTM1)	5–100	10	50	20–100	3*33	6	2.0	RF, O
Berlin (Fritz Haber Institute)	3–300	1–5	20–50	200	50	4	0.5–1.5	RF, O
					40	11	1–3	
Turkey (TACIR II)	10–190	1–10	40	12–120	40	9	0.4–2.5	RF, O
Tallahassee (big light)	2–1500	1–10	50	50	15,30	5.5	4.0	ERL, O