LUCX PRE-BUNCHED E-BEAM GENERATION AND ITS APPLICATION TO THz EXPERIMENTAL STUDIES

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on behalf of

Advanced Generation of THz and X-ray (AGTaX) collaboration

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The 9th Asian Forum for Accelerators and Detectors (AFAD)
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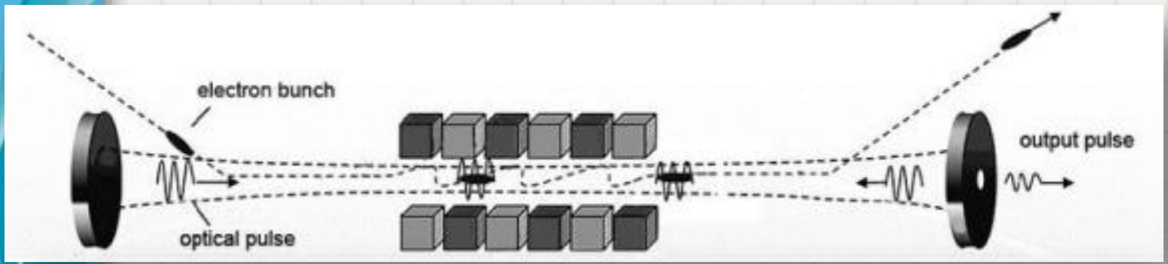
Daejeon, Korea

Outline

- Motivation
- Compact pre-bunched generation schemes
- Pre-bunched coherent emission
- In-house developments
  - LUCX facility
    - List of developments
    - Ti:Sa laser system (FSTB), Laser "Buncher"
    - Multi-micro-bunch, implementation
    - Space-charge force suppression
- Collaborative experiments, review
- Summary, conclusion

Motivation

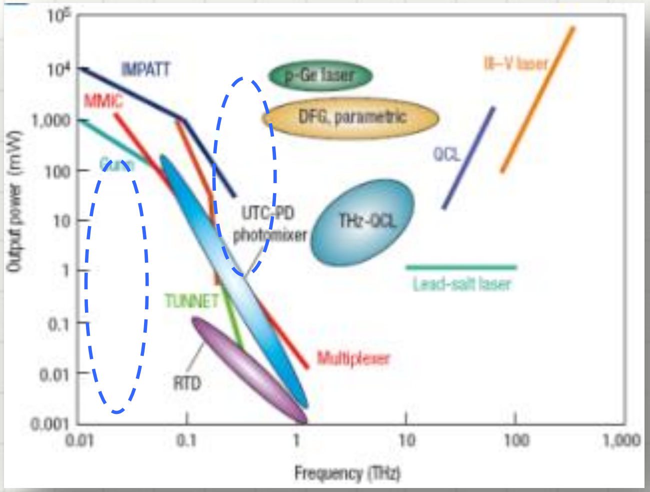
Madey, John, J. Appl. Phys. 42, 1906 (1971)
Madey, John, US Patent 38 22 410,1974



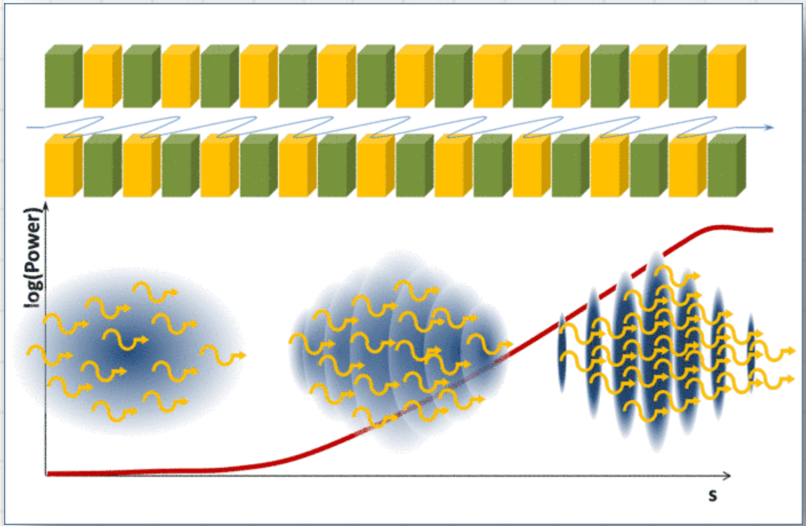
Wavelength of FEL radiation:

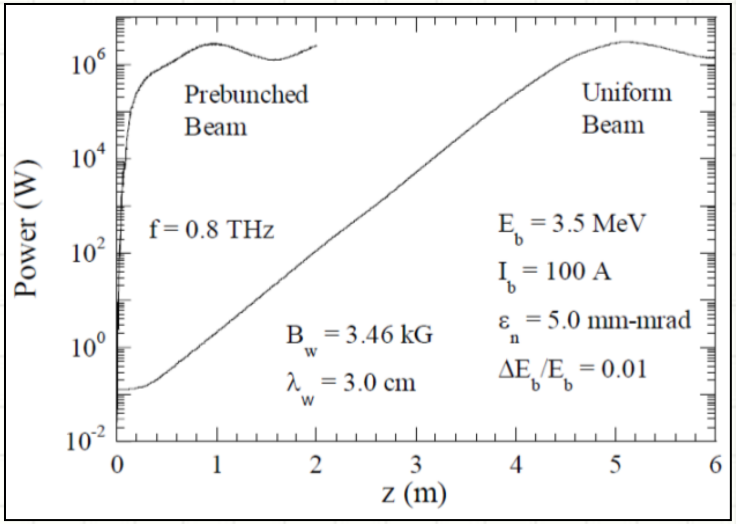
$$\lambda(cm^{-1}) = \frac{\lambda_w}{2\gamma^2}(1+\frac{K^2}{2})$$

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)



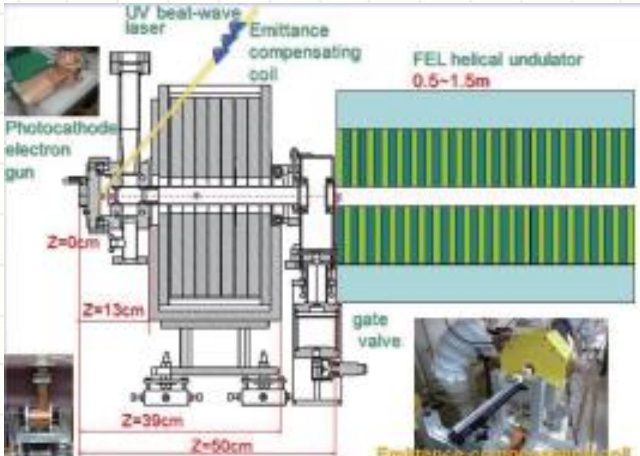
Pre-bunched injection: "Super-radiant" emission & Spectra manipulation



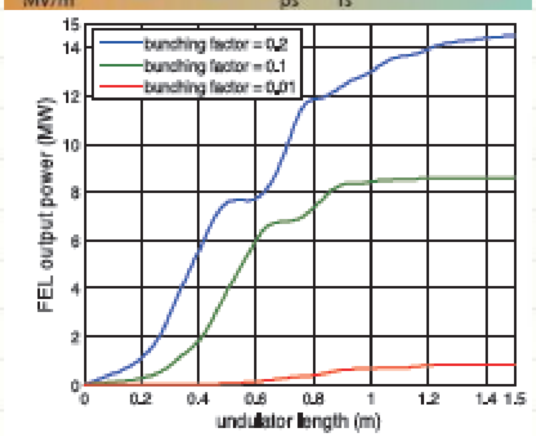


Compact pre-bunched generation schemes

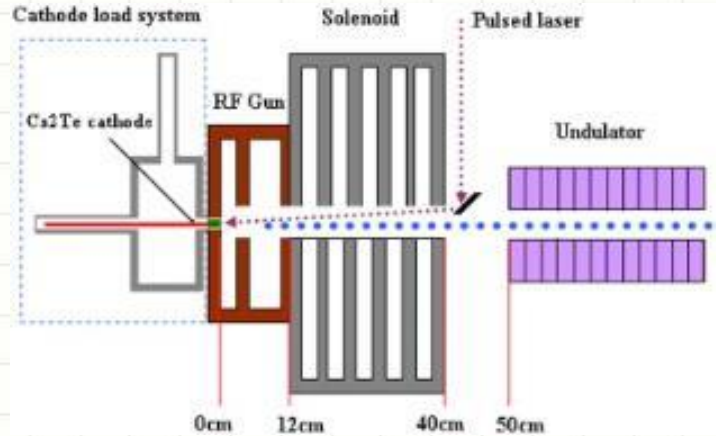
Prof. Y.-C. Huang, National Tsinghua University, Hsinchu, Taiwan



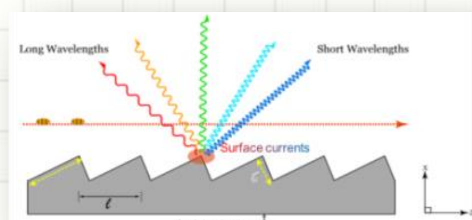
peak gradient	Charges	rms beam radius (mm)	σ_w	σ_μ	micro-pulse rate	Bunching factor @ 2 THz
120 MV/m	1 nC	0.6	4.25 ps	50 fs	2 THz	0.85

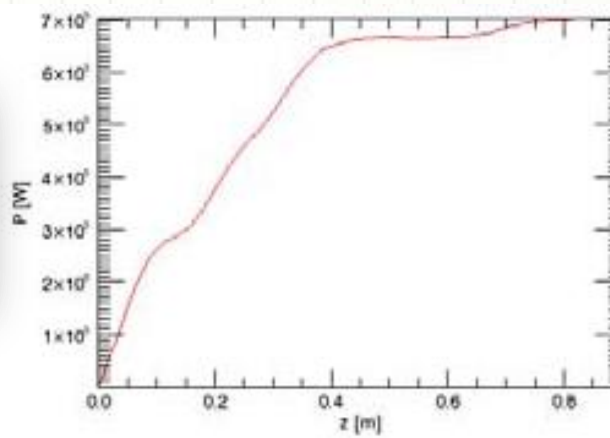


Shengguang Liu, Yen-Chieh Huang, NIM A 637 (2011) S172–S176

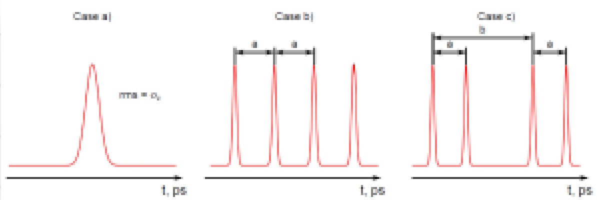


@2THz (150 um), time spacing between laser pulses is 500fs. 16-pulse train of 50fs. Pulse train charge more than200pC, photocathode Q.E. 1%. Peak power at megawatt(MW) level, 0.1 mJ





Pre-bunched coherent emission

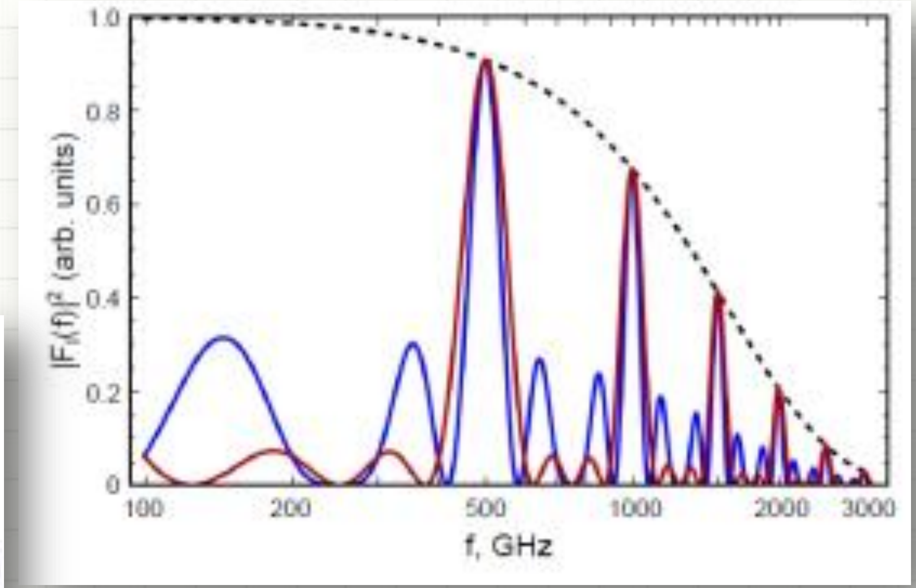


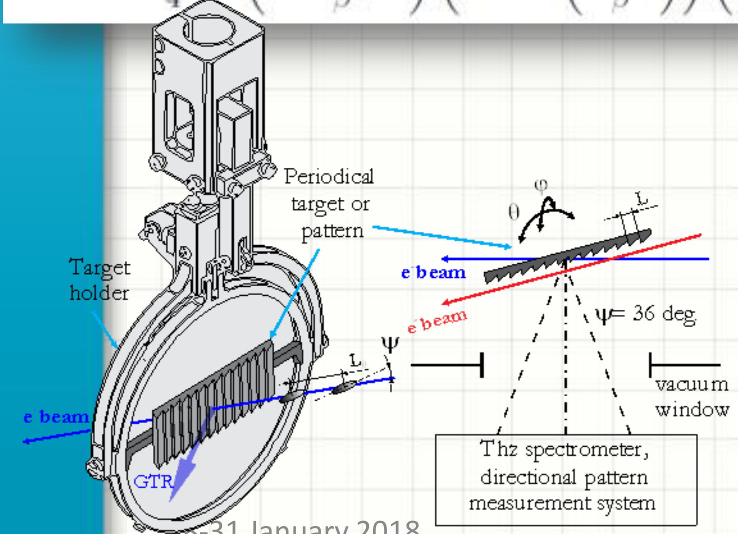
$$\frac{d^2W^s_{tot}}{d\omega d\Omega} = \frac{d^2W_{sing}}{d\omega d\Omega} N_e(1+(N_e-1)|f_l(\omega)|^2)$$

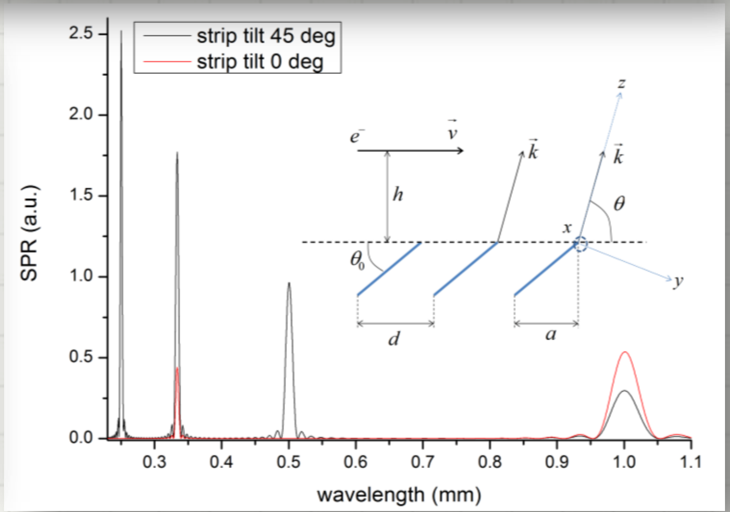
$$|F_l^a(f)|^2 = \exp\left(-\frac{4\pi^2 f^2\sigma_z^2}{\beta^2}\right)$$

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

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

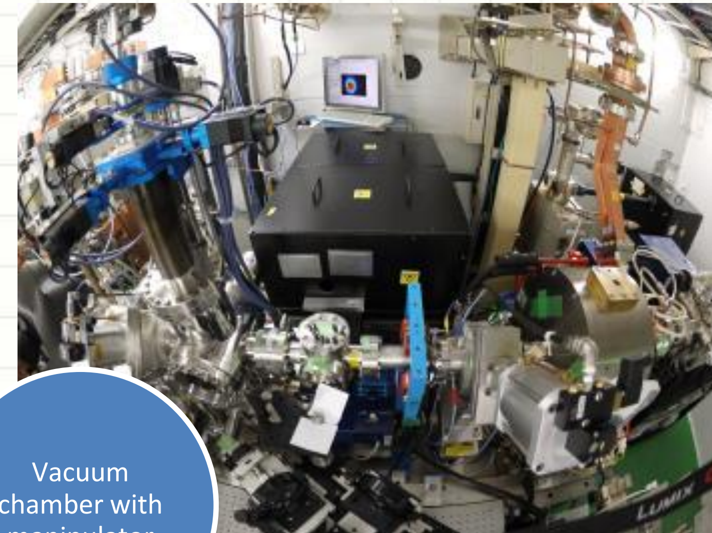


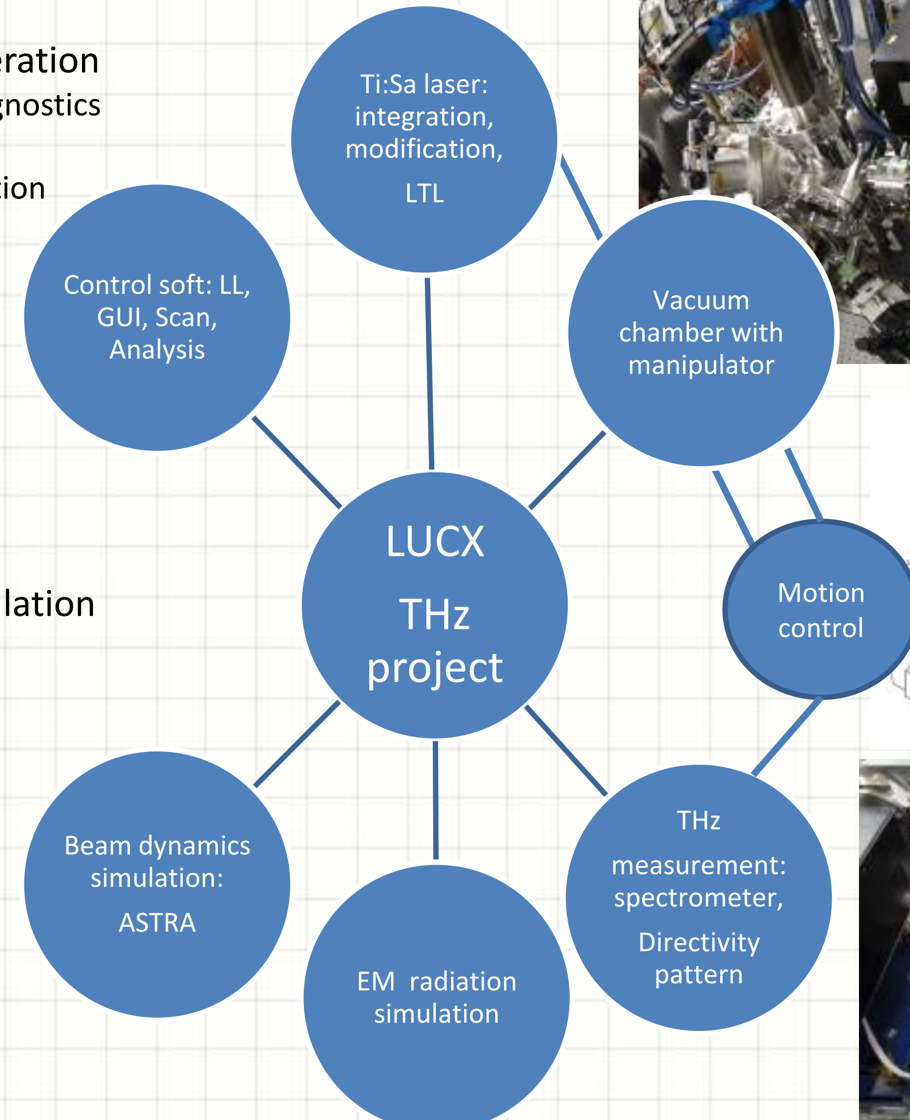


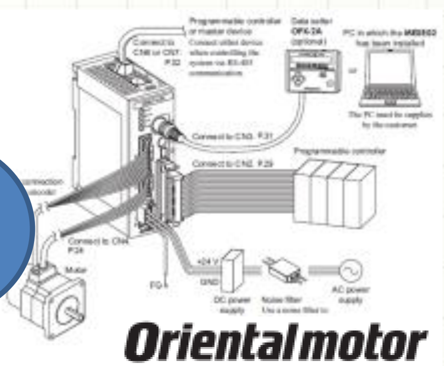


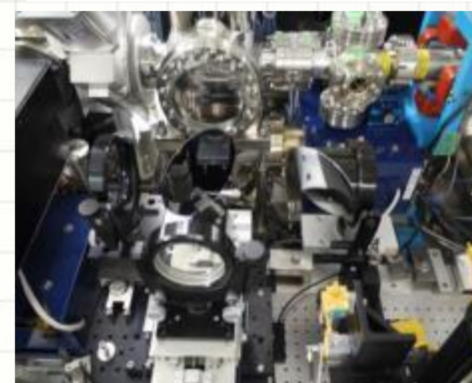
In-house developments

- Pre-bunched fs e-beam generation
  - fs e-beam longitudinal diagnostics
  - Cathode response time
  - Micro-multi-bunch generation
- THz radiation generation
  - Simulation and experi-mental validation
  - Tuning procedure + diag-nostics
- THz experiments
  - Preparation
  - Vacuum work
  - DAQ
- RF Gun beam dynamics simulation
  - ASTRA
- Laser developments
  - Pulse splitting
  - Fiber laser

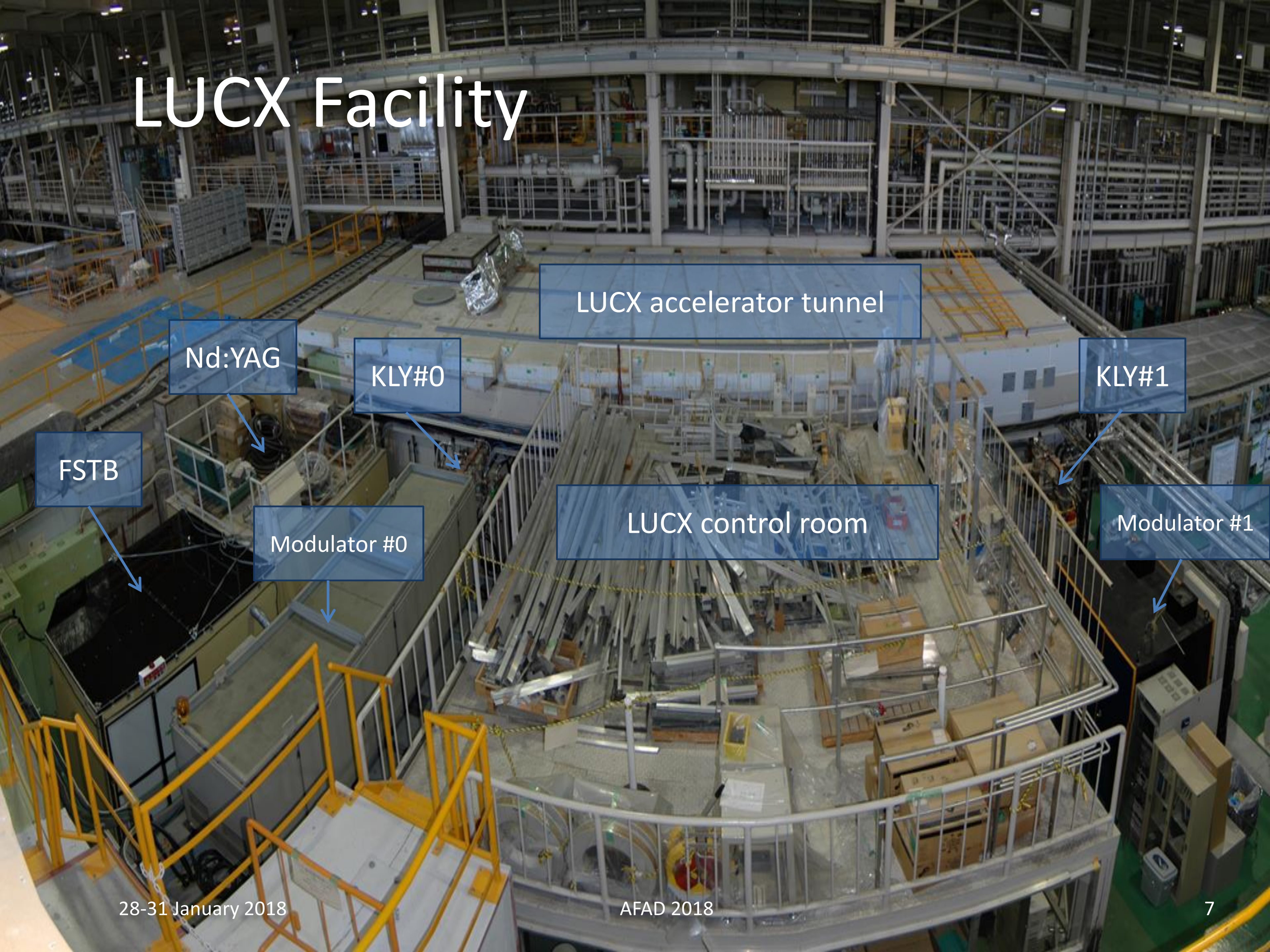




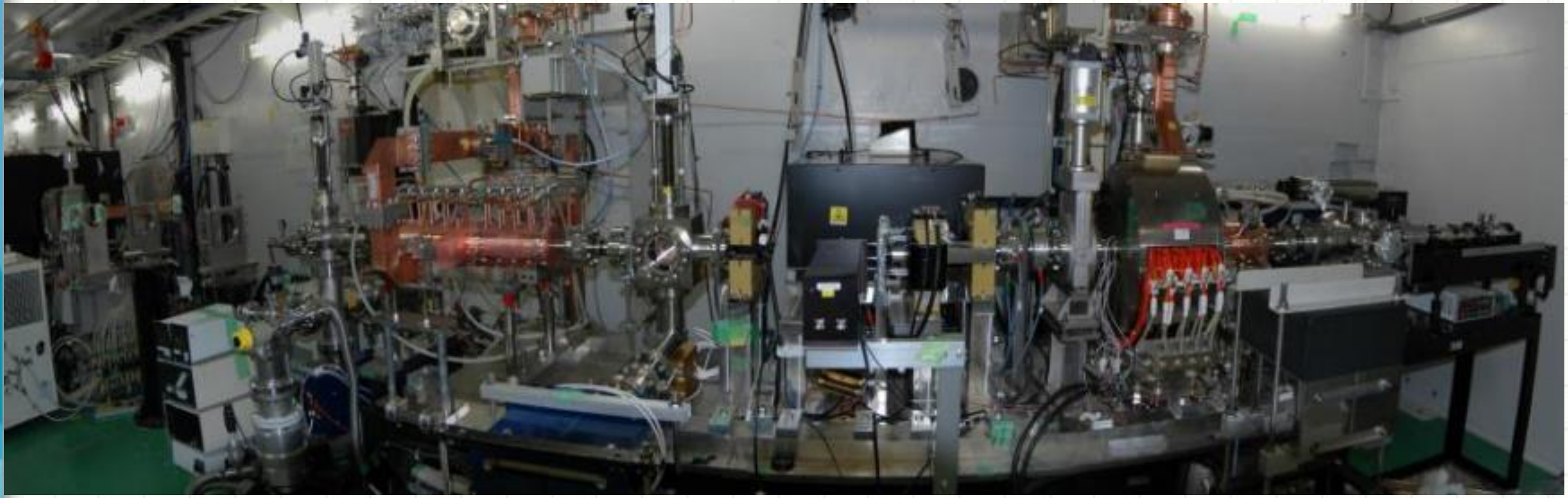




LUCX Facility

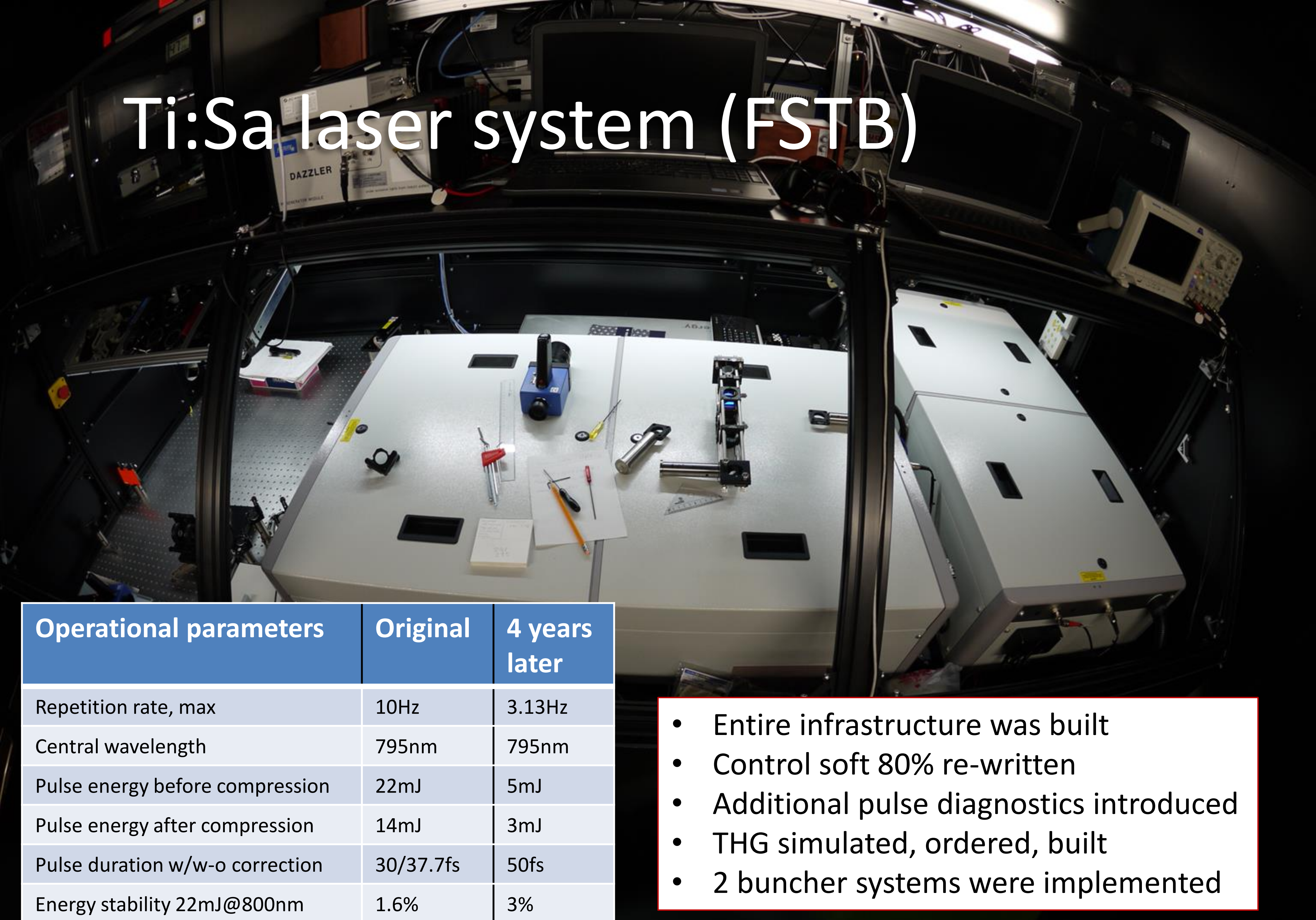


LUCX beamline and operation modes



"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

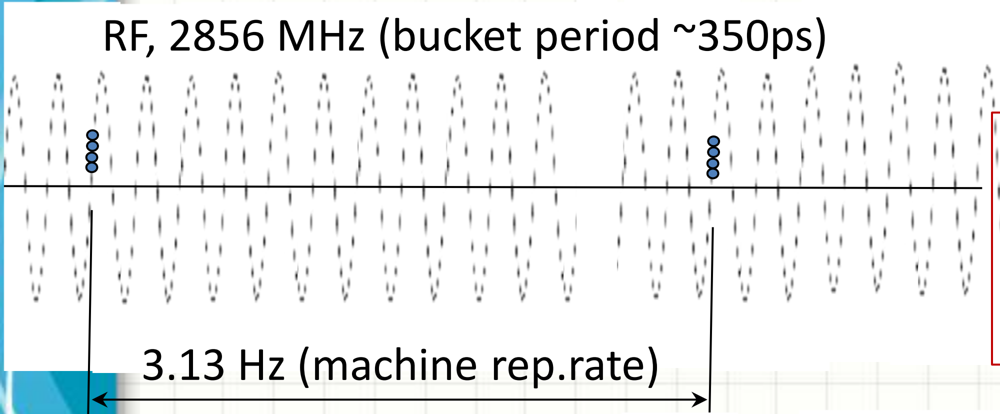
Ti:Sa laser system (FSTB)



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%

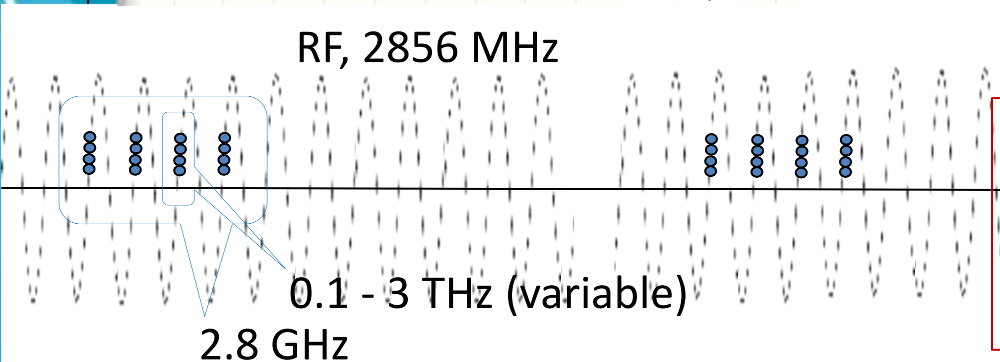
- Entire infrastructure was built
- Control soft 80% re-written
- Additional pulse diagnostics introduced
- THG simulated, ordered, built
- 2 buncher systems were implemented

Multi-micro-bunch, 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 ?**



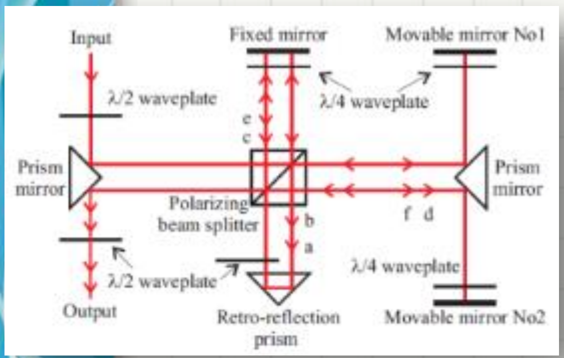
4 micro-bunches
4 multi-bunch (4 RF buckets)

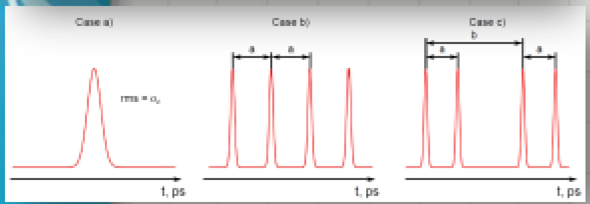
- DAQ sees this micro-train as a single event (no trigger modification is required)
- Micro-bunch spacing can be changed simultaneously in all buckets

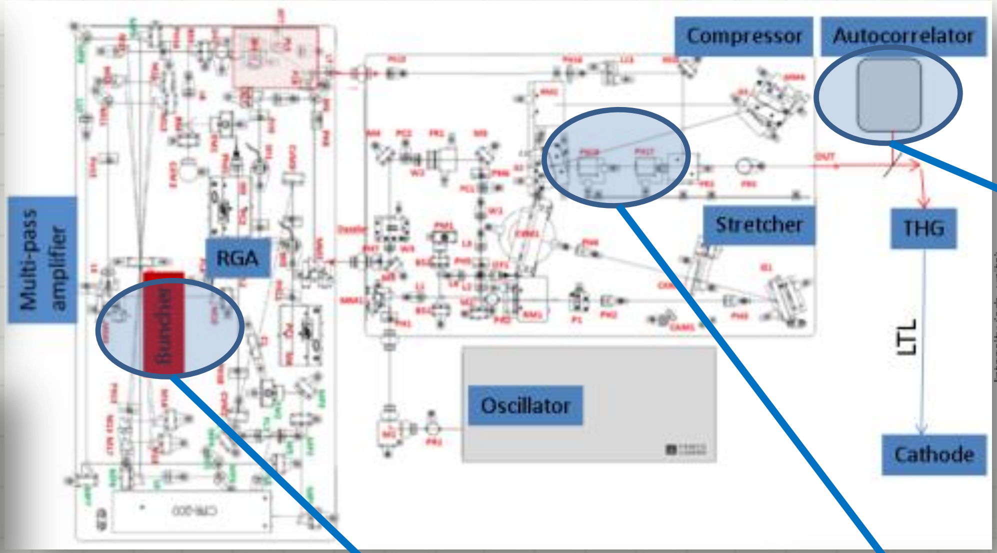
- One of the typical S-band accelerator parameters:
  - Multi-bunch rep.rate (from the RF gun laser oscillator) ~ 357MHz (every 9th RF bucket)
  - RF pulse width ~ 4 us => max 1400 bunches (roughly) – filling time etc. ~ 1250 bunches
- Applying 8-times pulse split -> 10000 bunches/4 us !!!
- Effects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

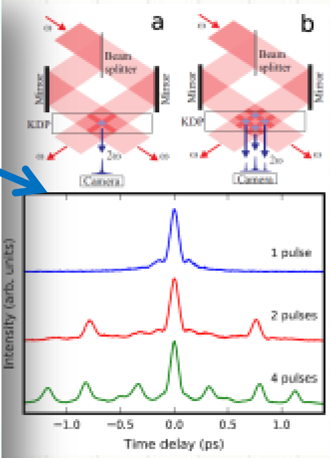
Multi-micro-bunch, implementation

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

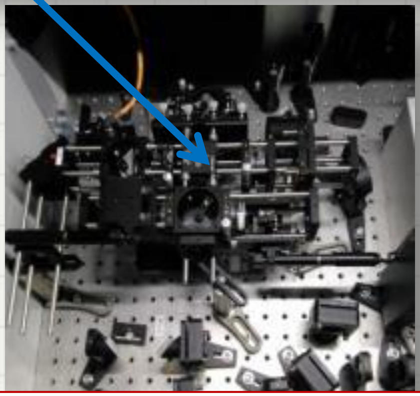




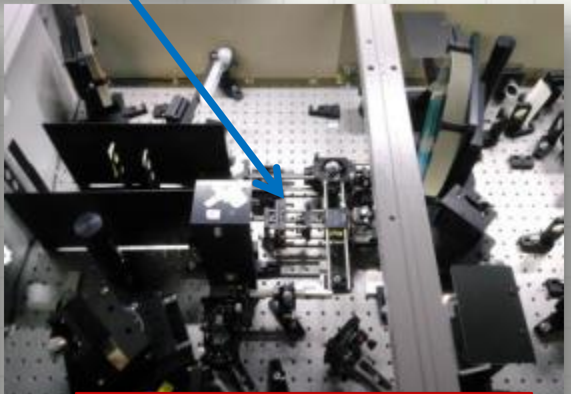




- **Total splitting efficiency ~20%**
- New design with total 10-20% loses is possible.
- Beam expander was removed.
- Multi-pass Amp, Compressor, THG, LTL re-tuned.
- Micro-bunch
  - Separation: +/- 5 ps
  - Stability: < 20 fs (lower than meas. resolution)
- Multi-bunch
  - Separation: 350ps +/- 30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



Motorized delay control



Manual delay control

Laser pulse divider, current prototype

General scheme

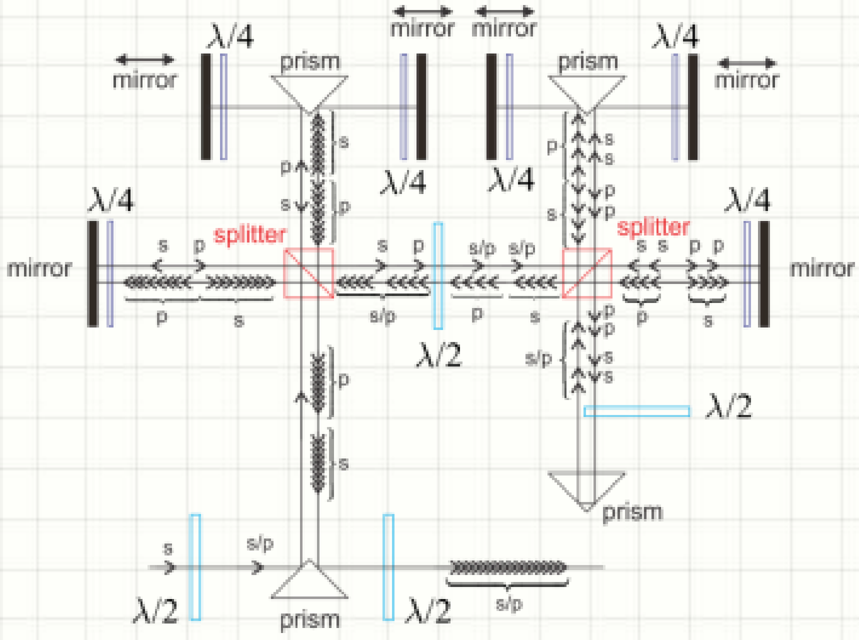
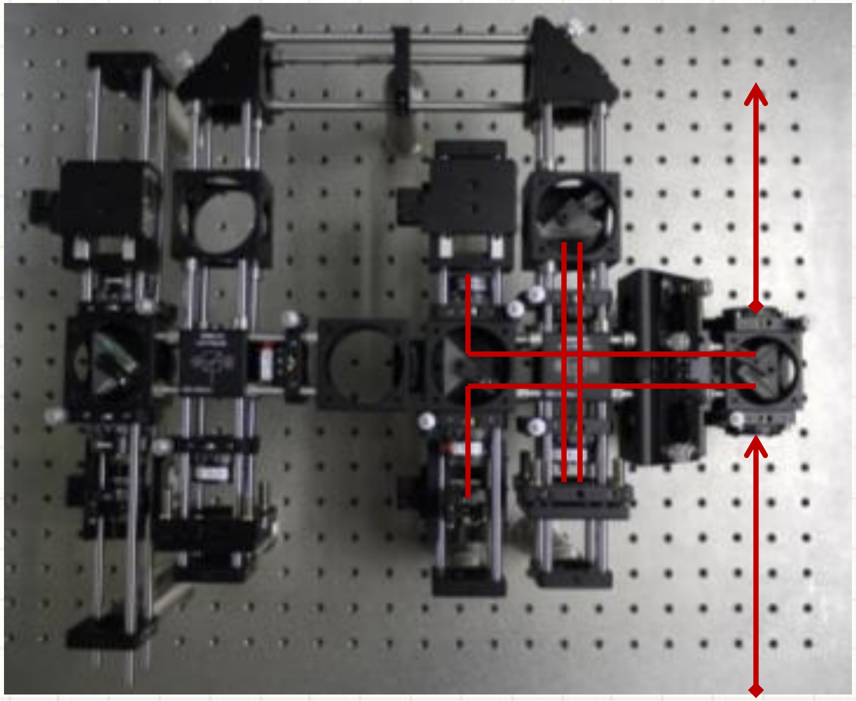


Photo of pre-assembled system



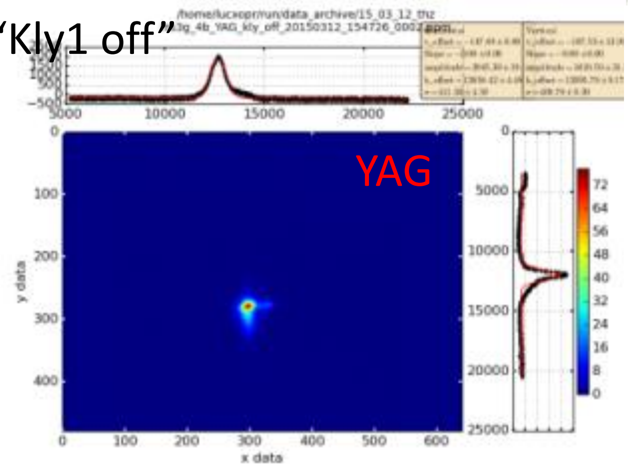
- All bits were delivered in September 2014.
- Assembled and tested (laser side only) in Nov.-Dec. 2014
- Tested (e-beam generation) in Jan. – Feb. 2015

4-micro bunch generation

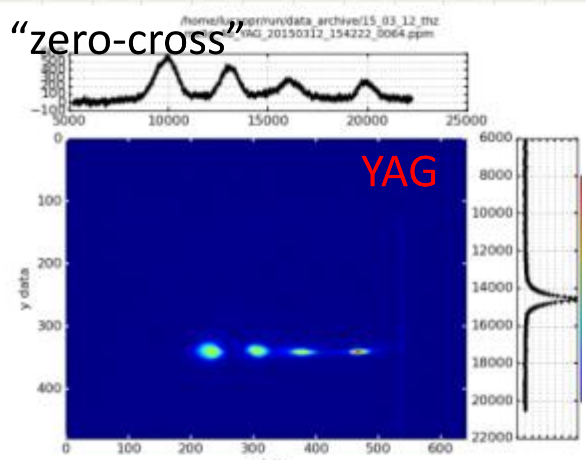
A. Aryshev, M. Shevelev, Y. Honda, N. Terunuma, J. Urakawa, Femtosecond response time measurements of a Cs2Te photocathode, Appl. Phys. Lett. 111, 033508 (2017).

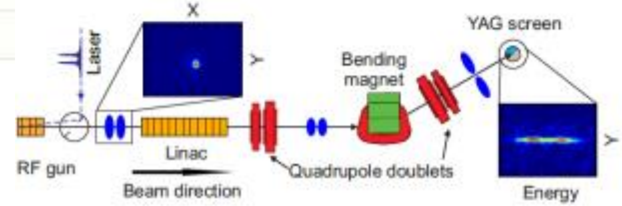
Measured Cs2Te photocathode peak-to-peak response time **369.48 ± 27 fs.**

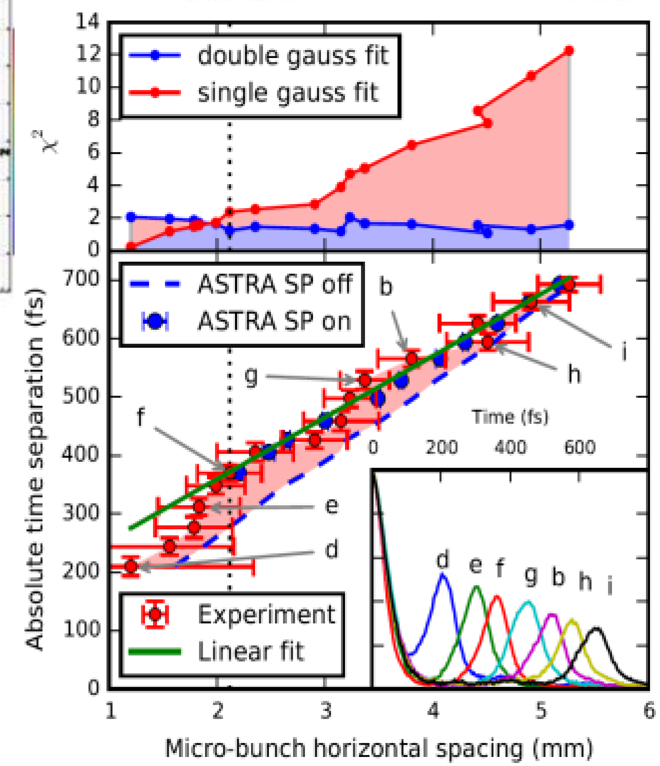
“Kly1 off”

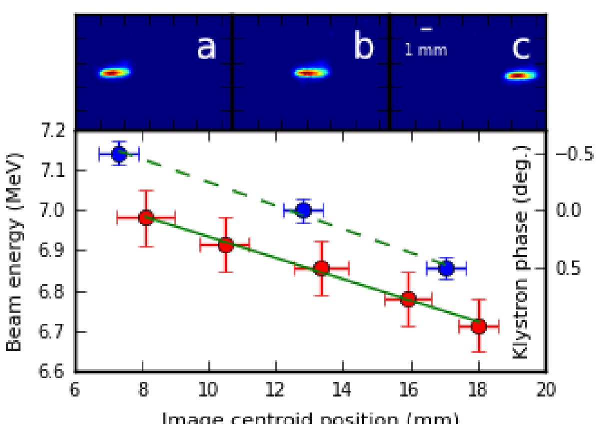


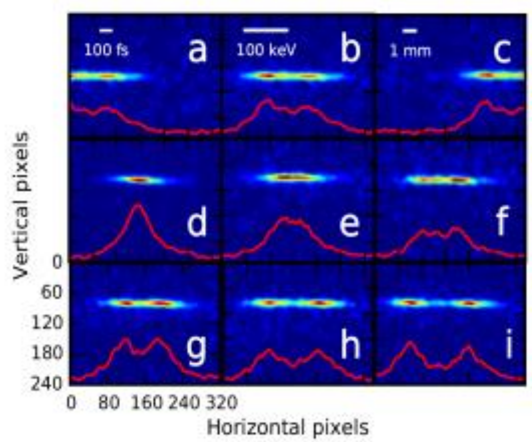
“zero-cross”











Tunability

Accepted Paper

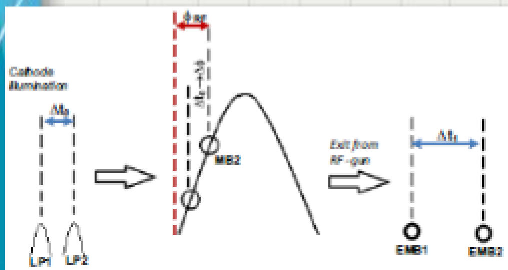
Generation of a femtosecond electron microbunch train from a photocathode using twofold Michelson interferometer

Phys. Rev. Accel. Beams

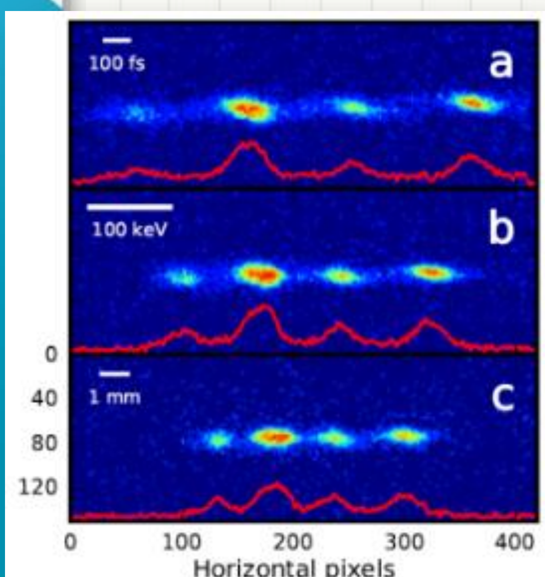
M. Shevelev, A. Aryshev, N. Terunuma, and J. Urakawa

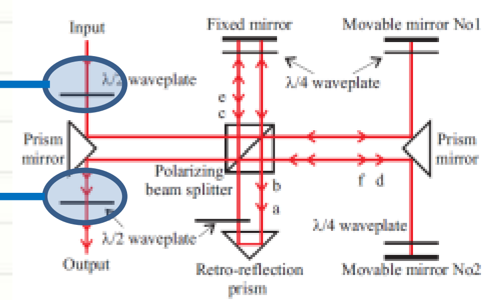
Accepted 14 September 2017

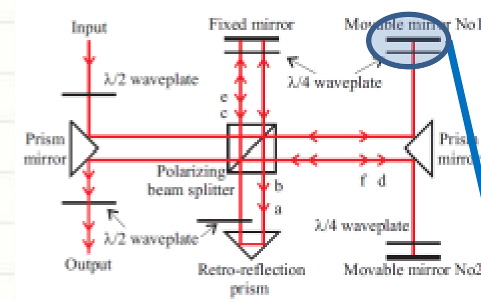
"phase" modulation



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

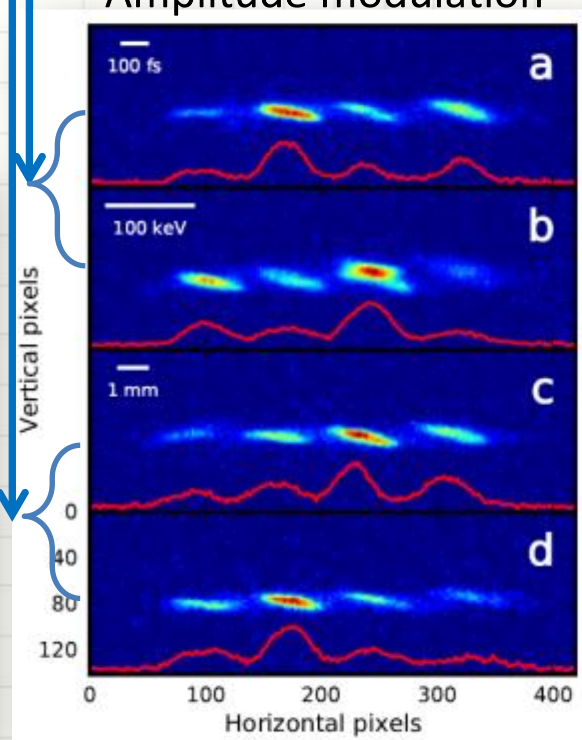


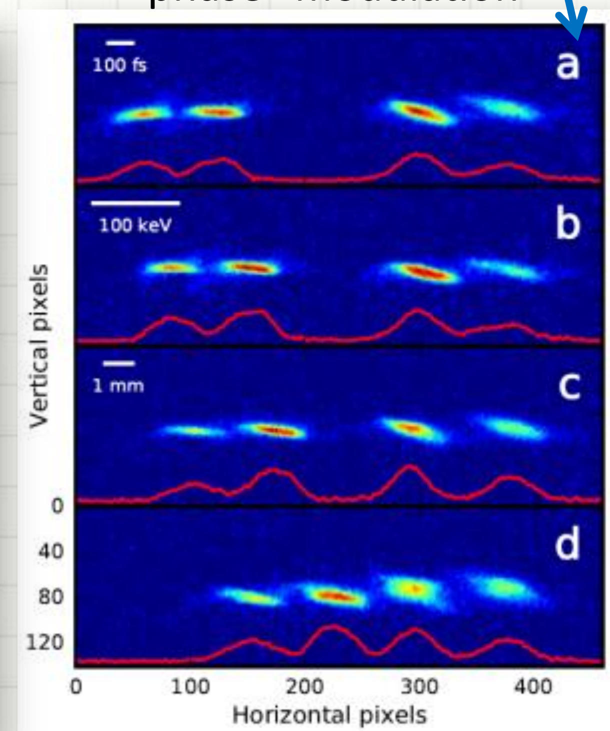




Amplitude modulation

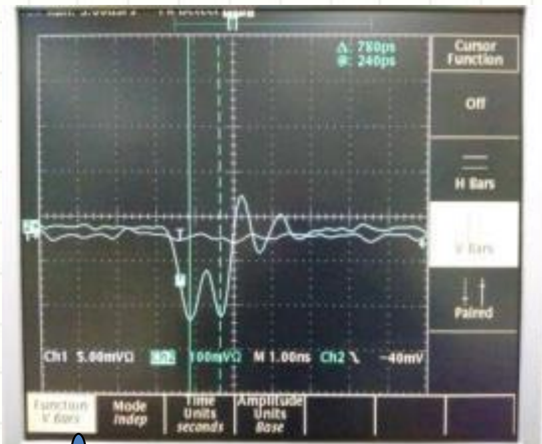
"phase" modulation



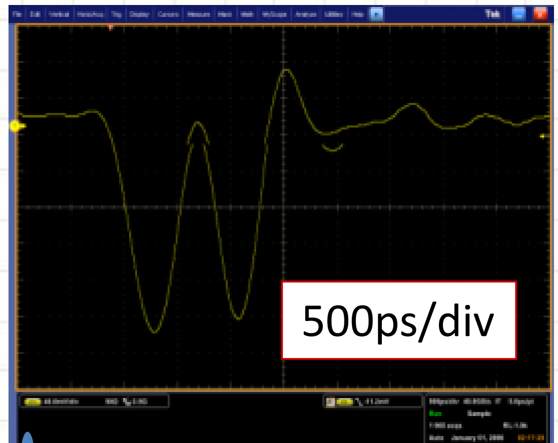


4-multi bunch generation

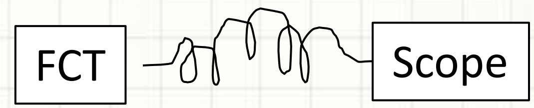
Tek TDC 684B, 1GHz, 5Gs/s



Tek DPO 7354, 5GHz, 40Gs/s

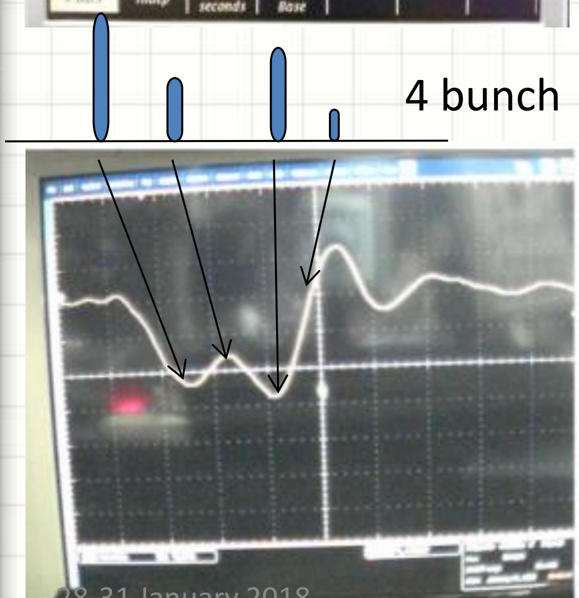


500ps/div



30m RF cable

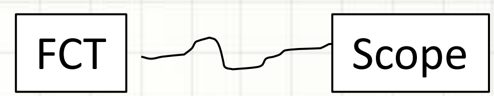
Every second bucket (~700ps



4 bunch

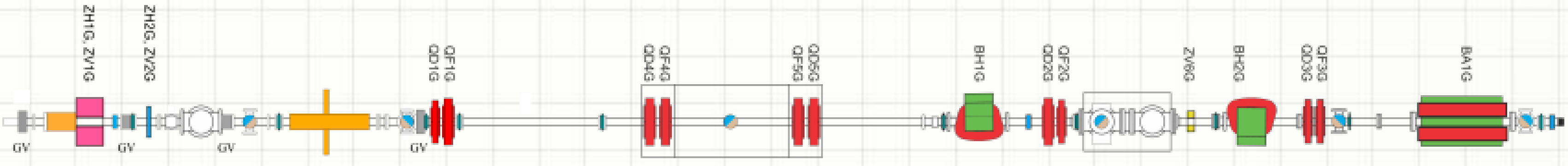
2 bunch

500ps/div

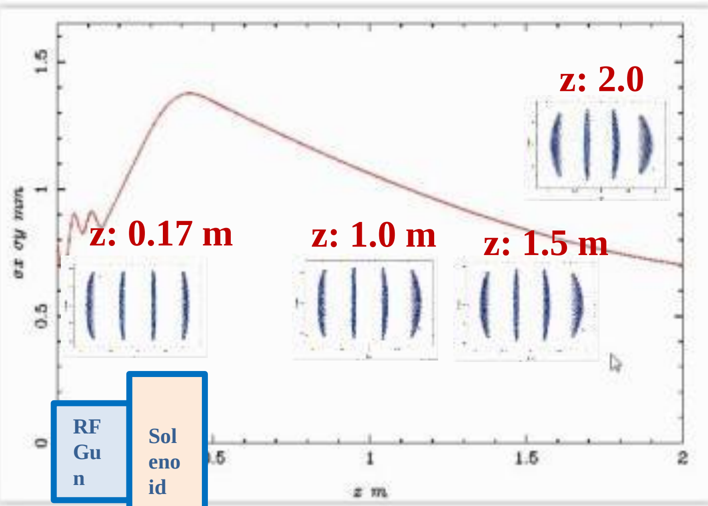


1m RF cable

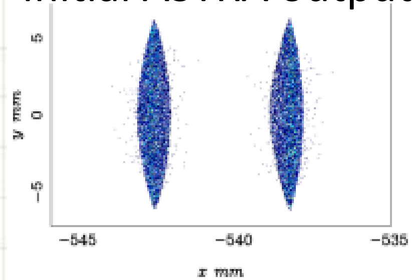
ASTRA simulation



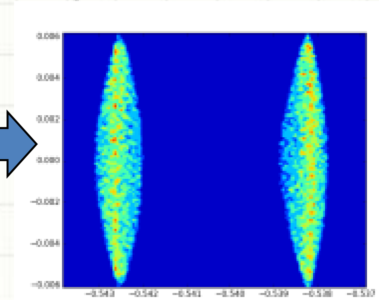
Calculation parameters: $\tau_g^l = 100$ fs, $\sigma_g^l = 450\ \mu$m, $Q = 25$ pC,
MaxB$=0.225$ T (solenoid field), MaxE$=77$ MV/m, $z = 1.31$ m.



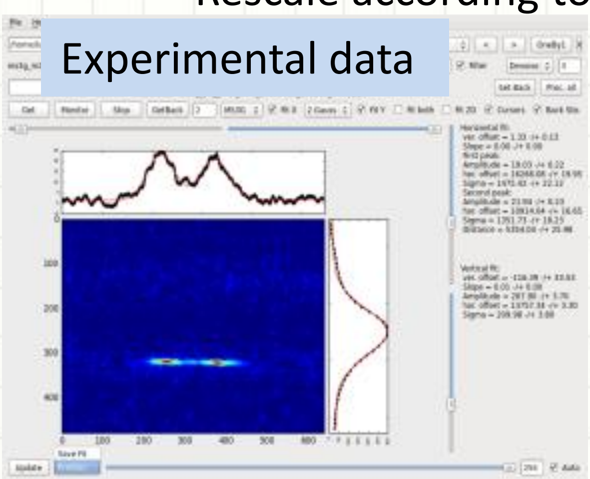
Initial ASTRA output XY plot

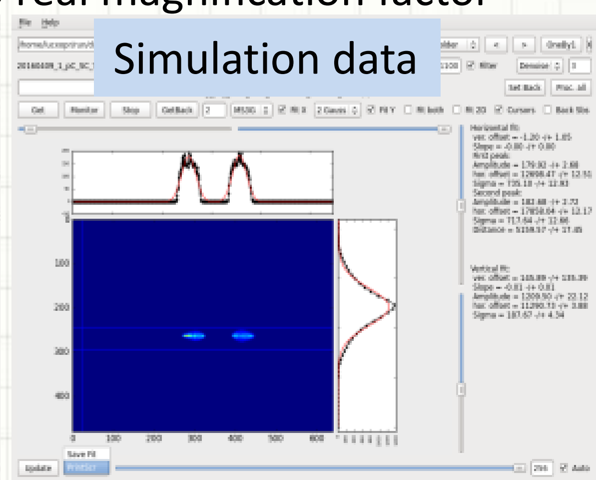


2D re-binning (effectively histogram)



Rescale according to real magnification factor





Beam Size minimum: 0.70 mm at 2 m

Normalized Emittance: 0.68 π-mm-mrad

Space-charge force suppression

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

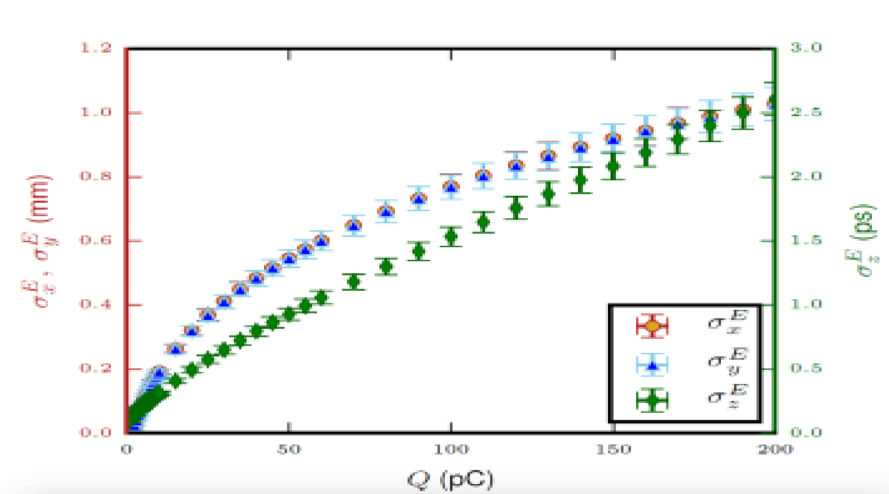
$$\Delta L_{sc} = \frac{4Qc}{I_A \gamma'^2 R^2} f(A, \gamma_f) \qquad (6)$$

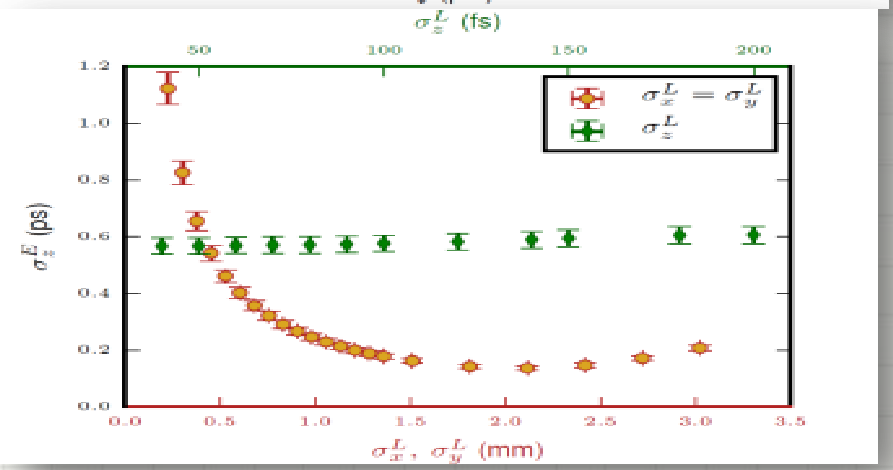
where I_A is the Alfven current, Q the bunch charge, and

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

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, 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 (work in progress, will be published in JINST).
- 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

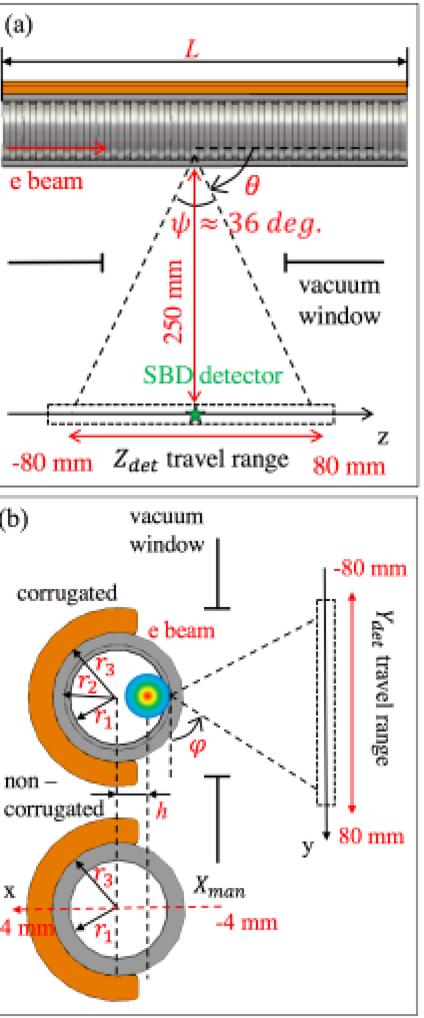
Collaborative experiments

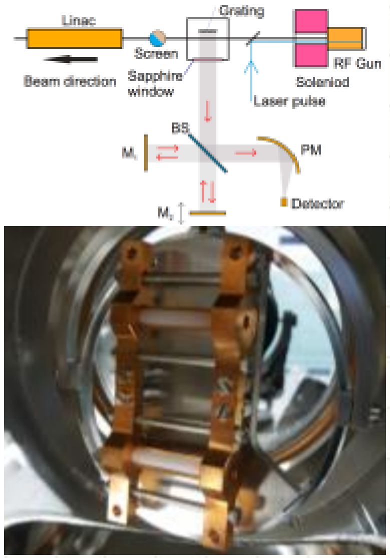
1. **KEK-RHUL-MEPhI, Experimental Investigations of THz radiation from composite corrugated capillaries.**
    - Spectra-angular, polarimetry. Single- and micro-bunches.
2. **KEK-RHUL-MEPhI, Drive-witness acceleration scheme based on corrugated dielectric mm-scale capillary.**
    - E, dE, (emittance in future). Beamline optics, micro-bunches.
3. **KEK-Oxford, Longitudinal beam diagnostics development based on coherent Smith-Purcell radiation.**
    - Modified Fabry-Perot interferometer.
    - Spectra-angular, polarimetry. Single- and micro-bunches.
4. **KEK-TPU, Intense THz source development using periodical conductive structures.**
    - cSPR, GDR/GTR, single- and micro-bunches.
    - Spectra-angular, polarimetry.
5. **KEK-TPU-(Oxford), Super-radiant radiation emission study.**
    - Spectra measurements
    - E-beam characterization

KEK-RHUL-MEPhI

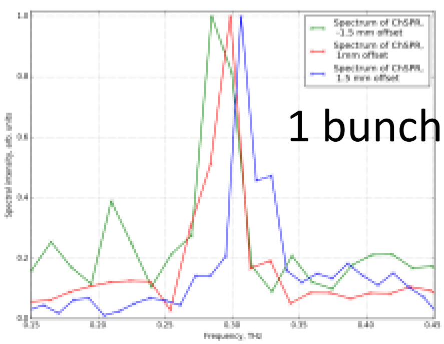
Experimental Investigations of THz radiation from composite corrugated capillaries

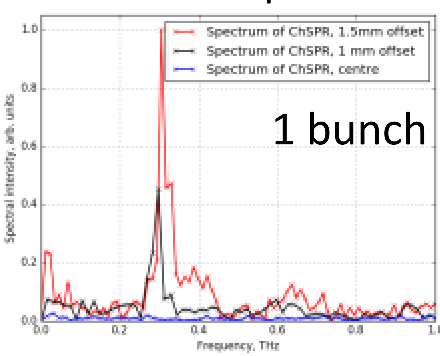
- K. Lekomtsev, A. Aryshev, A.A. Tishchenko, M. Shevelev, A.A. Ponomarenko, P. Karataev, N. Terunuma, J. Urakawa, "Sub-THz radiation from dielectric capillaries with reflectors",**Nucl. Inst. Meth. Phys. Res. B**, 402 (2017), 148–152.
- K. Lekomtsev, A. Aryshev, N. Terunuma, J. Urakawa, A. A. Ponomarenko, A. A. Tishchenko, "Experimental investigation of THz Smith-Purcell radiation from composite corrugated capillary", **Proceedings of IPAC16**, TUPOW044.
- K. Lekomtsev, M. Shevelev, N.Terunuma, J. Urakawa, A. Aryshev, A. Ponomarenko, V. Sukharev, A. Tishchenko, M.N Strikhanov, "Corrugated capillary as THz Cherenkov Smith-Purcell radiator", **Journal of Physics Conference Series** 732, 012038 (2016).

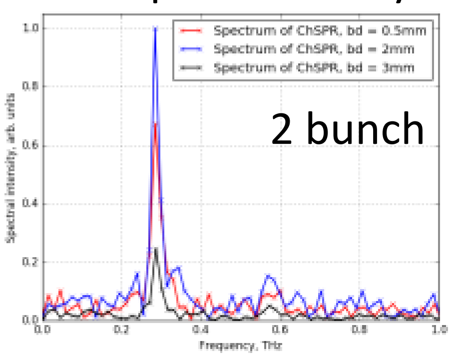




- Technological developments
- Simulation
  - CST, Vorpal, Analytical model
- Experimental results
  - Spectra-spatio-polarization measurements
  - 1 bunch
    - Spectral dependence on impact parameter
  - 2 bunch
    - Frequency locking
- Plans
  - Structure optimization, E-field pattern study



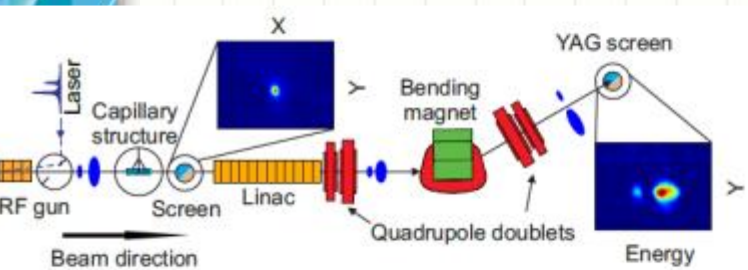




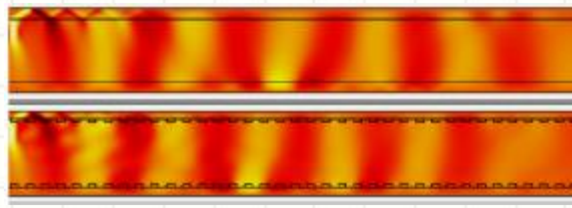
KEK-RHUL-MEPhI

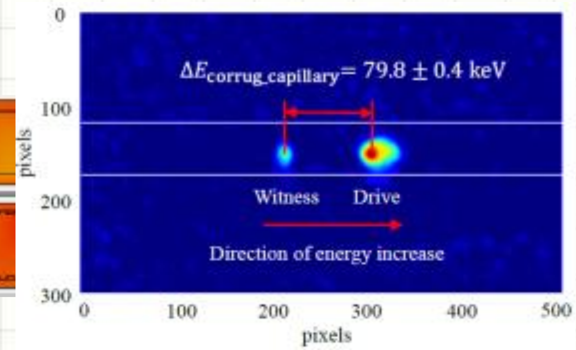
Drive-witness acceleration scheme based on corrugated dielectric mm-scale capillary.

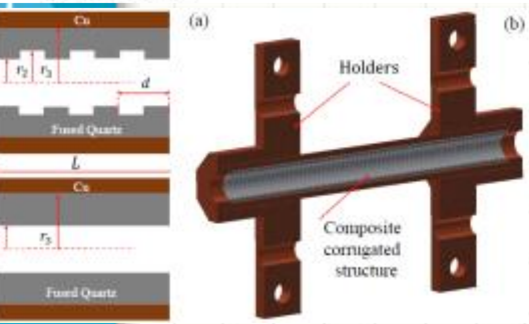
- K. Lekomtsev, A. Lyapin, S. Boogert, P. Karataev, A. Aryshev, M. Shevelev, N. Terunuma, J. Urakawa, A.A. Tishchenko, “Drive-witness acceleration scheme based on corrugated dielectric mm-scale capillary”, **will be submitted to PRAB**.
- K. Lekomtsev, A. Lyapin, S. Boogert, P. Karataev, A. Aryshev, M. Shevelev, N. Terunuma, J. Urakawa, A.A. Tishchenko, “Drive-Witness Acceleration Scheme Based On Corrugated Dielectric Mm-Scale Capillary”, WEPVA018, **Proceedings of IPAC2017**, Copenhagen, Denmark.

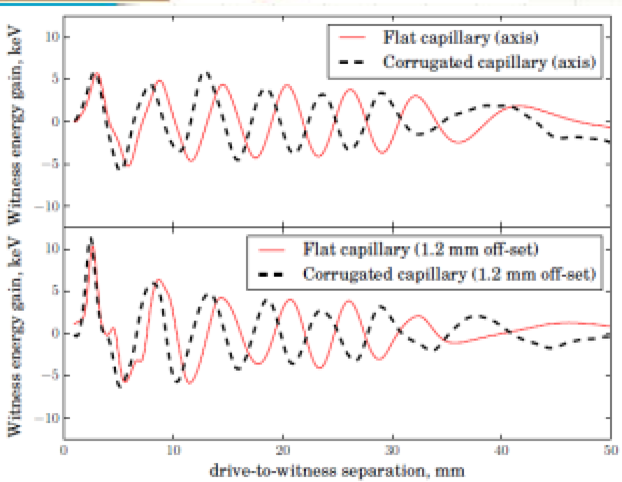


CST simulation







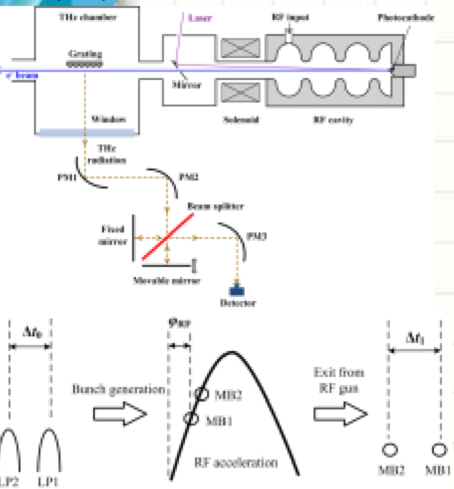


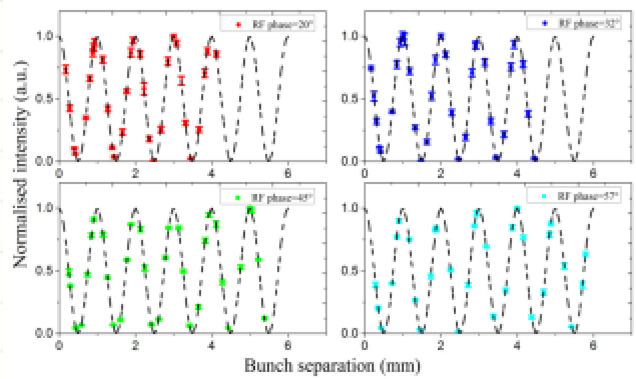
- Technological developments
- Simulation
  - CST, Vorpal, Analytical model
- Experimental results
  - Drive-witness 2 bunch
    - 200 keV/m acceleration gradient
    - Drive few per cent chirping
    - Witness 10-30% dechirping
- Plans
  - Structure optimization, Higher Acc. Gradient
  - Coherent excitation
  - E-beam cooling

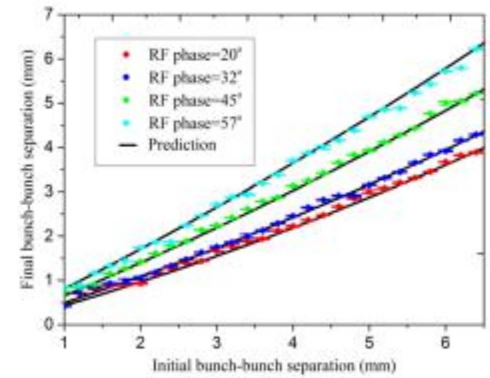
KEK-Oxford

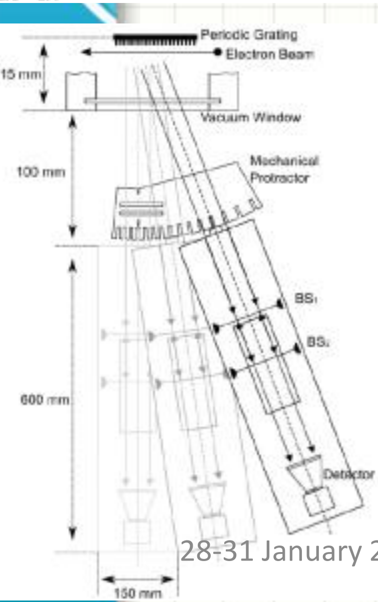
Longitudinal beam diagnostics development based on coherent Smith-Purcell radiation

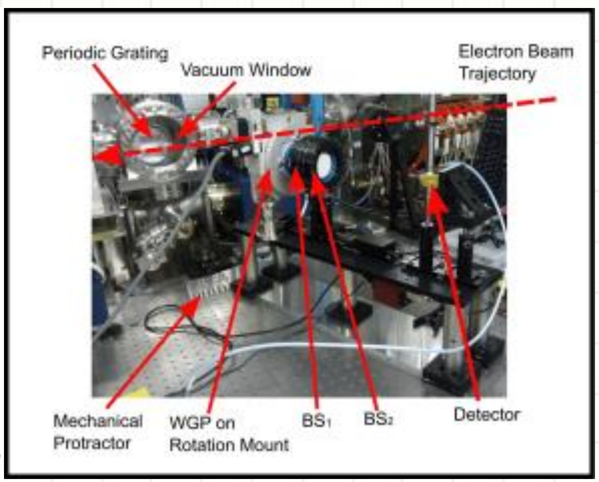
- H. Zhang , I. V. Konoplev, A. J Lancaster , H. Harrison , G. Doucas , A. Aryshev , M. Shevelev , N. Terunuma , J. Urakawa, “Non-destructive measurement and monitoring of separation of charged particle micro-bunches”, **Applied Physics Letters**, 111, 043505 (2017)
- H. Harrison, A. J. Lancaster, G. Doucas, I. V. Konoplev, A. Aryshev, “First steps towards a single-shot longitudinal profile monitor: study of the properties of coherent Smith-Purcell radiation using the surface current model”, **Proceedings of IPAC16**, SUPSS069









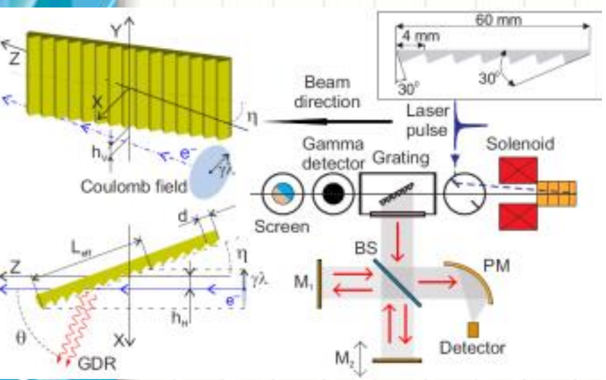


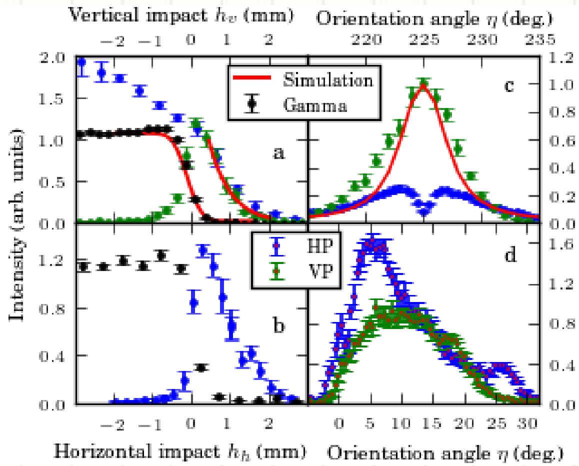
- Simulation
  - Analytical model
- Experimental results
  - Bunch-bunch distance monitor
  - New interferometer design and test (Fabry-Perot + Martin-Puplett)
- Plans
  - 2 Oxford Ph.D.
  - Continuation of a micro-bunch study

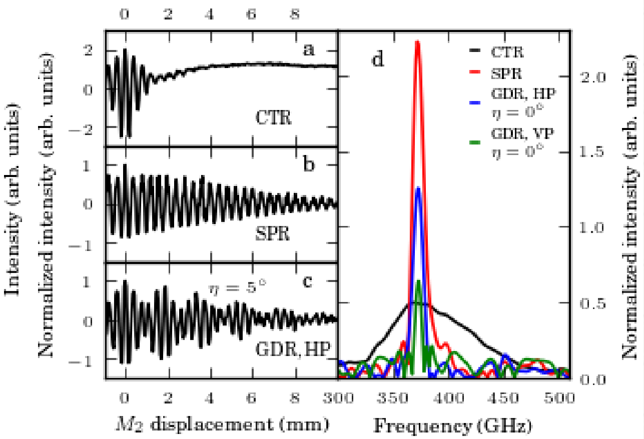
KEK-TPU

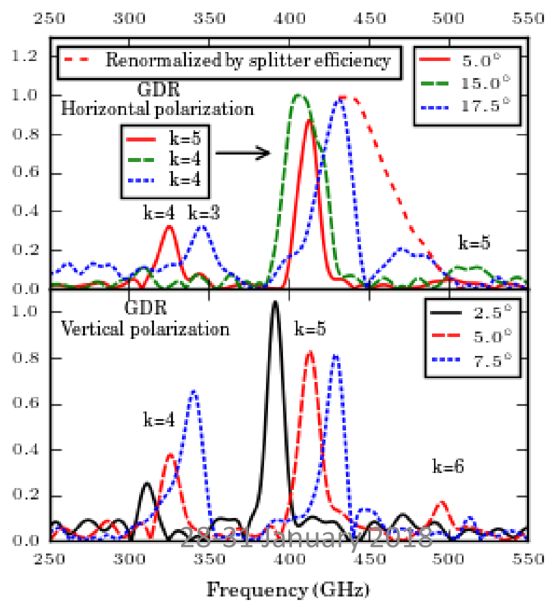
Intense THz source development using periodical conductive structures.

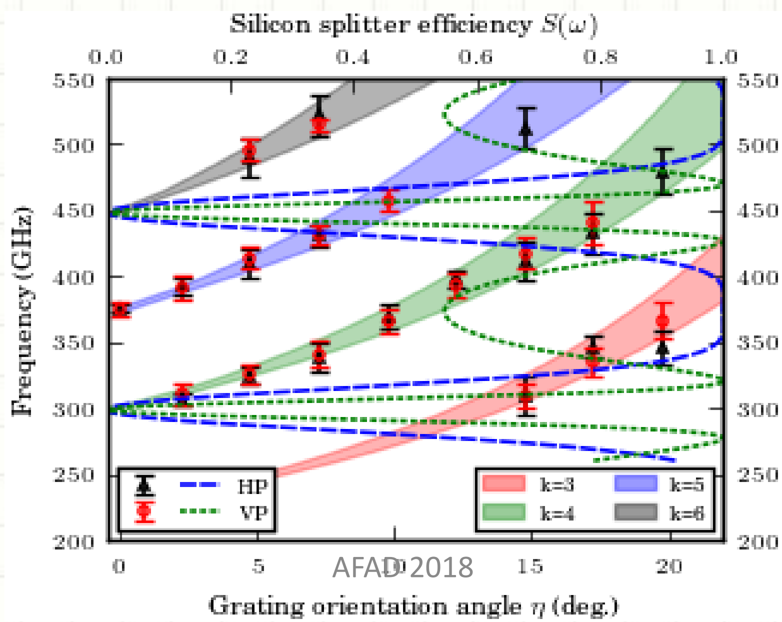
- A.P. Potylitsyn, A. Aryshev, G.A. Naumenko, L.G. Sukhikh, and D. Shkitov, M. Shevelev, N. Terunuma, and J. Urakawa, “First observation of the grating diffraction radiation”, **will be submitted to PRL**.
- A. Aryshev, A. Potylitsyn, G. Naumenko, M. Shevelev, K. Lekomtsev, L. Sukhikh, P. Karataev, Y. Honda, N. Terunuma, J. Urakawa, “Monochromaticity of coherent Smith-Purcell radiation from finite size grating”, **Phys. Rev. Accel. Beams** 20, 024701 (2017).











$$\lambda_k = \frac{d}{k}\left(\frac{\cos\eta}{\beta} - \cos(\theta - \eta)\right)$$

For η>20 deg…
Spectra peaks
Does not follow
Dispersion relation

KEK-TPU

Intense THz source development using periodical conductive structures.

- Simulation
  - Analytical model, Semi-analytical calculations
- Experimental results
  - Monochromaticity of cSPR
  - Coherent GTR
  - First observation of GDR
  - Constant improvements on spectra measurements (Interferometer, FFT, DAQ)
- Plans
  - Extended theory
    - Optimized GDR target
      - Both geometry and phases
      - Slit-grating
      - Variable period (“zone-plate”), pre-wave zone compensation.
  - New target holder
    - Clear edge w/o ring
    - Rotation axis coincidence
    - YAG screen
  - Micro-bunch beam experiments

Summary, conclusion

- There are 2 rather small semi-active projects
  - RF generator powered deflecting cavity.
  - One-click emittance measurements.
- Before 2017 we have organized 10 AGTaX collaboration meetings at:
  - KEK, MEPhI, Oxford, Strathclyde University, IUAC, and other.
- Research plans already extended up to 2020.

Thank you for your attention