Development of THz Sources Based on Femtosecond Electron Pulse Train

- test Accelerator as Coherent THz Source, t-ACTS -

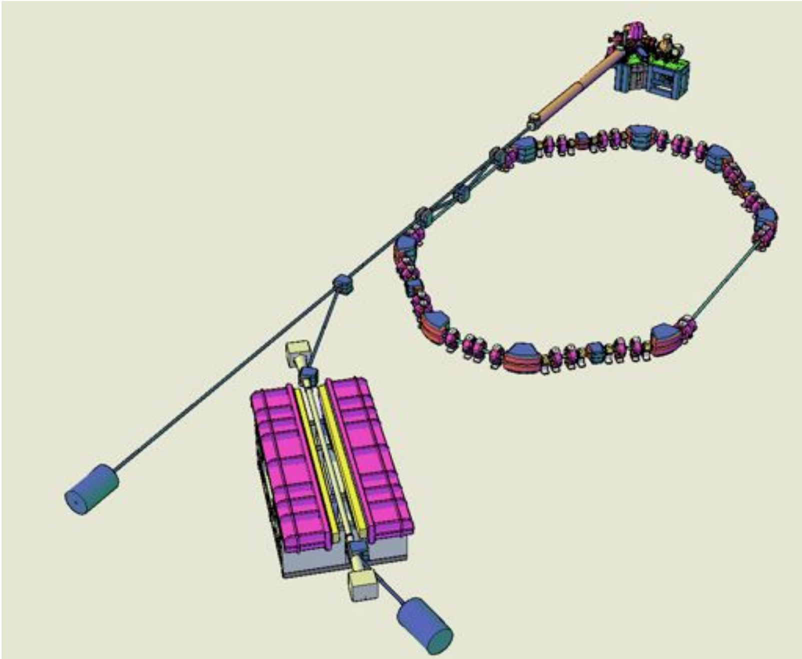
30 July, 2012 @ ANL, Argonne, IL
Workshop on Terahertz Sources for Time Resolved Studies of Matter

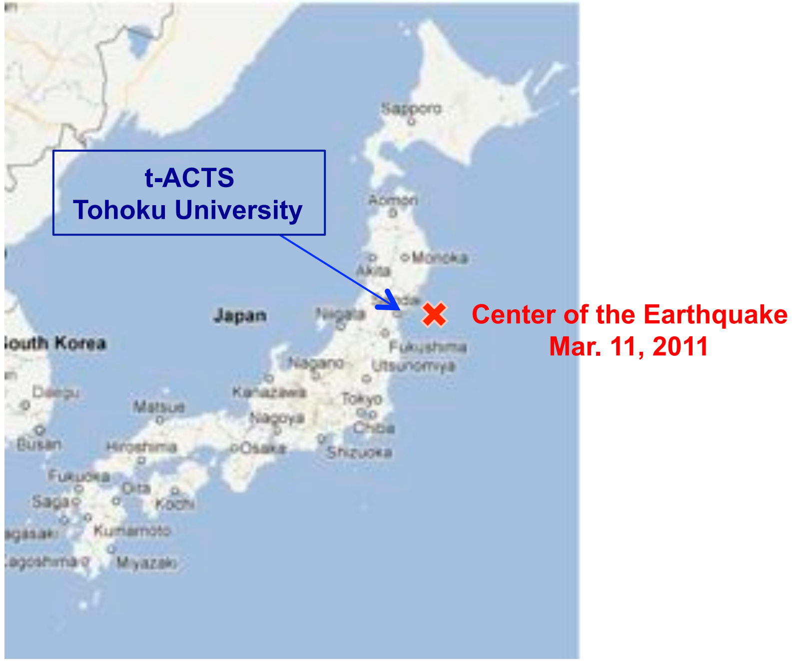
Hiroyuki Hama
and
M. Kawai, S. Kashiwagi, F. Hinode, N-Y. Huang, T. Muto, K. Nanbu,
Y. Shibasaki, I, Nagasawa, K. Takahashi

Electron Light Science Centre, Tohoku University
1-2-1 Mikamine, Taihaku-ku, Sendai 982-0826, Japan

*hama@lns.tohoku.ac.jp

What is t-ACTS @ Tohoku University





Goal : **Accelerator-based novel THz source facility**

Beam : **S-band femto-second bunch train**

Broadband source : **Isochronous accumulator ring**

Narrowband source : **THz (long period) undulator**

(Smith-Purcell BWO FEL with a low emittance DC gun)

Future : **Extend wavelength range**

We never use external lasers because of money !

Outline

1. Introduction; coherent synchrotron radiation
2. Production of femtosecond electron pulse train
3. THz undulator and beam dynamics issue
4. Property of the radiation from THz undulator
5. Manipulation of wave cycle by an optical cavity
6. Status and prospect of t-ACTS

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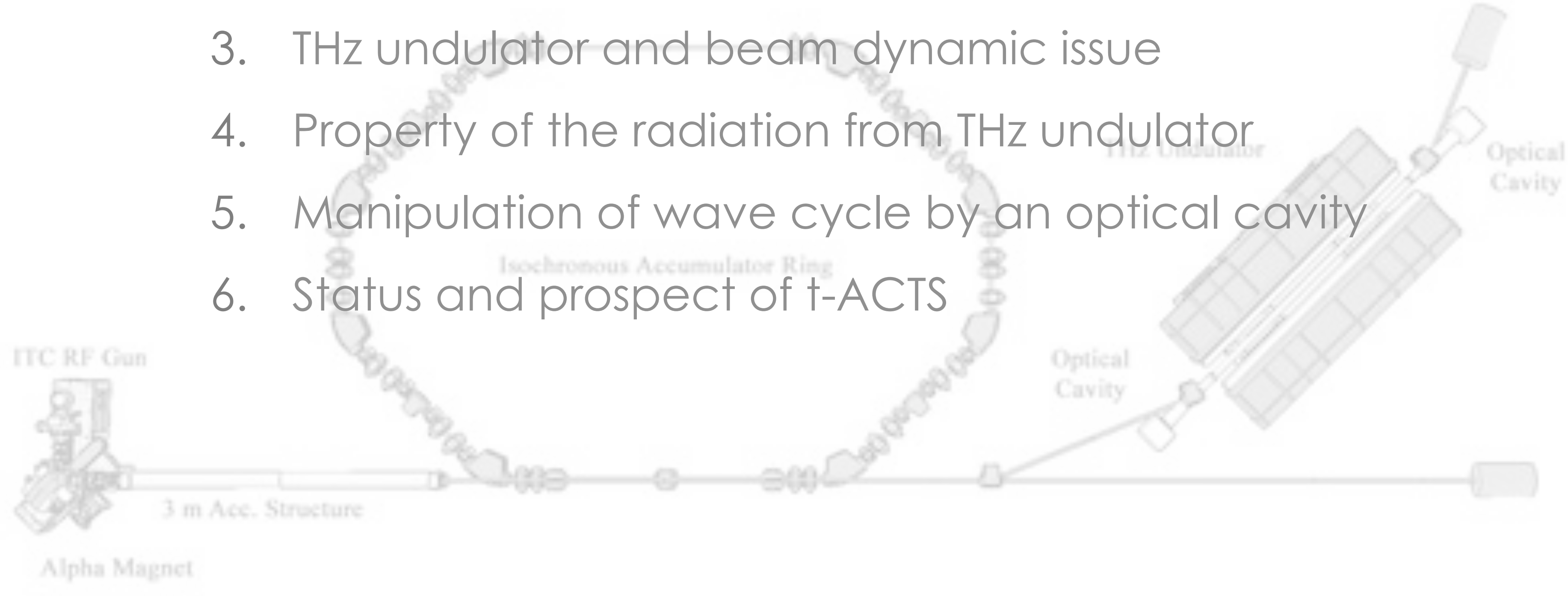


Reminder; Coherent synchrotron radiation

Radiation spectrum is deduced from Fourier transform of radiative field described by Lienard-Wiechert potential with far-field approximation

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \frac{n \times \{(n-\beta) \times \dot{\beta}\}}{(1-\beta \cdot n)^2} e^{i\omega(t - n \cdot r(t)/c)} dt \right|$$

How about many-particle system ?

No simple sum of power spectrum of single particle.
The wave-equation under "principle of superposition".

$$\left.\frac{d^2 I}{d\omega d\Omega}\right|_{multi-particle} = \{\underbrace{N[1 - f(\omega)]}_{\text{In-coherent part}} + \underbrace{N^2 f(\omega)}_{\text{Coherent part}}\} \left.\frac{d^2 I}{d\omega d\Omega}\right|_{single\ \ prticle}$$

In-coherent part   Coherent part

Longitudinal bunch formfactor : $f(\omega) = \left| \int_{-\infty}^{+\infty} S(\vec{r}) e^{i\omega \vec{n} \cdot \vec{r}/c} d\vec{r} \right|^2$

Formfactor

Gaussian bunch	rectangular bunch

Distribution function

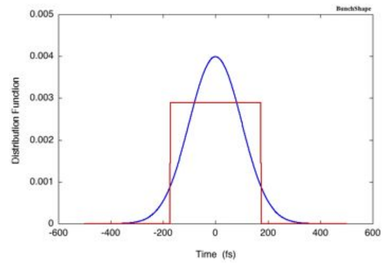
$$S(z) = \frac{1}{\sqrt{2\pi}\sigma_b} \exp\left(-\frac{z^2}{2\sigma_b{}^2}\right) \qquad S(z) = \frac{1}{2\sqrt{3}\sigma_b} : |z| < \sqrt{3}\sigma_b$$

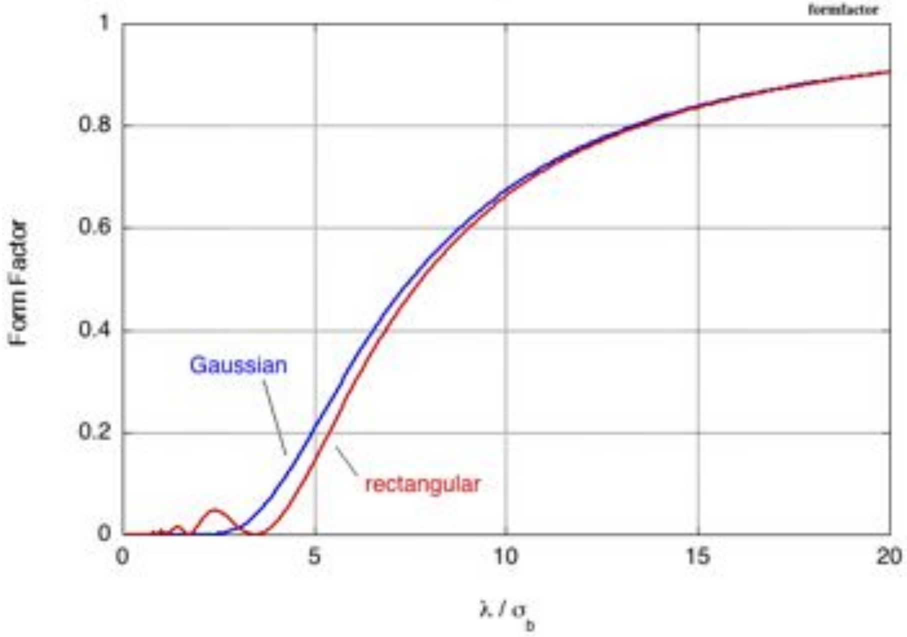
Formfactor in freq. domain

$$f(\omega) = \left| \exp\left(-\frac{\omega^2 \sigma_b{}^2}{2}\right) \right|^2 \qquad f(\omega) = \left| \frac{\sin\sqrt{3}\sigma_b \omega}{\sqrt{3}\sigma_b \omega} \right|^2$$

Formfactor in spatial domain

$$f(\lambda) = \left| \exp\left(-2\pi^2 \frac{\sigma_b{}^2}{\lambda^2}\right) \right|^2 \qquad f(\lambda) = \left| \frac{\sin 2\sqrt{3}\pi \frac{\sigma_b}{\lambda}}{2\sqrt{3}\pi \frac{\sigma_b}{\lambda}} \right|^2$$



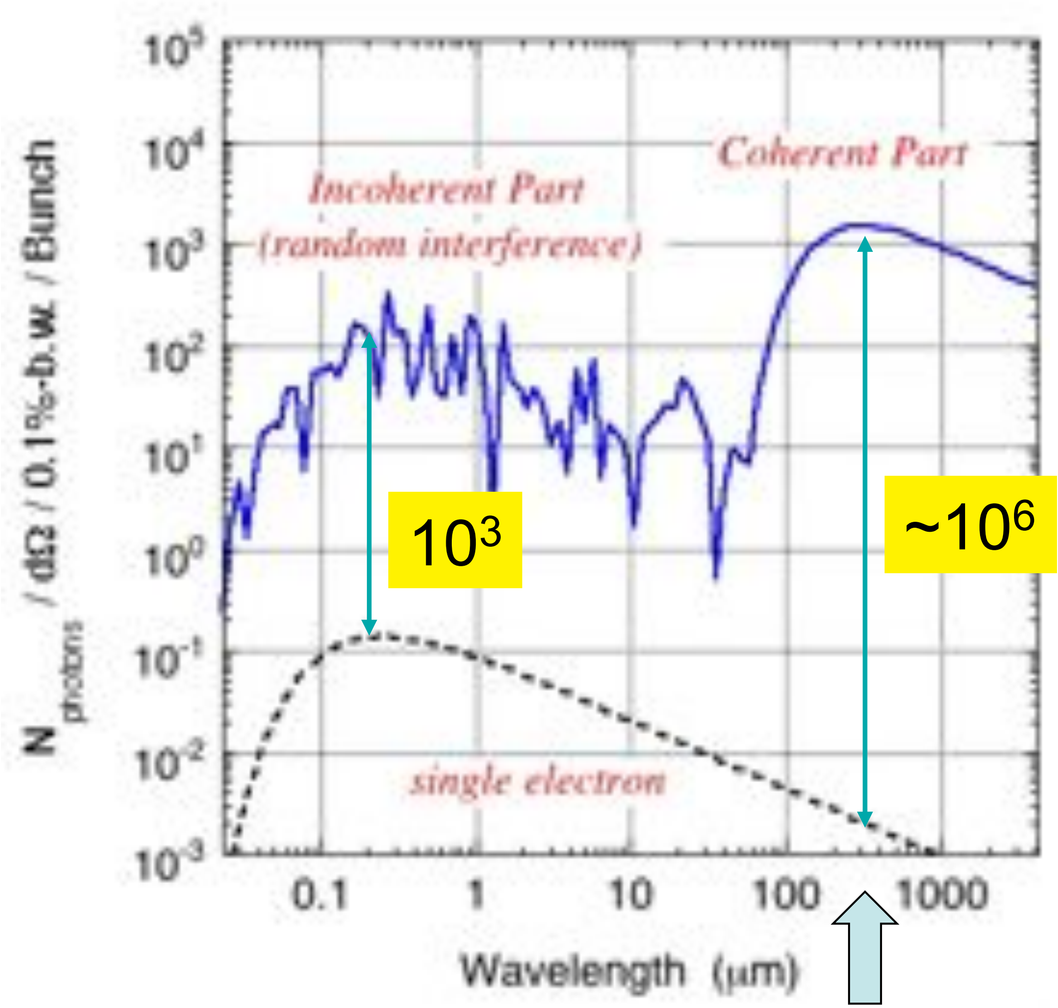


$$1\ \mathrm{THz} \ @\ \sigma_z = 30\ \mu\mathrm{m}\ (100\mathrm{fs})$$

The bunch length 10 times shorter than the wavelength is at least required.

Multi-particle simulation for Gaussian bunch

Dipole radiation spectrum simulated with 1000 electrons



$E = 200 MeV$

$\sigma_b = 100 fs$

$\rho = 3m$

1 THz

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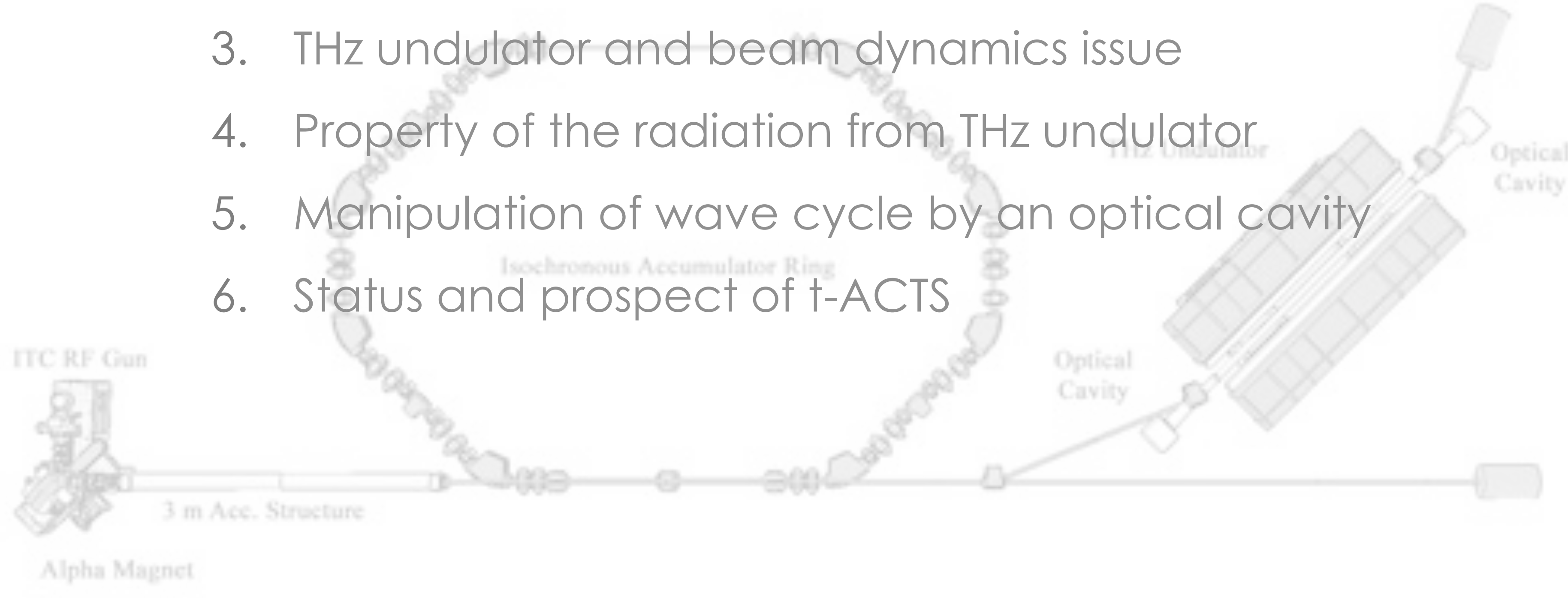


Why thermionic RF gun ?

University is poor

- Simple operation and apparatus because of no-laser. (& it is cheap !)
- Thermionic cathode is much more stable than photo-cathode.
- Potential ability has not cultivated yet.
- Though relatively low charge in a micropulse, macropulse can offer high average intensity in microsecond duration.

New approach for optimization of thermionic RF gun is challenge !

because 3 GHz repetition of micropulse is apparently different from the photocathode RF gun

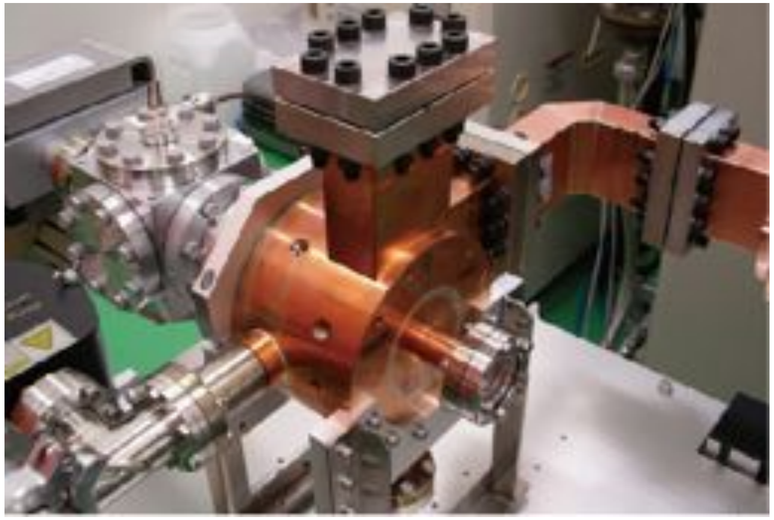
Employing "velocity bunching scheme",

femtosecond pulse train is feasible

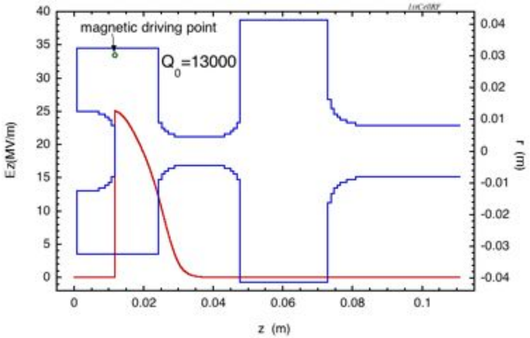
Operational

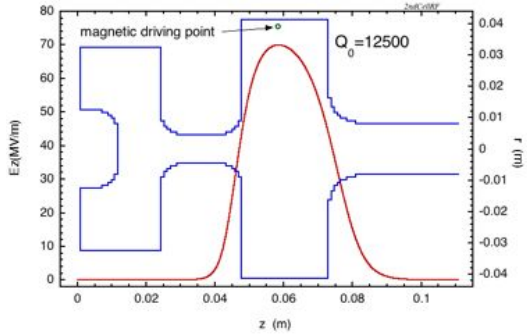
MARK-III (Duke Univ., Vanderbilt Univ.), KHI-FEL (Science Univ. of Tokyo), SUNSHINE (SLAC => Changmai Univ.), KU-FEL (Kyoto University), MAX-II Injector (Max-Lab)

Independently tunable cells (ITC) RF gun



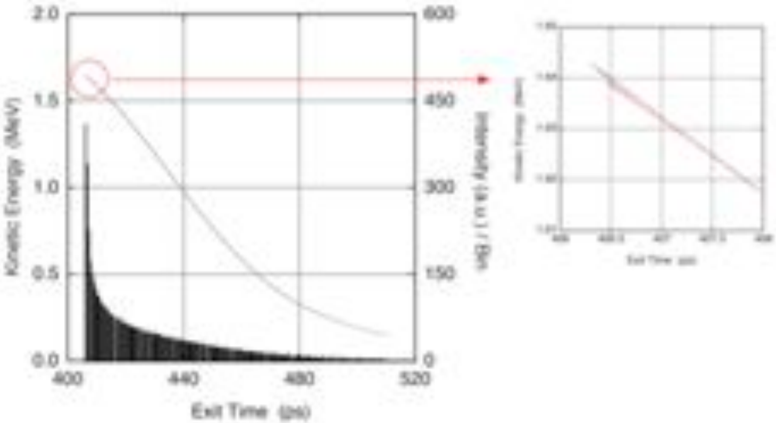
S-bad Thermionic RF gun (ITC RF Gun)

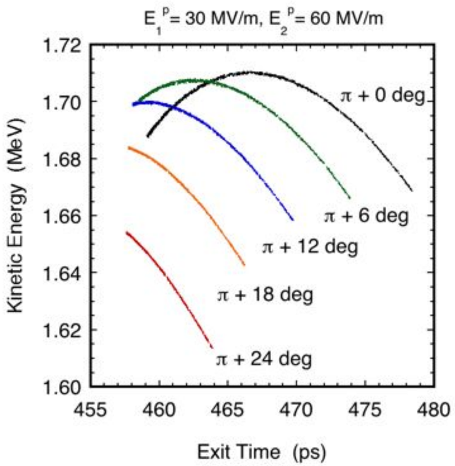




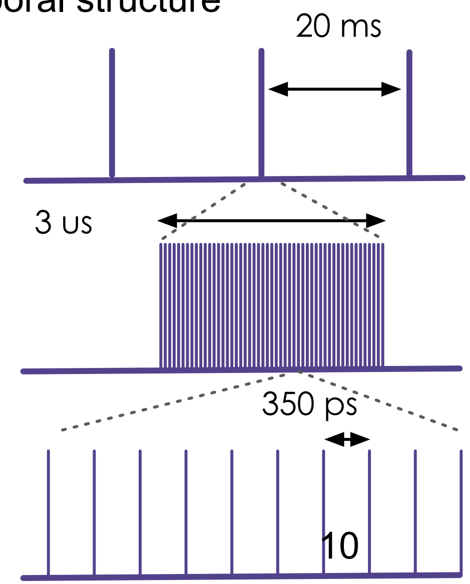
ITC RF gun

- ☞ two cells can be tuned independently
  - ☞ <u>linearized phase space possible</u>
    - ☞Preferred for bunch compression





Temporal structure



Velocity bunching in accelerating structure

Traveling wave acc. structure

$$E_z(t,z) = -E_0 \sin(\omega t - kz + \phi_0)$$

$$\psi(t,z) = -\omega t + kz - \phi_0$$

$$k = \omega / c$$

Phase slippage

$$\frac{d\psi}{dz} = -\omega \frac{dt}{dz} + k = -\frac{\omega}{\beta c} + k = -k\left(\frac{1}{\beta} - 1\right)$$

$$\Rightarrow \frac{d\psi}{dz} = k\left(1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right)$$

Energy gain

$$\Delta\gamma = \frac{-eE_z}{mc^2}\Delta z = \frac{eE_0}{mc^2}\sin(-\psi)\Delta z$$

$$\Rightarrow \frac{d\gamma}{dz} = \frac{eE_0}{mc^2}\sin(-\psi) = -\alpha k \sin(\psi)$$

Hamiltonian

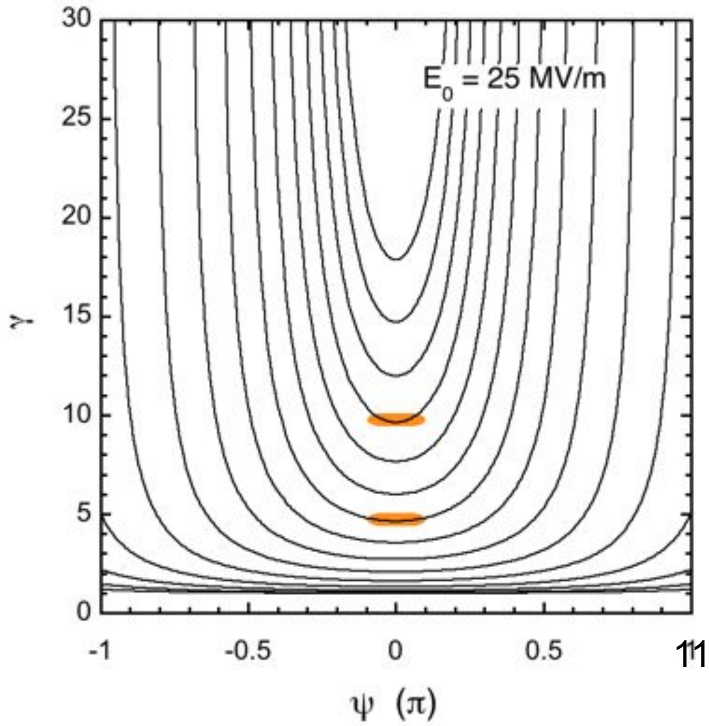
$$H' = \frac{1}{k}H = \gamma - \sqrt{\gamma^2 - 1} - \alpha\cos(\psi)$$

$$\frac{d\psi}{dz} = \frac{\partial H'}{\partial \gamma} = 1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}$$

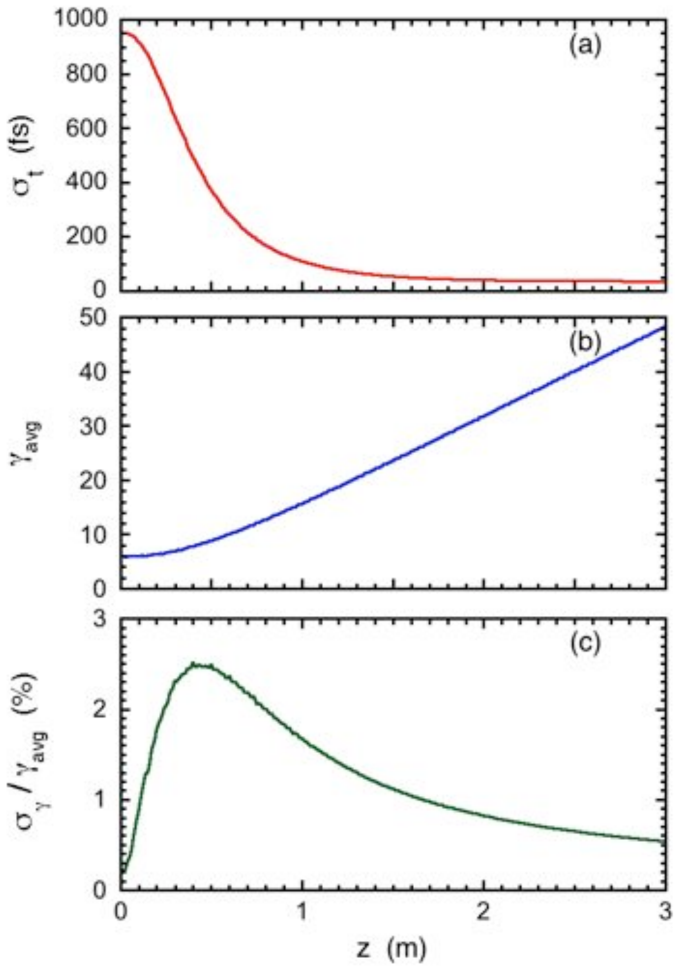
$$\frac{d\gamma}{dz} = -\frac{\partial H'}{\partial \psi} = -\alpha \sin(\psi)$$

Linac normalizer

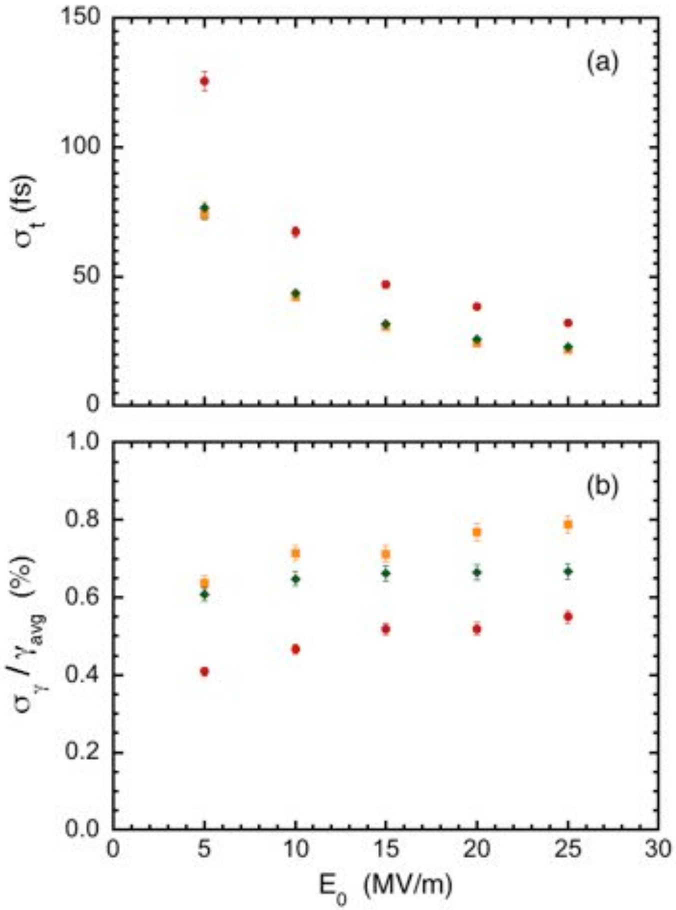
$$\alpha \equiv \frac{eE_0}{mc^2 k}$$



Sub-hundred femtosecond pulse is feasible

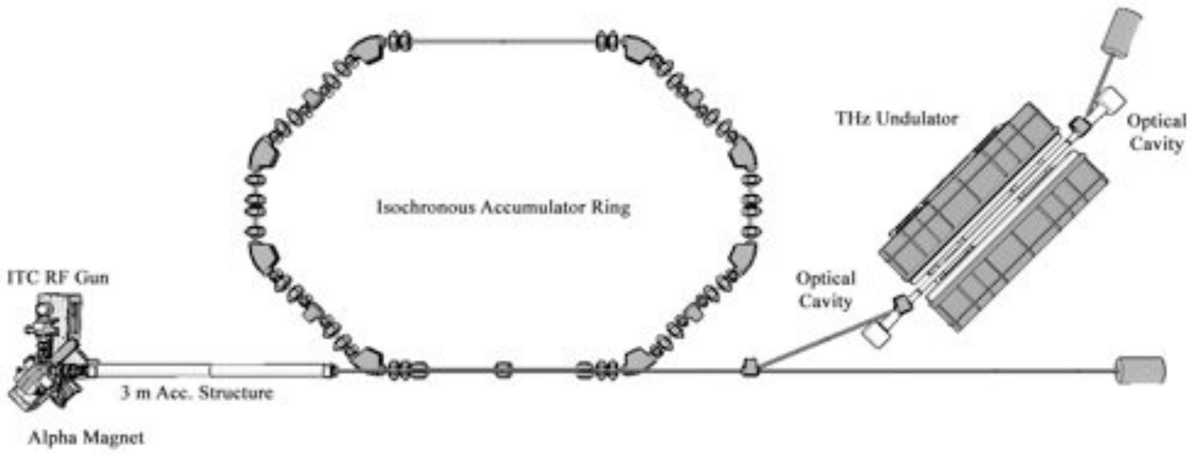


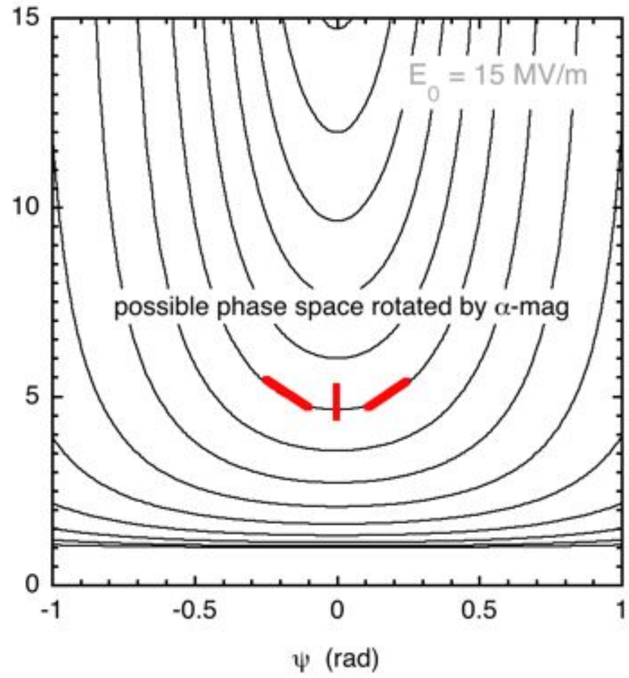
The longitudinal beam evolution through the 3 m long linac when the peak field is set at 20 MV/m.



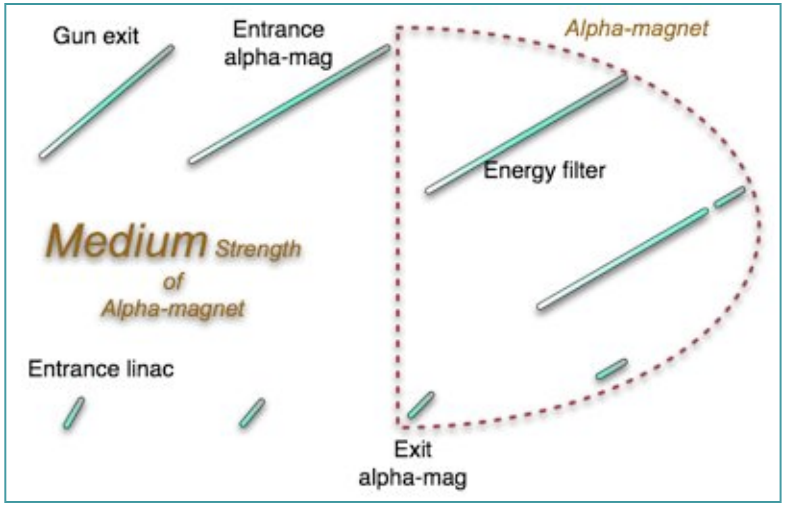
The red square symbol is the GPT calculation result by 3DSPACECHARGE routine, the blue triangle symbol is the GPT calculation without space charge consideration, and the green circle symbol is the result calculated by Hamiltonian system.

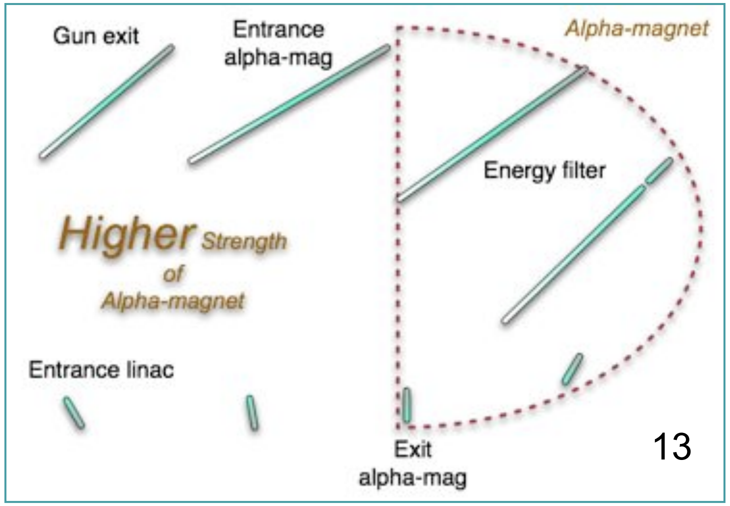
Velocity bunching scheme in t-ACTS

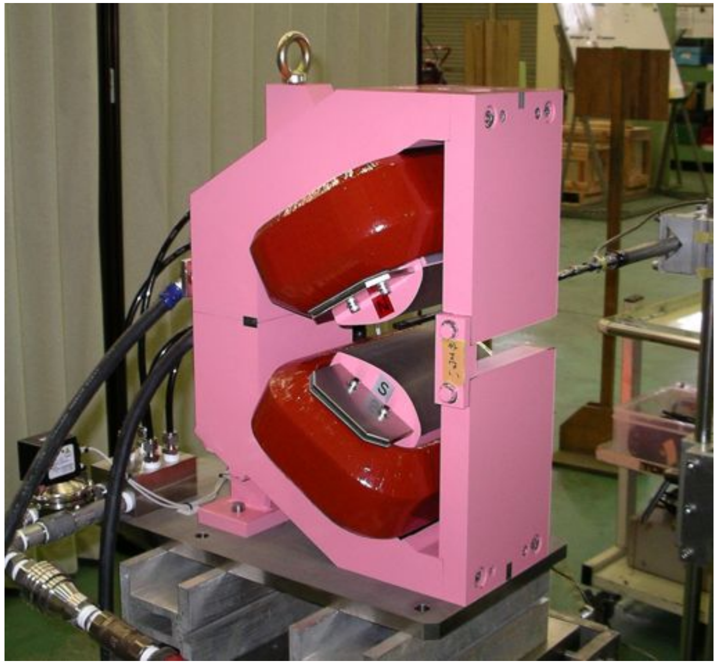




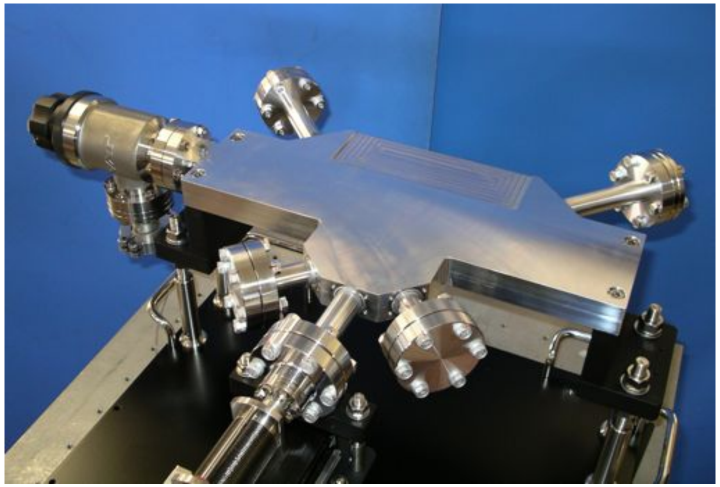
Alpha magnet is NOT a bunch compressor for non-relativistic beam !
"Longitudinal phase space rotator"







Alpha Magnet



Alpha Chamber

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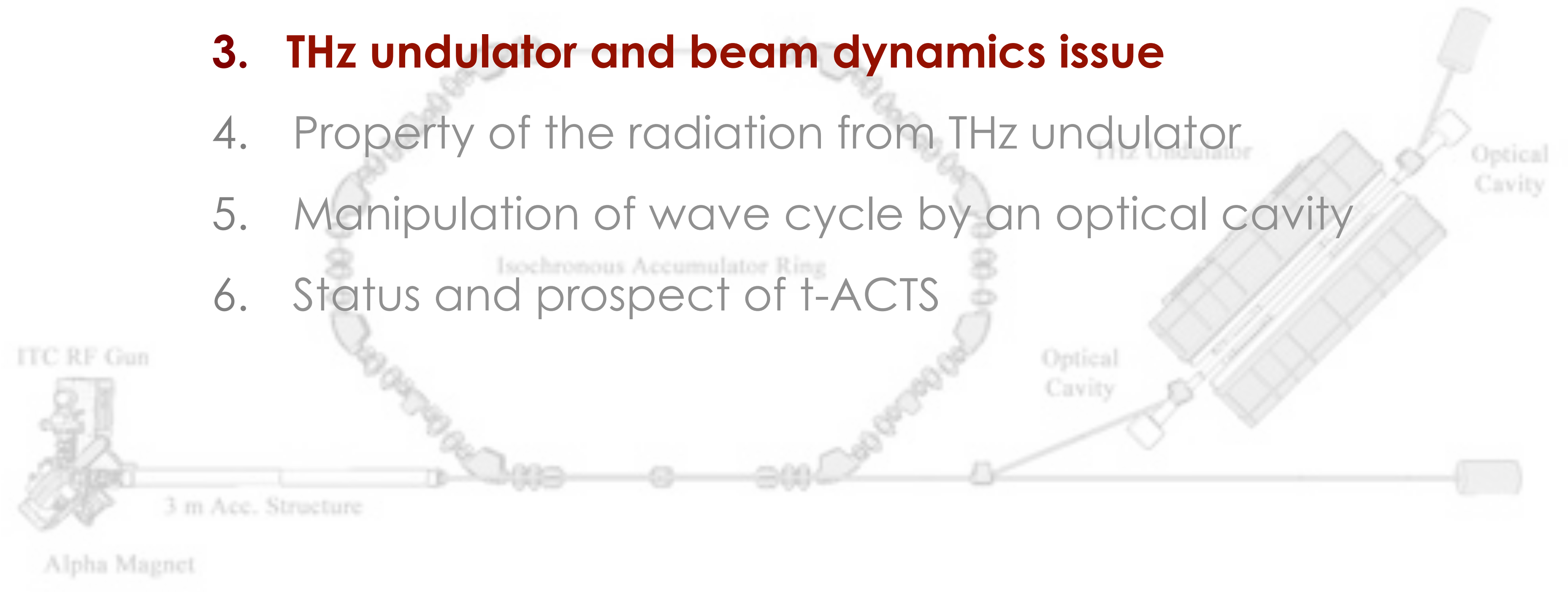


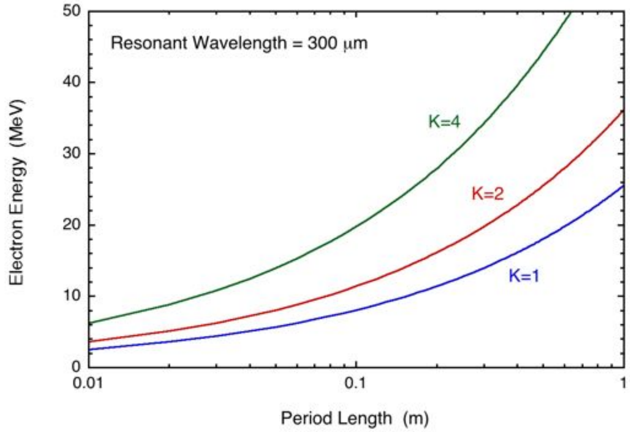
THz undulator

Undulator will be powerful narrow-band THz source
However because of long wavelength….

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad \text{where } K = \frac{eB_0\lambda_u}{2\pi m_e c}$$

1) Period length and K have to be larger
2) Beam energy should be lower
3) => Focusing power is increasing

$$k = \frac{1}{2}\left(\frac{B_0}{B\rho}\right)^2 = \frac{1}{2}\left[B_0 / \left(\sqrt{E^2 - \left(mc^2\right)^2} / c\right)\right]^2$$

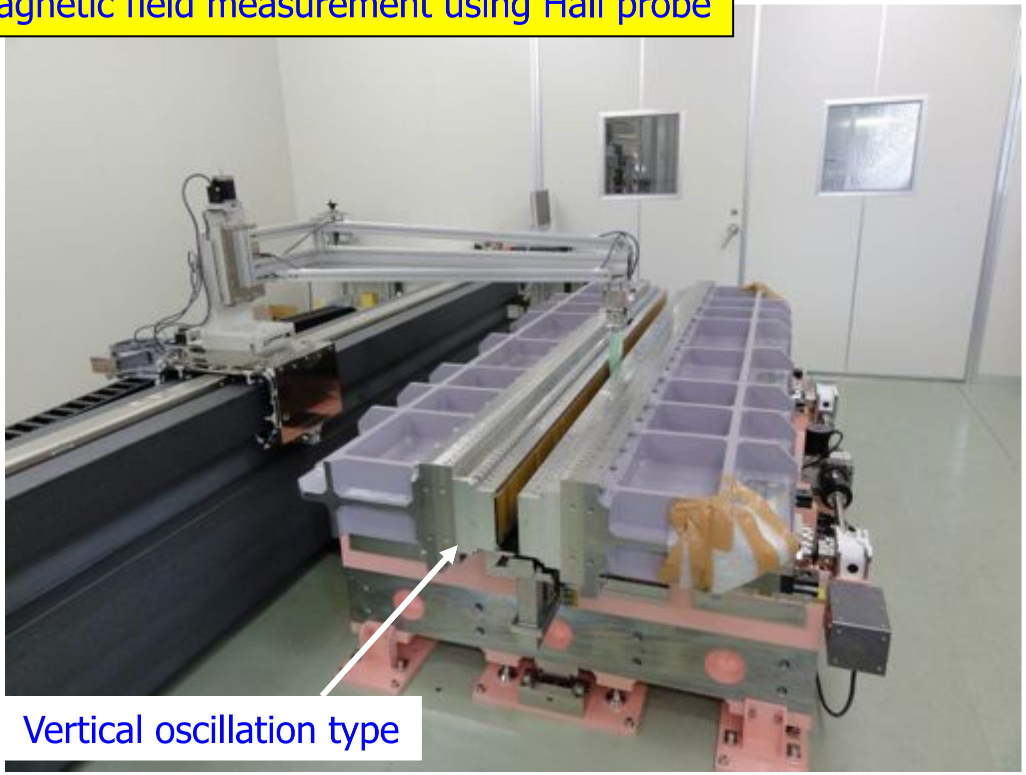


4) Gap should be large because of large spreading radiation spreading angle (waveguide mode annoys us)

t-ACTS THz undulator

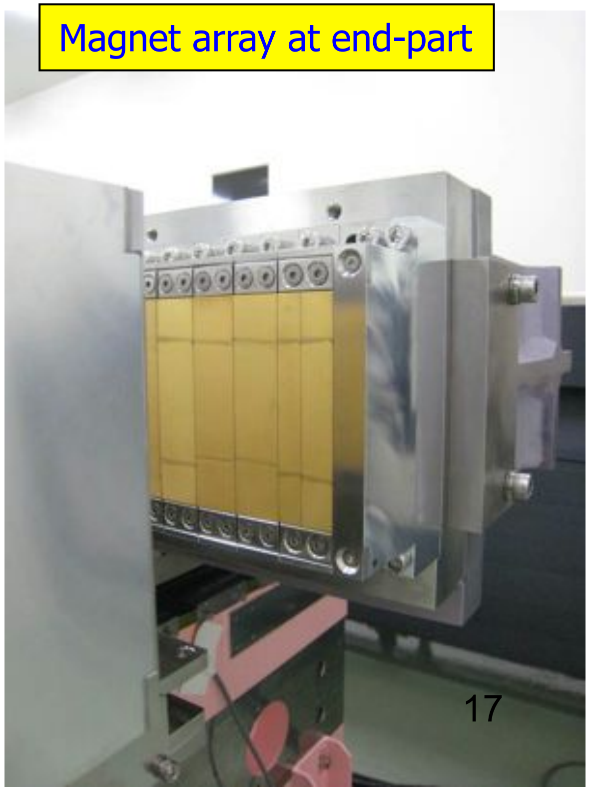
Undulator type	Halbach type (Planner)
Block size	110×65×25 mm^3
Material･Coating	Nd-Fe-B ･TiN
Period length / Number of periods	100 mm･25 periods
Total length	2.532 m
Peak magnetic fields	0.41 T (gap 54 mm)
K-value	3.82 (max)

Magnetic field measurement using Hall probe

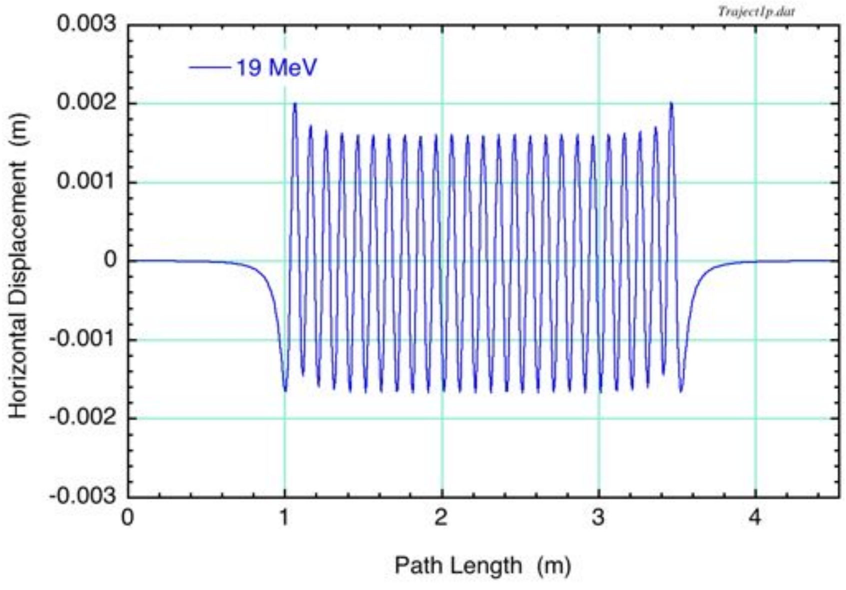


Vertical oscillation type

Magnet array at end-part



t-ACTS THz undulator

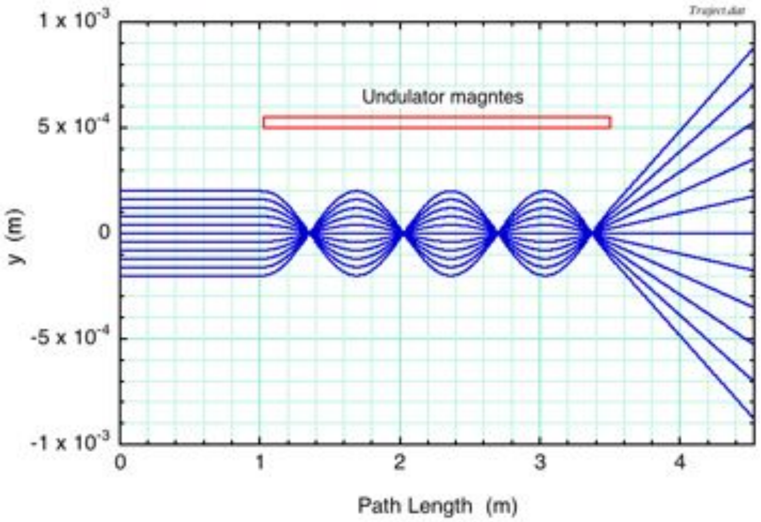


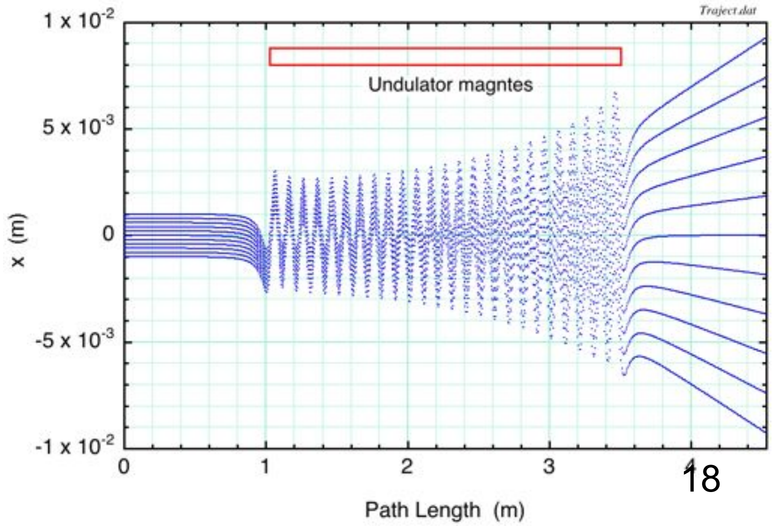
Expected focusing power from 3D magnetic field analysis

$$k_y = 20.85 \ \ [\mathrm{m}^{-2}]$$

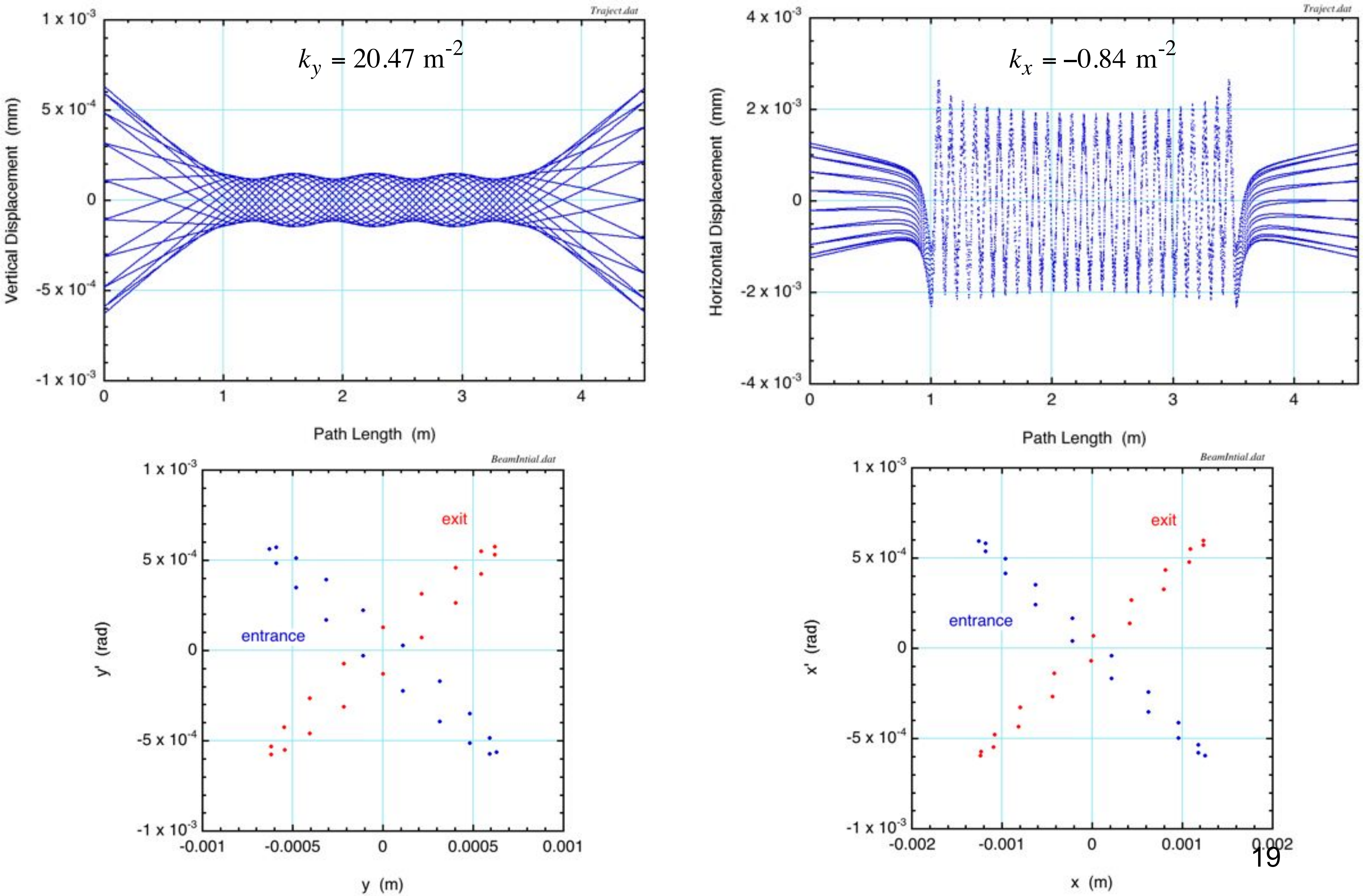
$$k_x = -0.847 \ \ [\mathrm{m}^{-2}]$$

Tracking for mismatched beam





Beam optics matching



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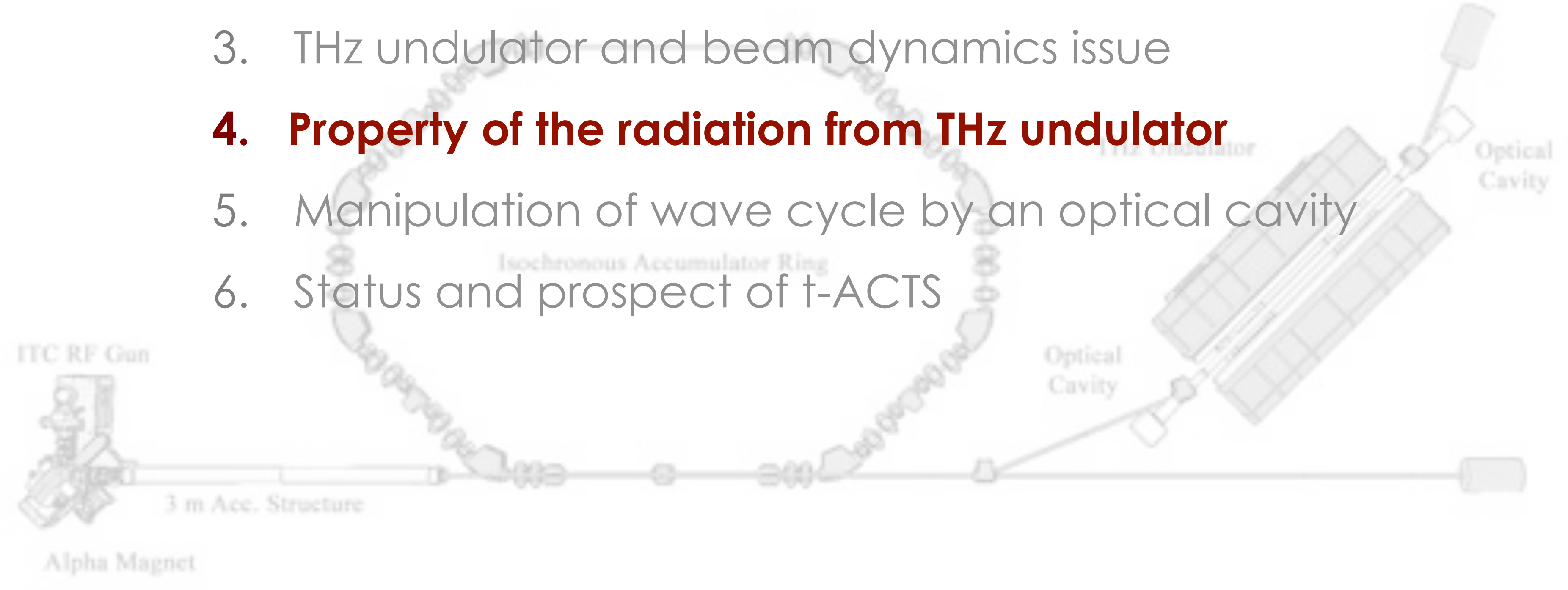
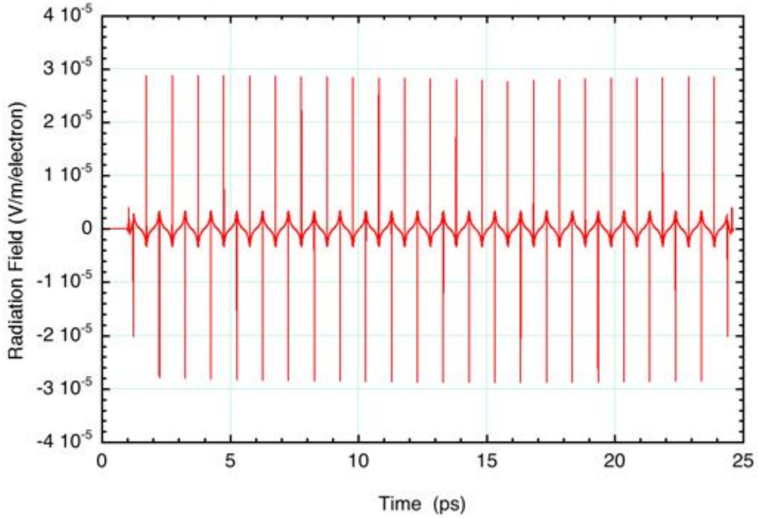
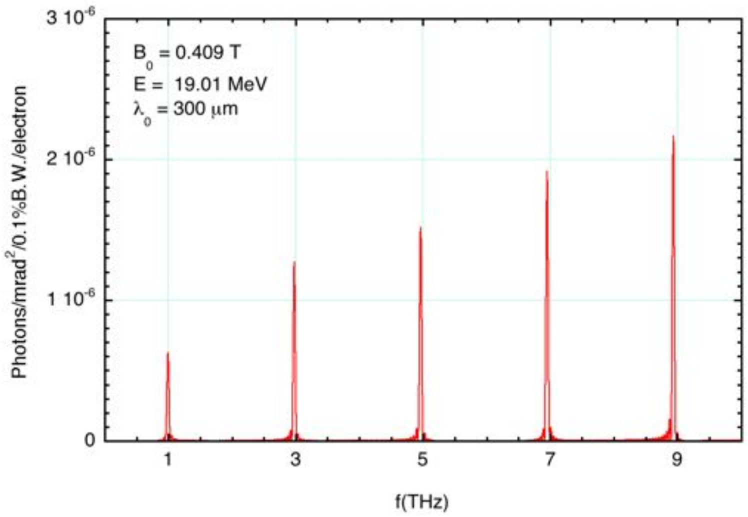


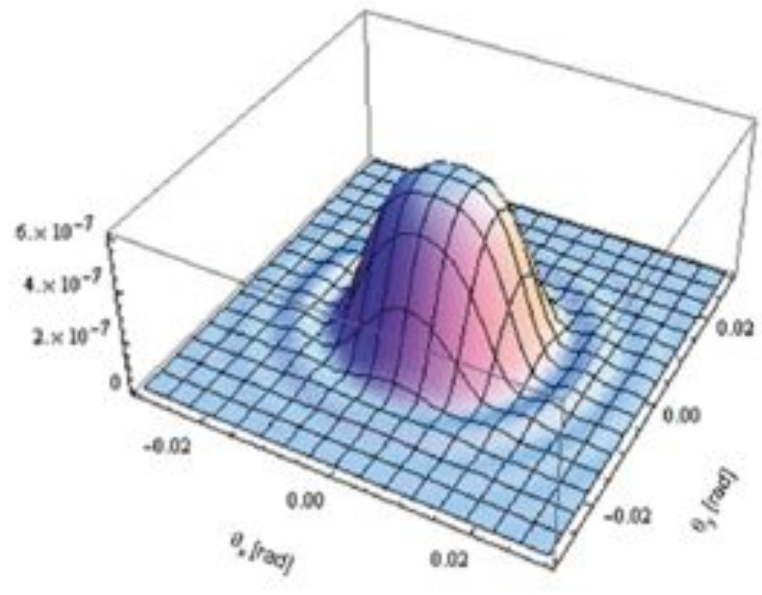
Property of the (incoherent) radiation

Radiation from an electron



Fourier transform

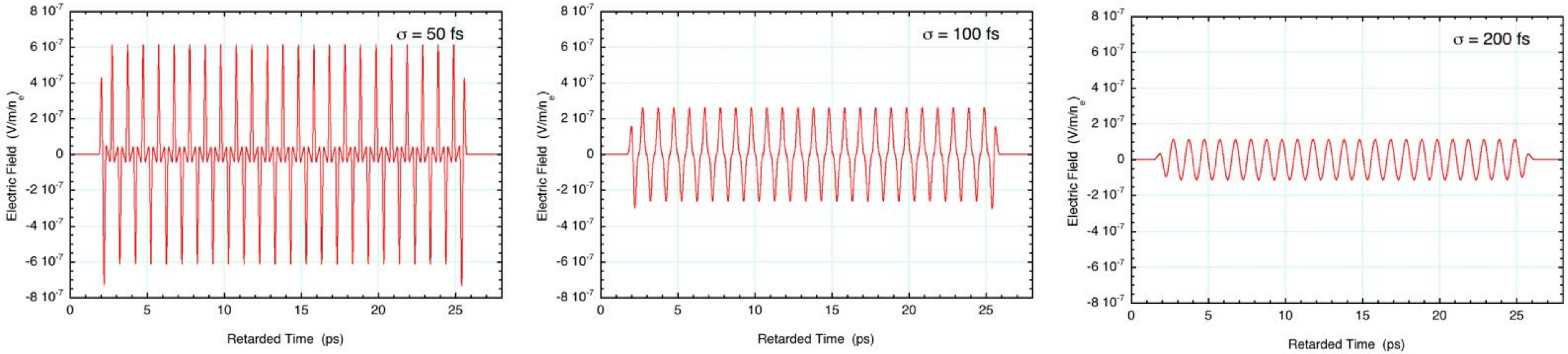




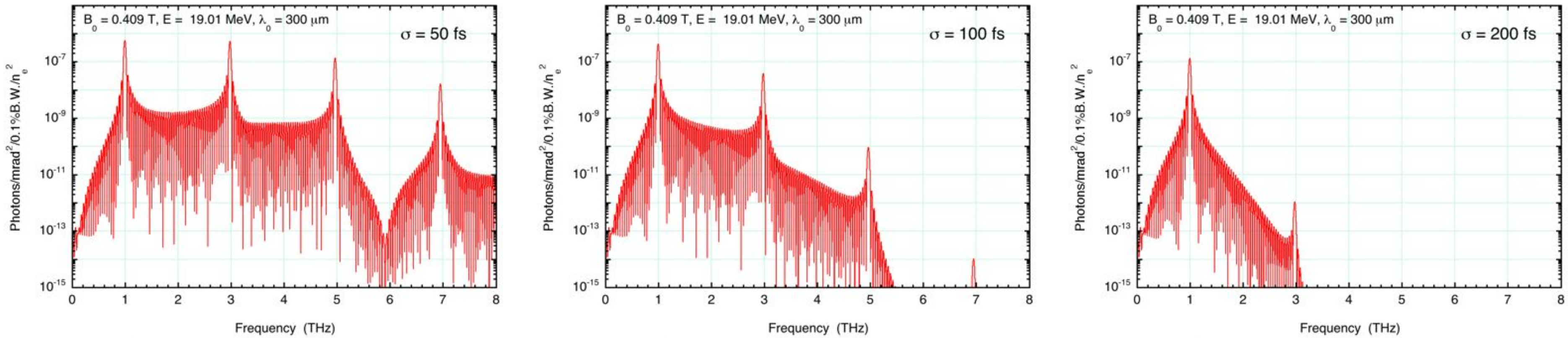
Spatial distribution of fundamental harmonics

Property of the (coherent) radiation

Radiation from femtosecond bunch



Moderate formfactor extracts fundamental radiation from the large-K undulator



CSR from THz undulator

	Near-future target
Wave cycle : 25 cycles	
Micropulse duration : > 100 *fs*	: ~ 50 *fs*
(radiation pulse duration ≈ 25 *ps*)	
Micropulse charge : > 20 *pC*	: ~ 100 *pC*
Micropulse repetition : 2856 *MHz*	
Macropulse duration : > 2 μs	
Number of micropulses : > 5700	
Macropulse repetition : 10 *Hz*	: 25 *Hz*
Micropulse energy : > 0.15 μJ	: ~ 5.4 μJ
Micropulse power : > 6 kW	: ~ 210 kW
Macropulse energy : > 850 μJ	: ~ 30 mJ
Macropulse power : > 430 W	: ~ 16 kW
Complete average power : > 8.6 mW	: ~ 770 mW

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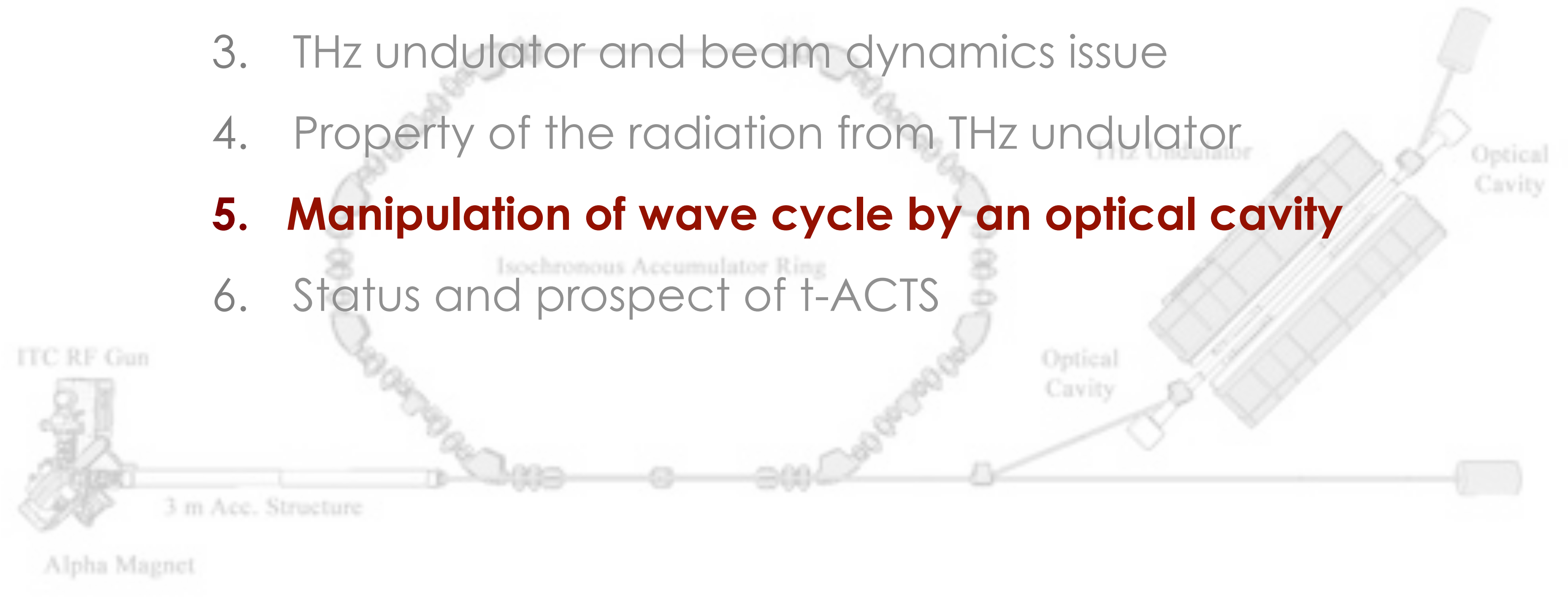


Wave cycle manipulation by optical cavity

Wave equation with SVEA (Slowly Varying Envelope Approximation)

$$\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)\underline{E}_L e^{i\phi L}=i\frac{ea_w}{2\varepsilon_0\gamma_r}\left[J_0(\xi)-J_1(\xi)\right]\frac{N}{V}\underline{\left\langle e^{-i\psi_i}\right\rangle}$$

Bunching factor
(100 fs bunch gives sufficiently large value)

1-D FEL equation

Field envelope amplitude

$$\frac{\partial}{\partial\tau}\underline{a}(\varsigma,\tau)=ij_e(\varsigma)\left\langle e^{-i\psi_i}\right\rangle_{|\varsigma=\varsigma_i(\tau)}$$

Relative electron energy

$$\frac{\partial}{\partial\tau}\mu_i(\tau)=\mathrm{Re}\left[i\underline{a}(\varsigma,\tau)\right]e^{i\psi_i(\tau)}$$

Electron phase

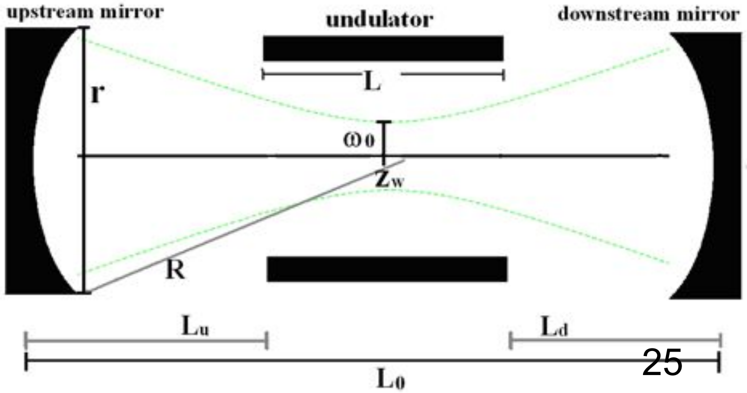
$$\frac{\partial}{\partial\tau}\varsigma_i(\tau)=-1$$

Electron position with respect to the field

$$\frac{\partial}{\partial\tau}\psi_i(\tau)=\mu_i(\tau)$$

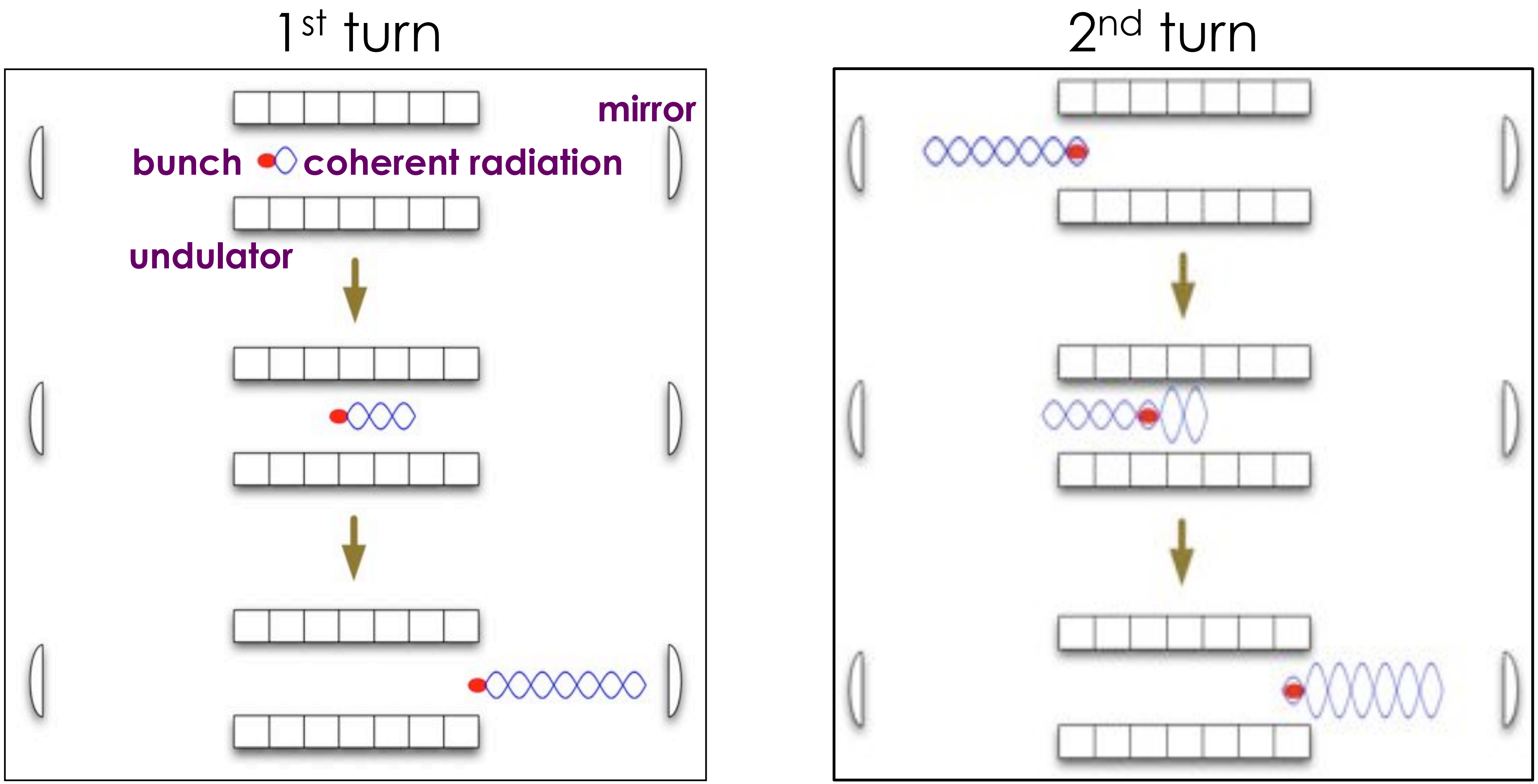
Table 1: Undulator and beam parameters

Undulator period	λ_w	0.08 m
Number of period	N_w	20
Peak magnetic field	B_w	0.3 T
Resonant wavelength	λ_r	254 μm
Beam energy	γ	23.5 (12 MeV)
Total beam current	Q	20 pC
Normalized emittance	ε_n	~ 2 π mm mrad
Peak current	I	80 A
FEL parameter	ρ	4.3E-3



Wave cycle manipulation by optical cavity

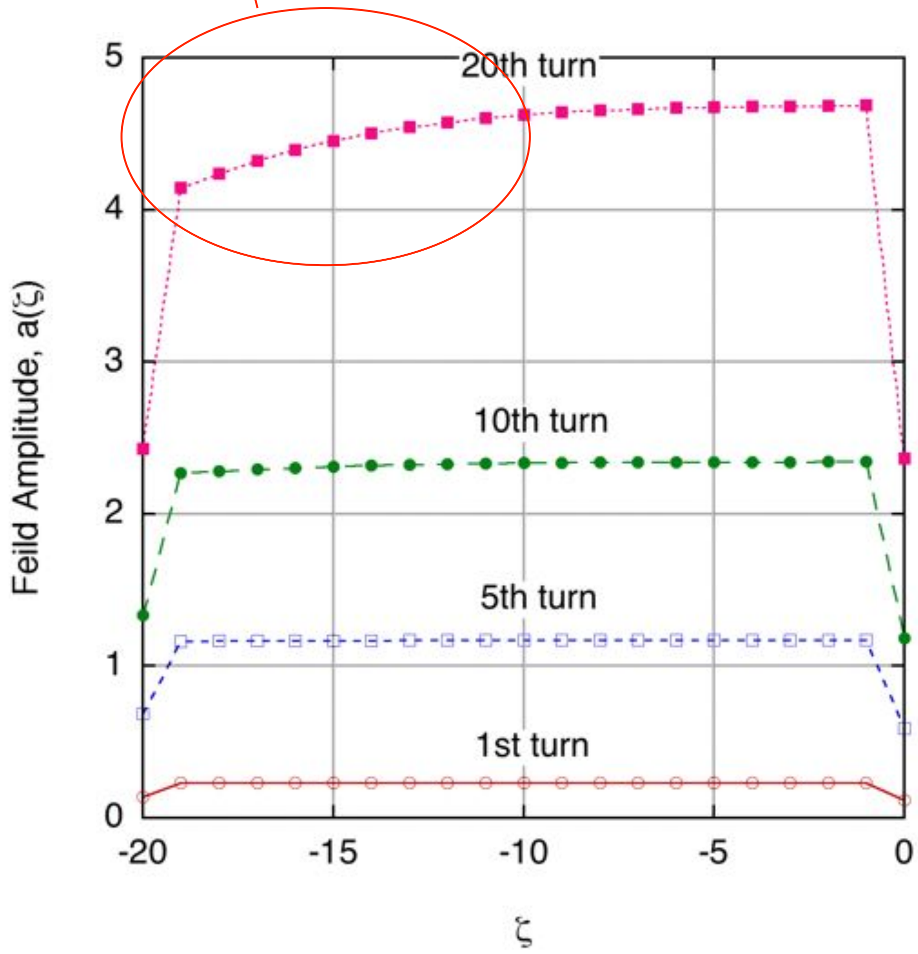
If the bunch length shorter than the FEL wavelength and complete synchronization .....

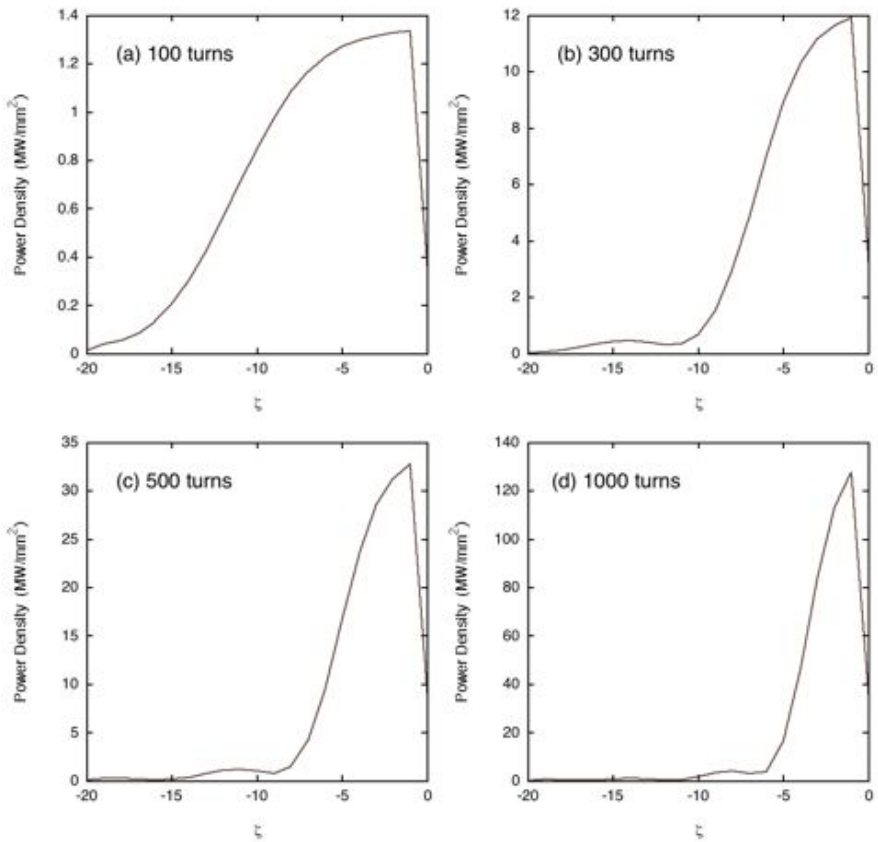


Is it simple pile-up of coherent radiation filed ?

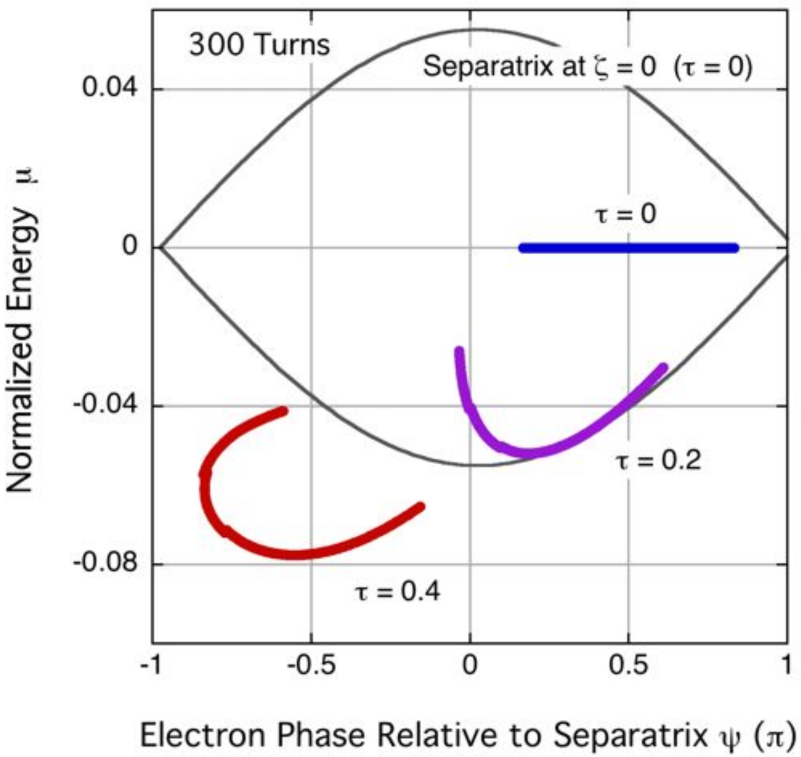
Wave cycle manipulation by optical cavity

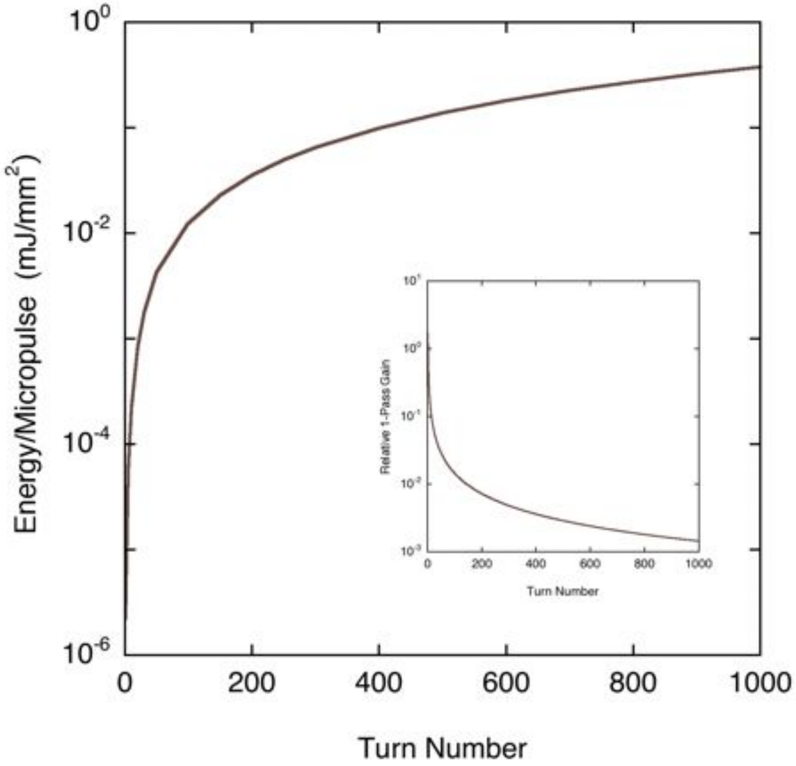
Pile-up saturation appeared





Wave cycle manipulation by optical cavity



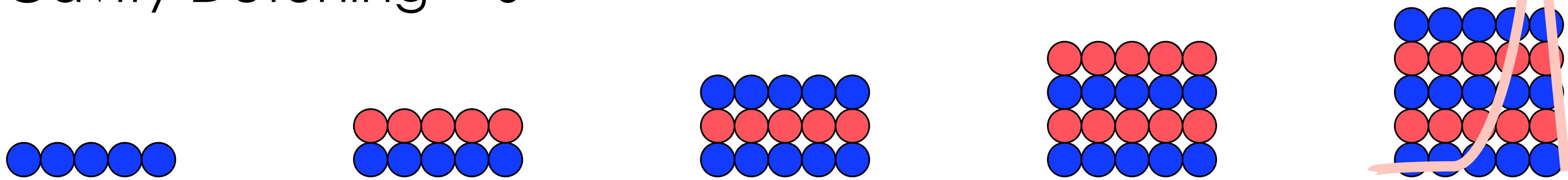


"bunched-FEL"

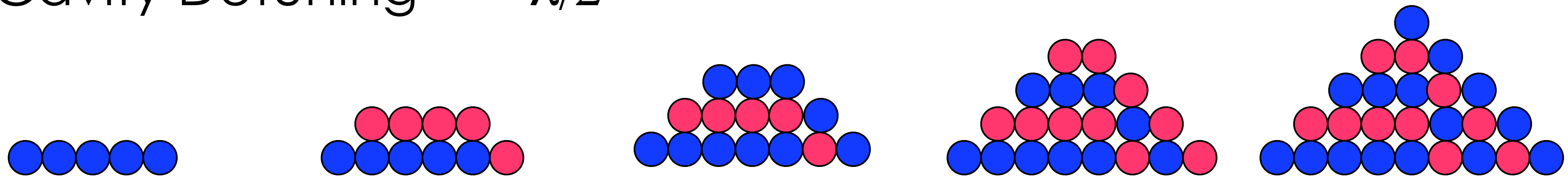
Wave cycle manipulation by optical cavity

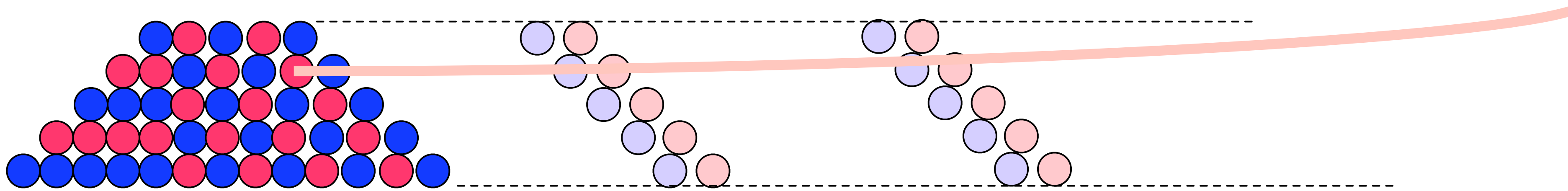
Several cycle pulse

Cavity Detuning = 0



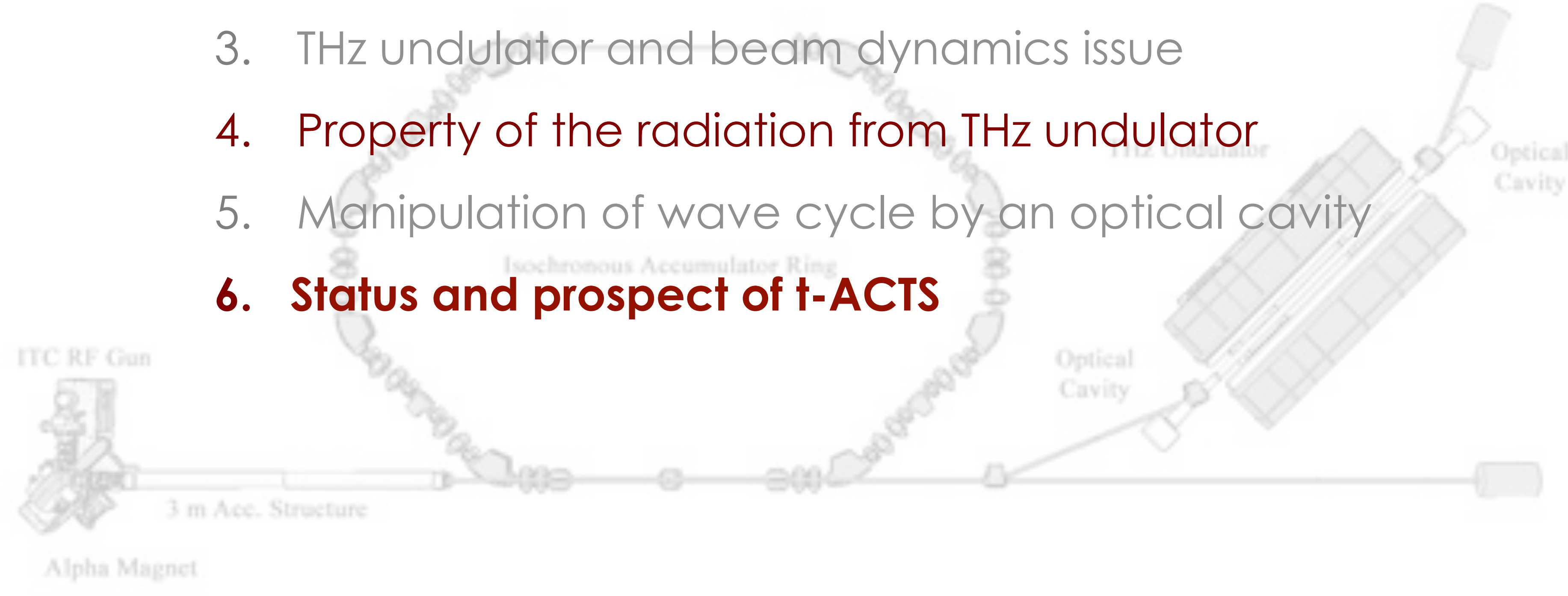
Cavity Detuning = + $\lambda/2$





Quasi-cw (but consider reflectivity)

1. **Introduction; coherent synchrotron radiation**
2. **Production of femtosecond electron pulse train**
3. THz undulator and beam dynamics issue
4. Property of the radiation from THz undulator
5. Manipulation of wave cycle by an optical cavity
6. **Status and prospect of t-ACTS**



Current status of t-ACTS @July, 2012

t-ACTS is now under developing

Hardware

ITC-RF gun	Beam characteristics under investigated
alpha magnet	Ready
acc. structure	Will be installed this year
50 MW klystron	get !
270kV modulator	get !
THz undulator	get !
Optical cavity	get !
isochronous ring	Under construction

House completed, March, 2010

Theoretical work

beam dynamics	mostly finished (rf gun)
	under investigation (velocity bunching)
	under investigation (ring)
FEL interaction	**3D needed for effect from transvers mode**

Proof-of-principle experiment will start March, 2013