MOCAU04: Focal Point Laser-Field as Optical Seeder

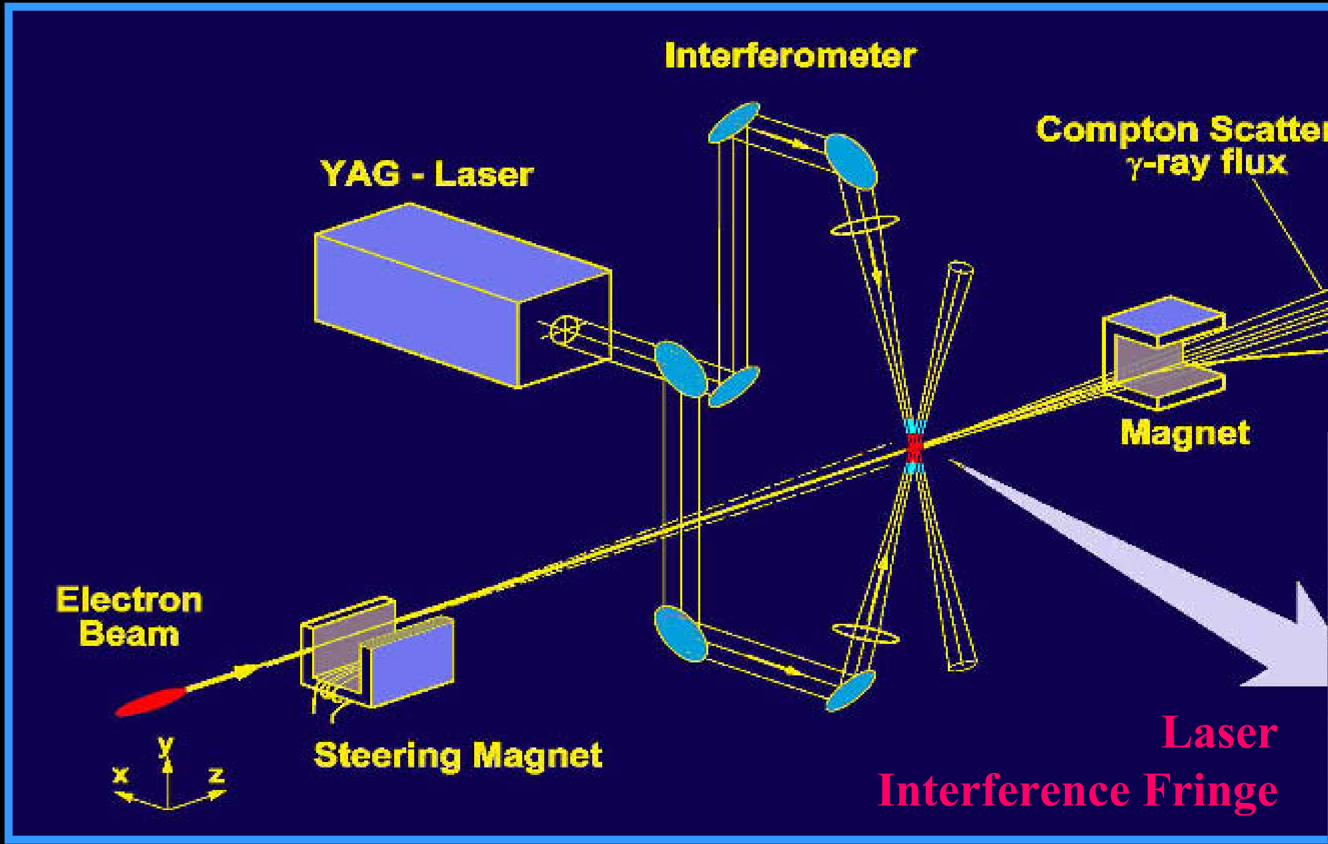
Tsumoru Shintake, RIKEN/SPring-8

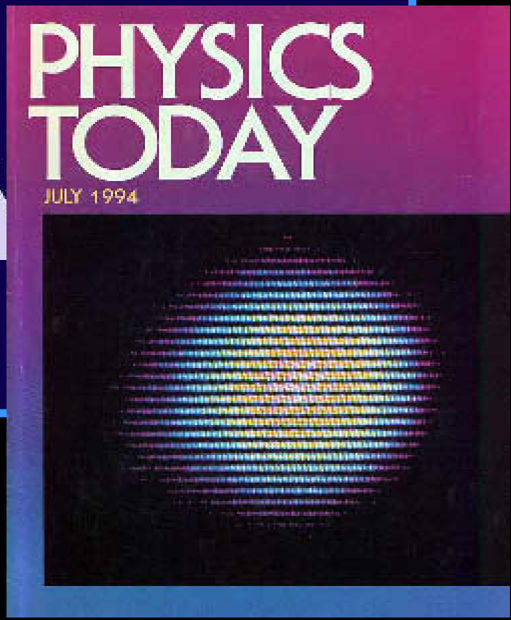
- **Back to the FFTB**
- **System Diagram**
- **Thermal diffusion problem**
- **How does it works**
- **Wavelength compression**
- **Atto-second X-ray**
  - **Femto-sec pulse at optical wavelength.**

Nanometer Beam Size Measurement

e+e- Linear Collider R&D

Spot-size Monitor based on Laser Interferometry



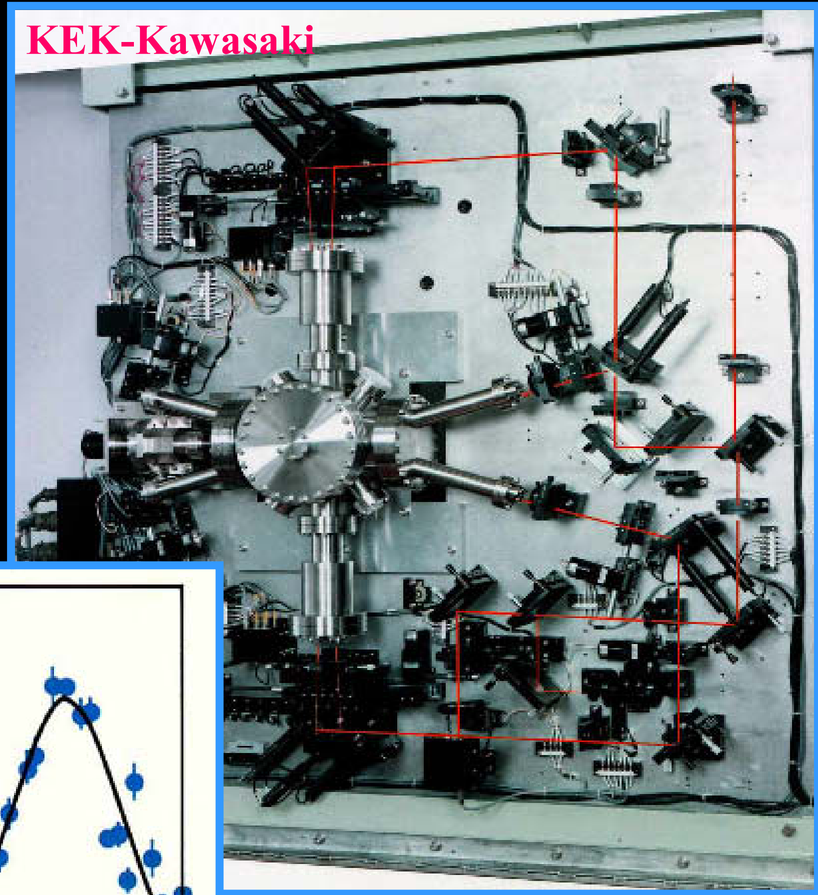


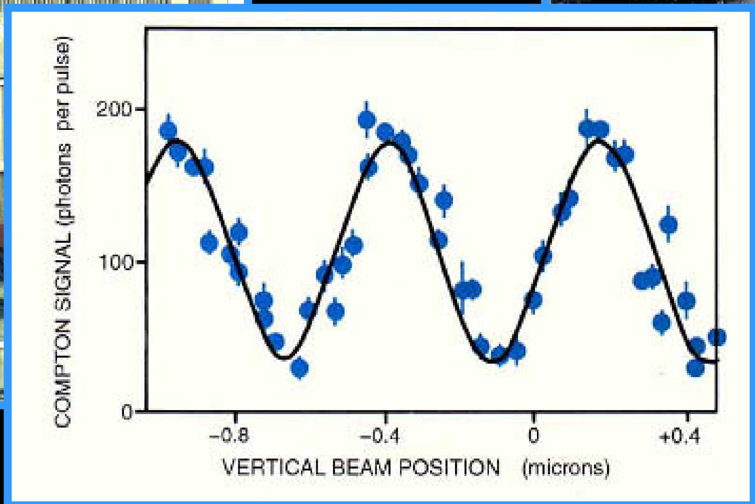
T. Shintake 1990

Experimental Test at FFTB

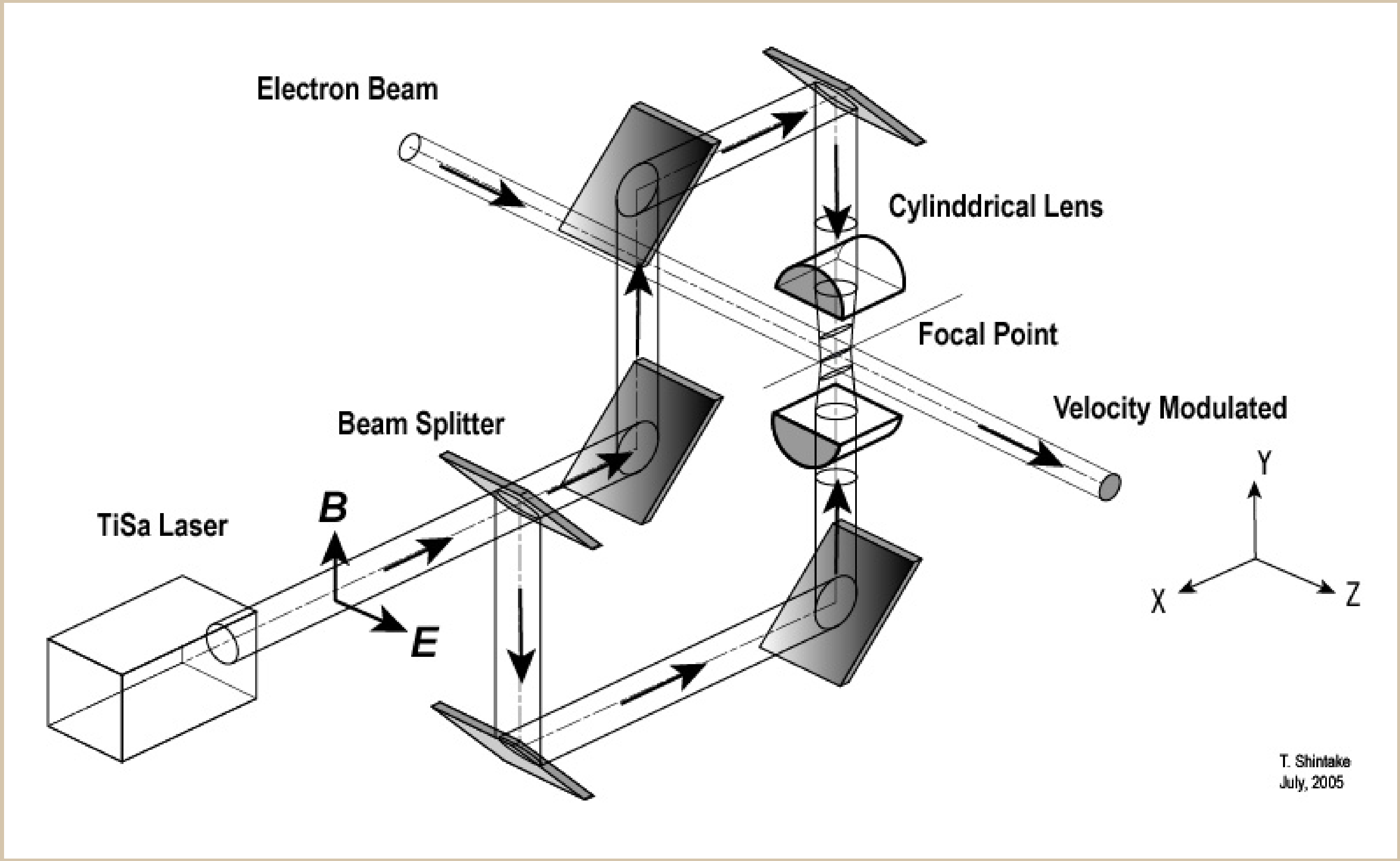
SLAC Two-mile Accelerator & FFTB

Laser Interferometer Table



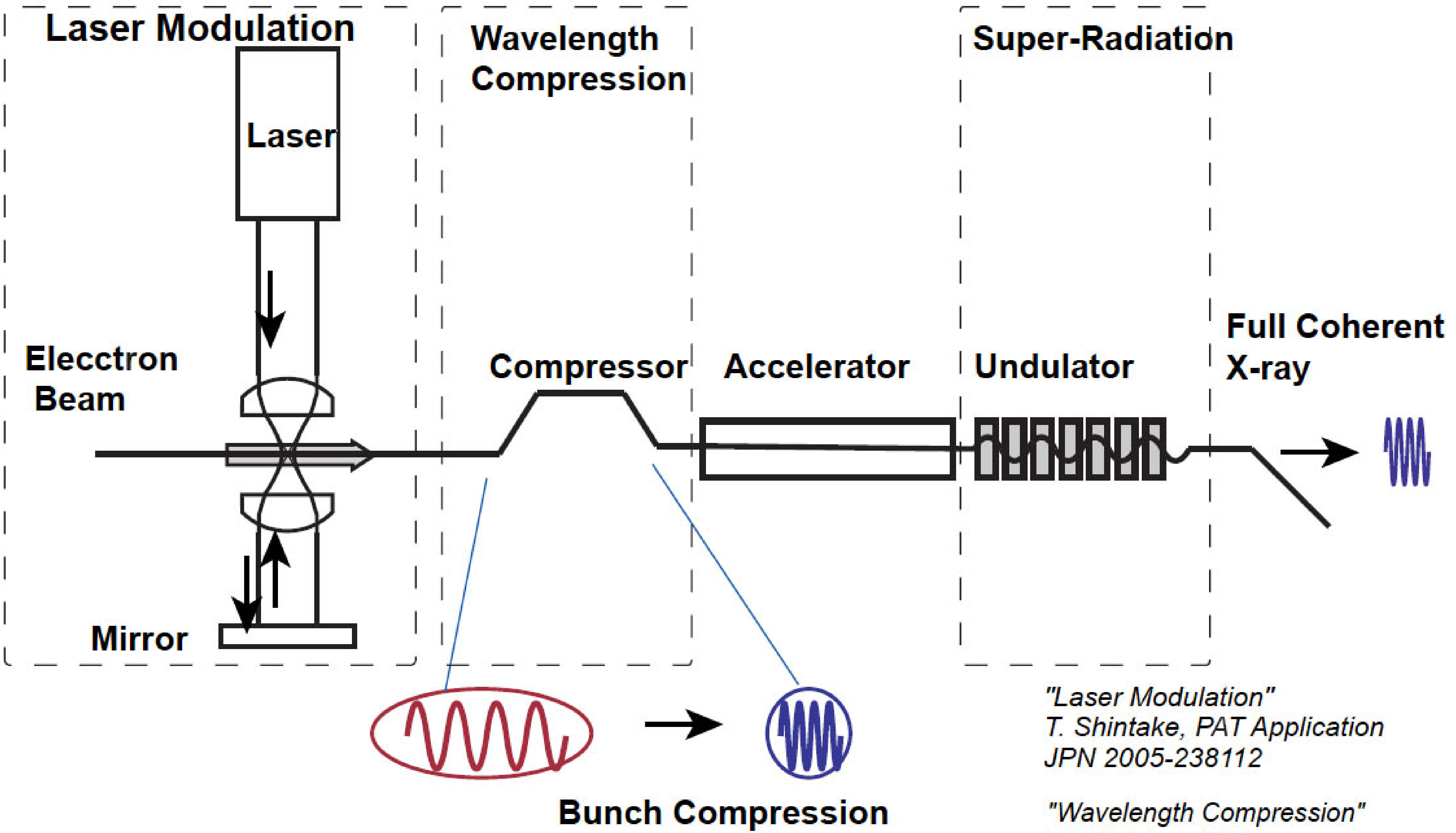


Laser modulation system



Laser Modulation and Wavelength Compression

T. Shintake
2005.08



"Laser Modulation"
T. Shintake, PAT Application
JPN 2005-238112

"Wavelength Compression"
T. Shintake, 1999
KEK AccLab-99-1

Thermal Diffusion Near Cathode

Can we use “Laser induced modulation on the cathode”, as seeder?

- **Thermal kinetic energy.**

$$\left\langle \frac{1}{2} m_e v_z^2 \right\rangle = \frac{1}{2} kT = \text{ 74 meV} \quad \text{..at 1500 deg.C}$$

- **Constant acceleration on E_z. (relativistic energy conservation)**

$$W_k(z) = eE_z \cdot z + W_{th}$$

z : distance from cathode.

W_k(z): kinetic energy at position z.

W_{th}: thermal energy at cathode.

- **Thermal Diffusion (see graph in next page)**
  - **t1 = 45 fsec**
  - **Ct1 = 14 μm**
  - **Z1 = 3.7 nm**

  at 20 MV/m

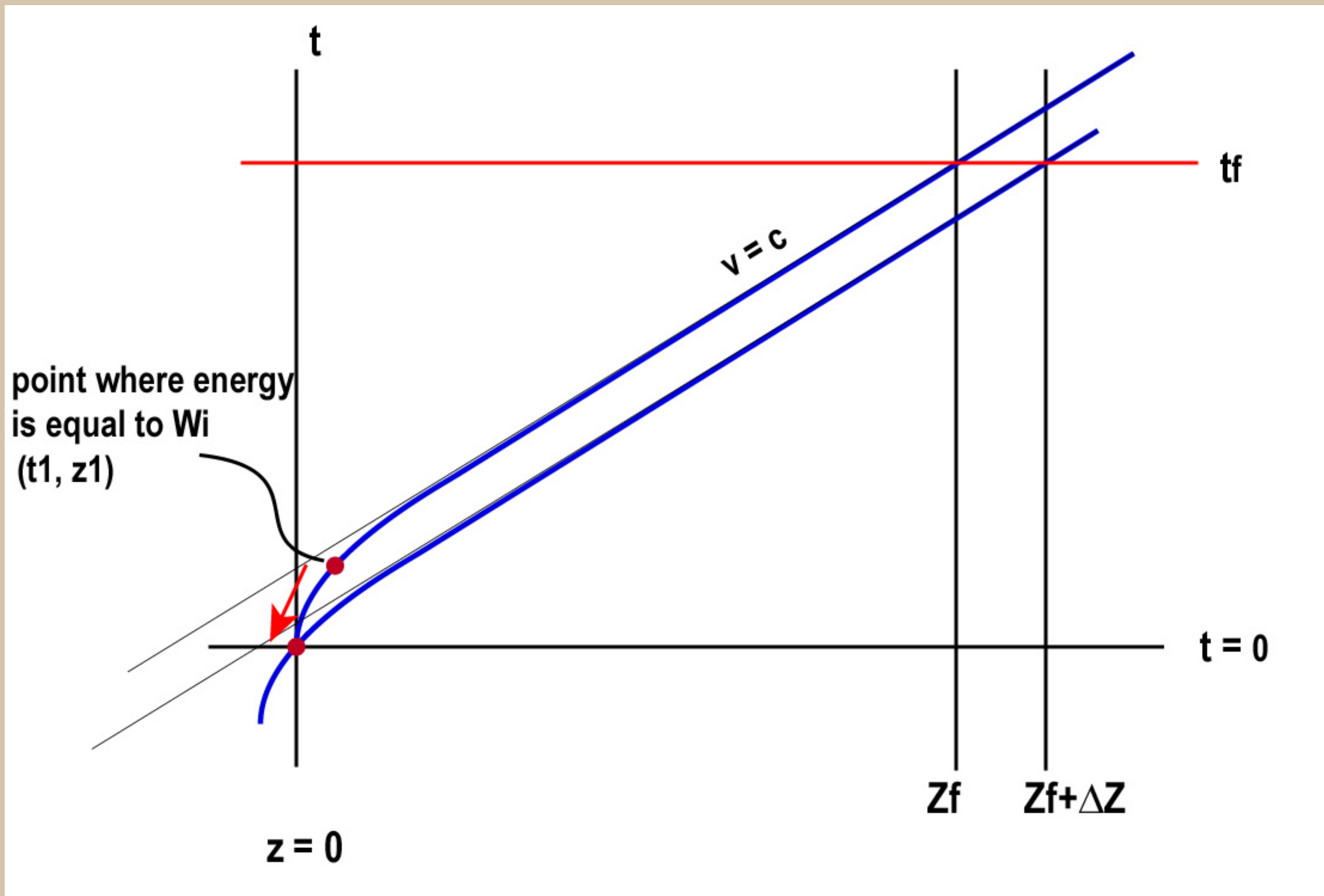
$$\Delta z = ct_1 - z_1$$

$$ct_1 = \frac{m_0 c^2}{eE_z} \sqrt{\frac{2W_i}{m_0 c^2}}, \quad z_1 = \frac{W_i}{E_z}$$

Even if you run your rf-gun at 100 MV/m, the thermal diffusion becomes 3 μm. It is still longer than optical wavelength. Thus, optical modulation, induced by laser field on the cathode, will smear out.

Thermal Diffusion from Cathode

Estimation of position difference for two electrons: zero initial velocity and with thermal velocity.



Thermal diffusion effect dominates near the cathode.

Thermal Diffusion at Relativistic Energy.

- **Thermal Diffusion during acceleration.**
  - **Initial velocity and energy : β_1 , γ_1**
  - **Final velocity and energy : β_2 , γ_2**
  - **Accelerating field : Ez**

$$\Delta z_{th} = \frac{\Delta\gamma}{\gamma'}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

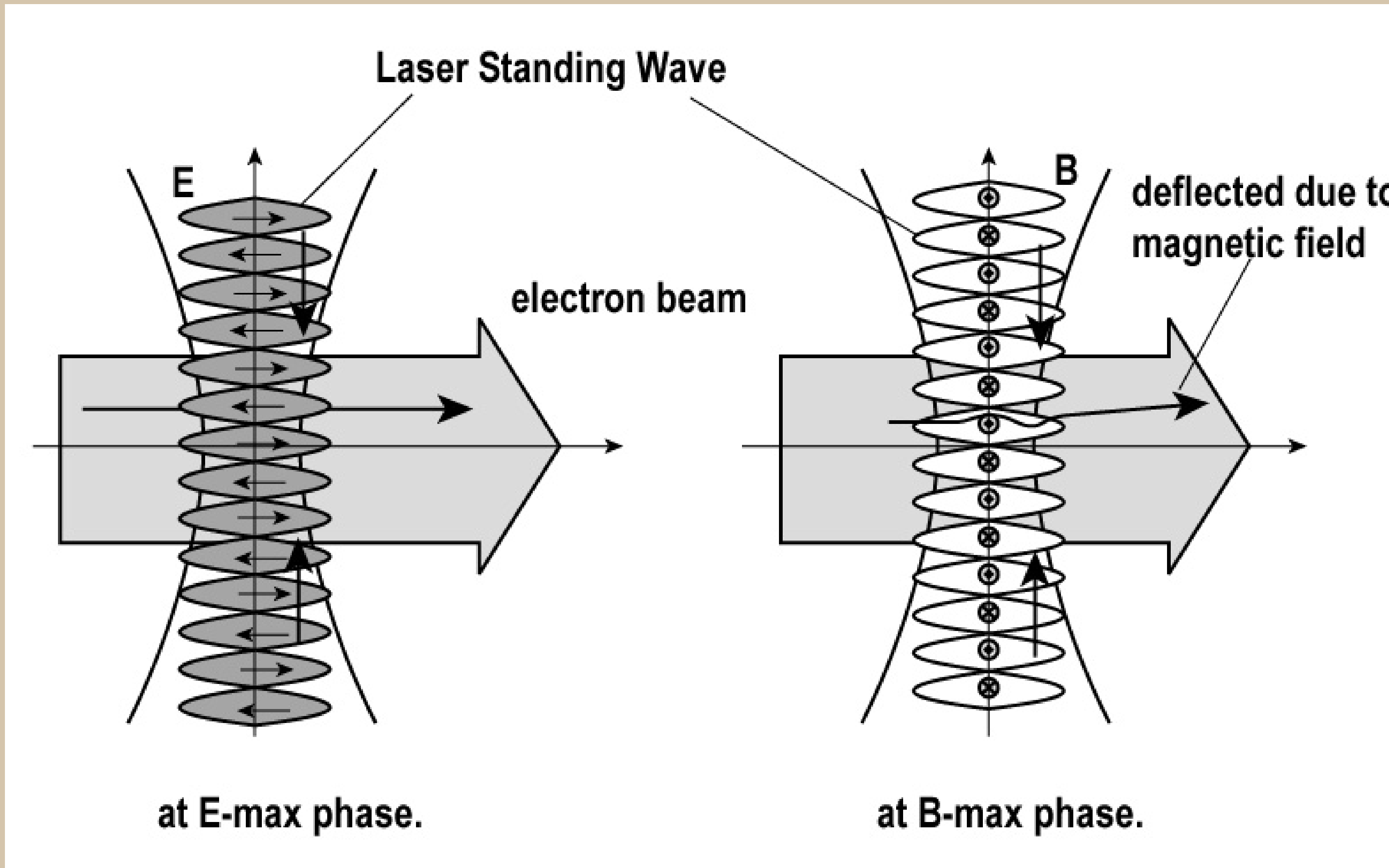
$$\gamma' = eE_z / m_0 c^2$$

- **Criterion to maintain modulation**

$$\Delta z_{th} < \lambda_{\mathrm{mod}} / 4$$

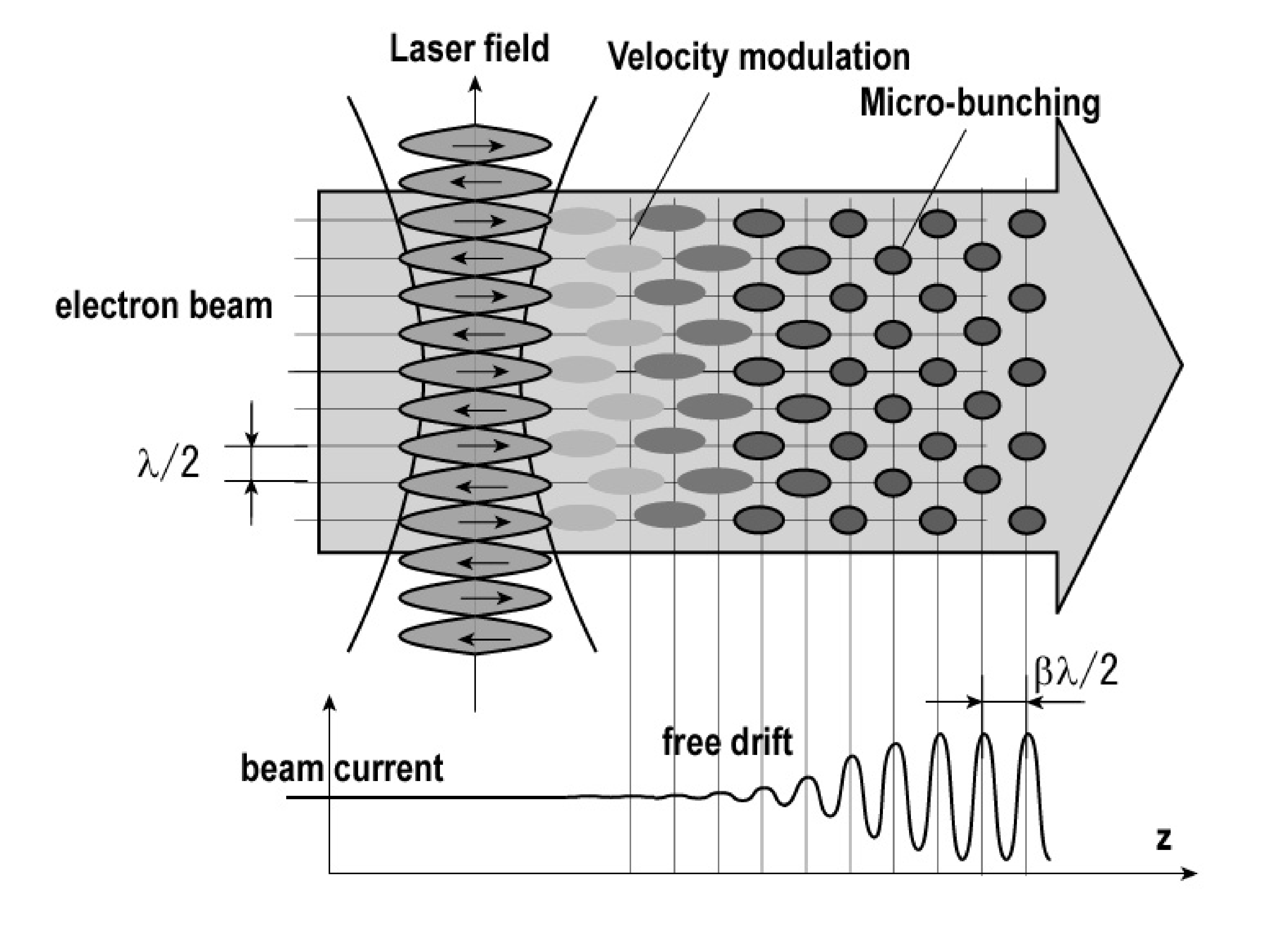
- **Example case.**
  - **λ = 200 nm, T = 1500 C, kT/2 = 74 meV, final energy 8 GeV**
  - **Acceleration 20 MV/m**
  - **Required minimum energy: 4.4 keV, this is quite low (0.2 mm from cathode)**
  - **If you located laser modulator after this energy, the modulation will kept up to very high energy.**

Standing laser field modulates beam energy.

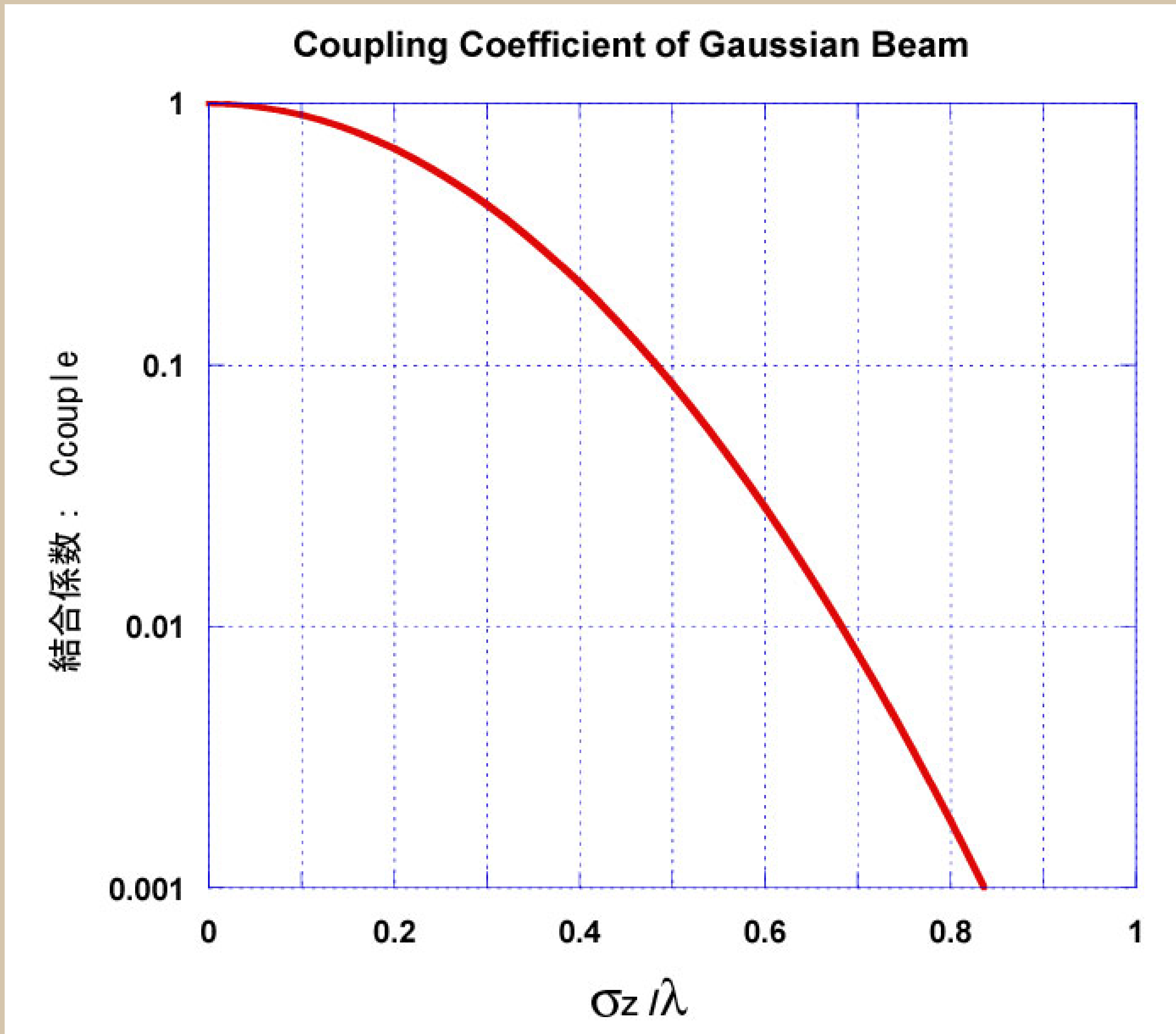


Use longitudinal electric field as energy modulator.

Creation of density modulation



Field coupling constant.

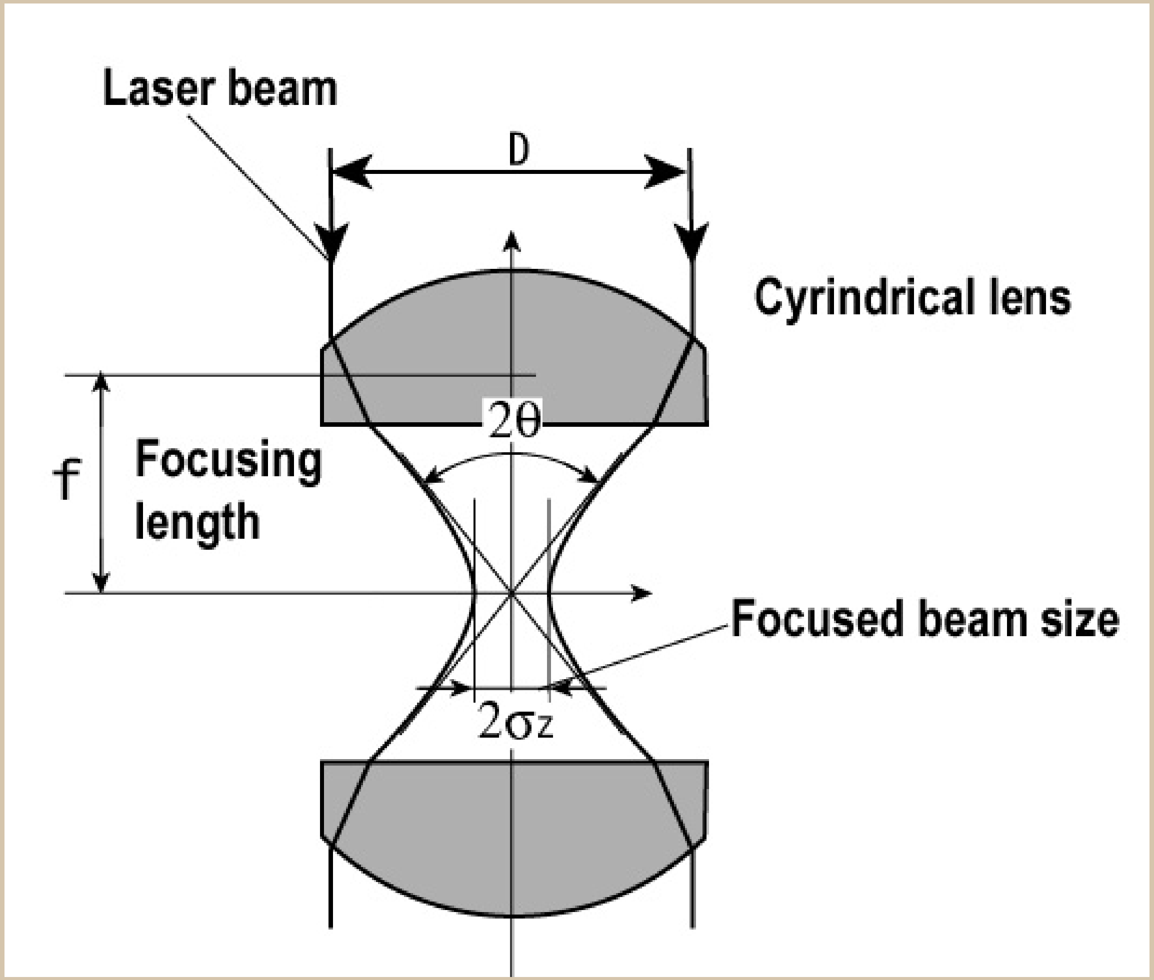


If the laser spot size is large, the laser field coupling becomes small, due to transit-time constant lowered.

Need, small laser spot size.

$$\sigma_z / \lambda < 0.5$$

High numerical aperture. NA~1



$$\sigma_z = \frac{\lambda}{\pi\theta}$$

$$NA = n \cdot \sin\theta$$

$$F = \frac{f}{D} \approx \frac{1}{2NA}$$

High NA > 0.5 is commercially available.

Example beam parameter

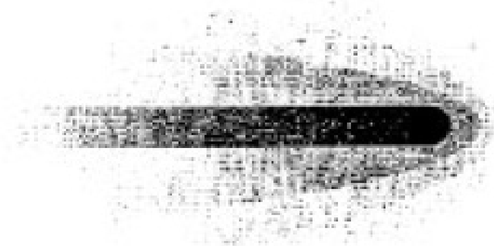
YAG-Laser 2nd			
wavelength	λ	532	nm
Output power		100 kW x 100 nsec	10 mJ
Focusing		Cylindrical lens	
Focusing length	f	5	mm
Numerical aperture	NA	0.6	
Matched laser beam size	$\sigma \sim 0.5D$	3	mm
Focused spot size	σ_{z0}	266	nm
Transverse width	σ_{x0}	3	mm
Field intensity	E_{z0}	170	MV/m
Modulation			
Modulation period	λ_{mod}	266	nm
Coupling Constant	C_{couple}	0.1	
Modulation Energy		16	eV

Talk at KEK, March 1999

Original Idea 1990

Wavelength Compression

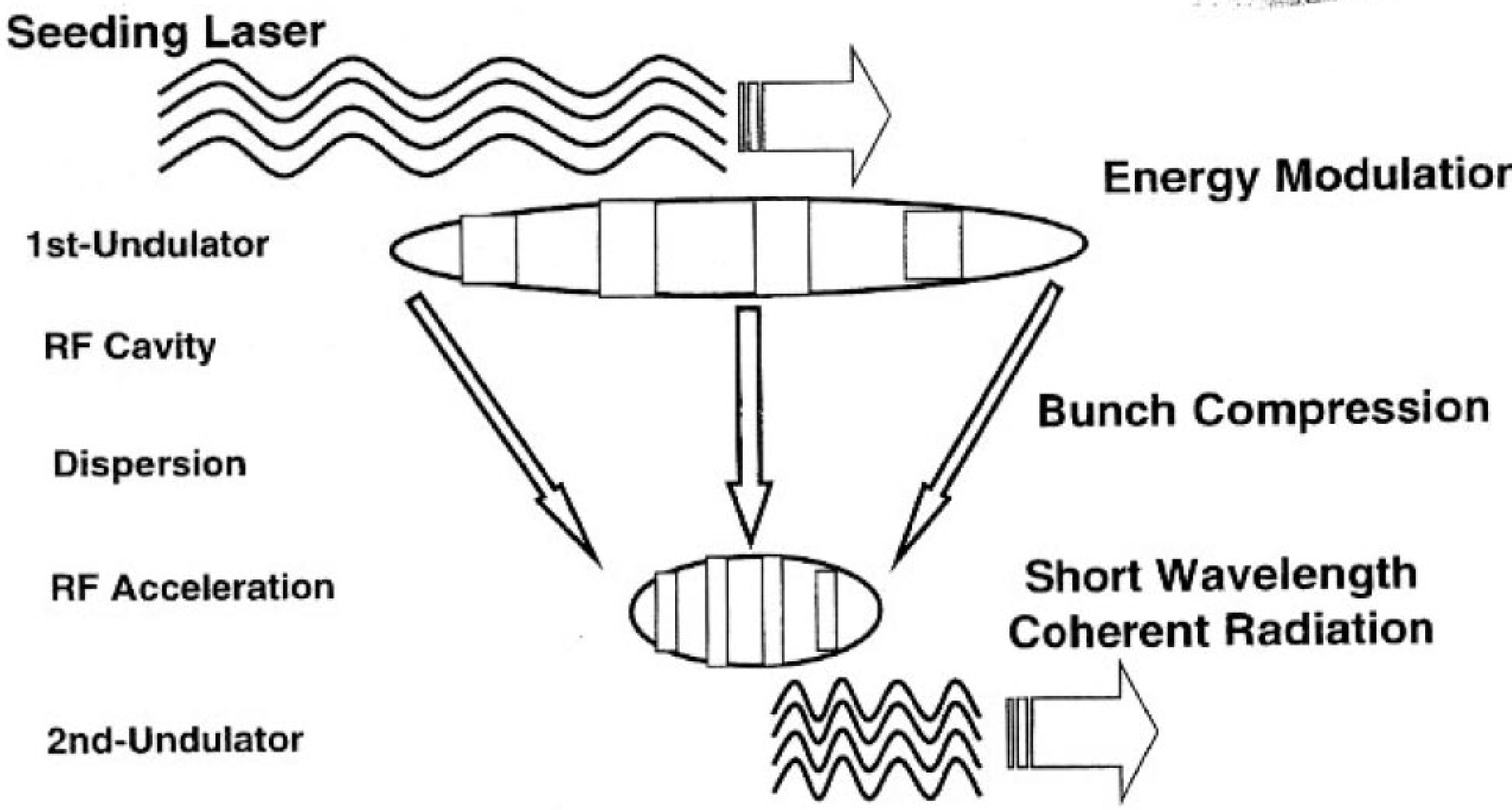
on Compressing Electron Bunch



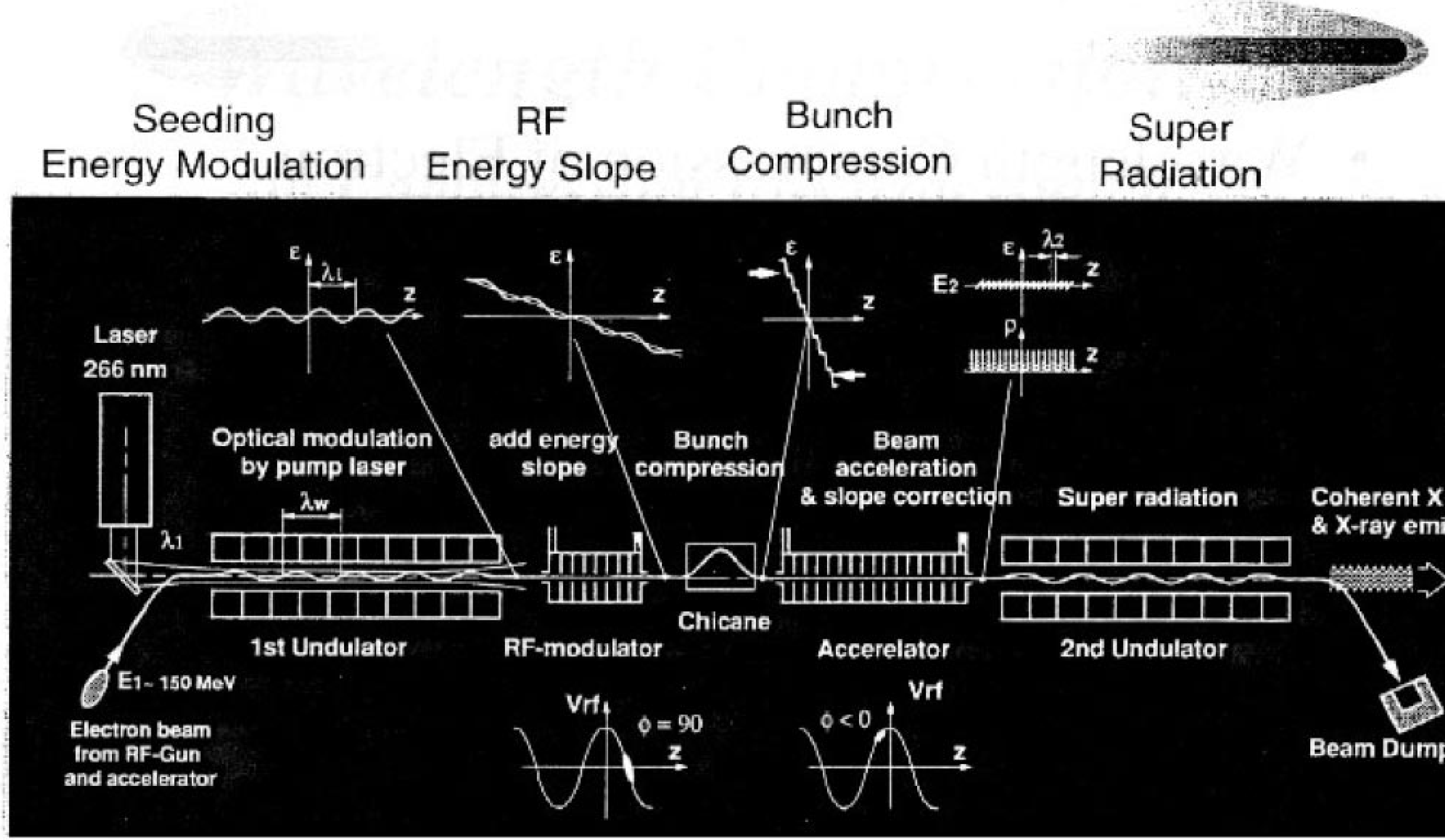
T. Shintake

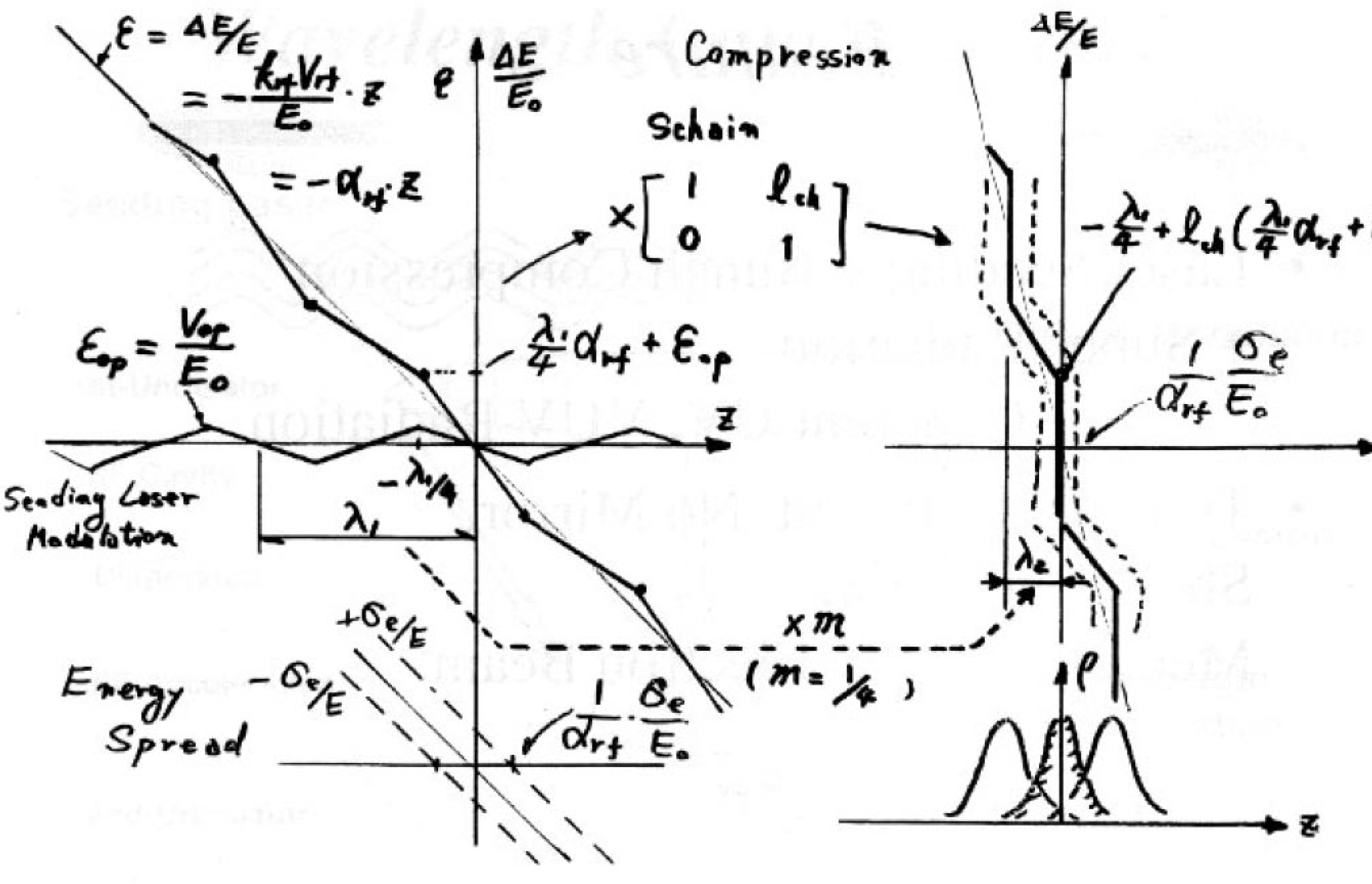
KEK : High Energy Accelerator Research Organization

Wavelength Compression?



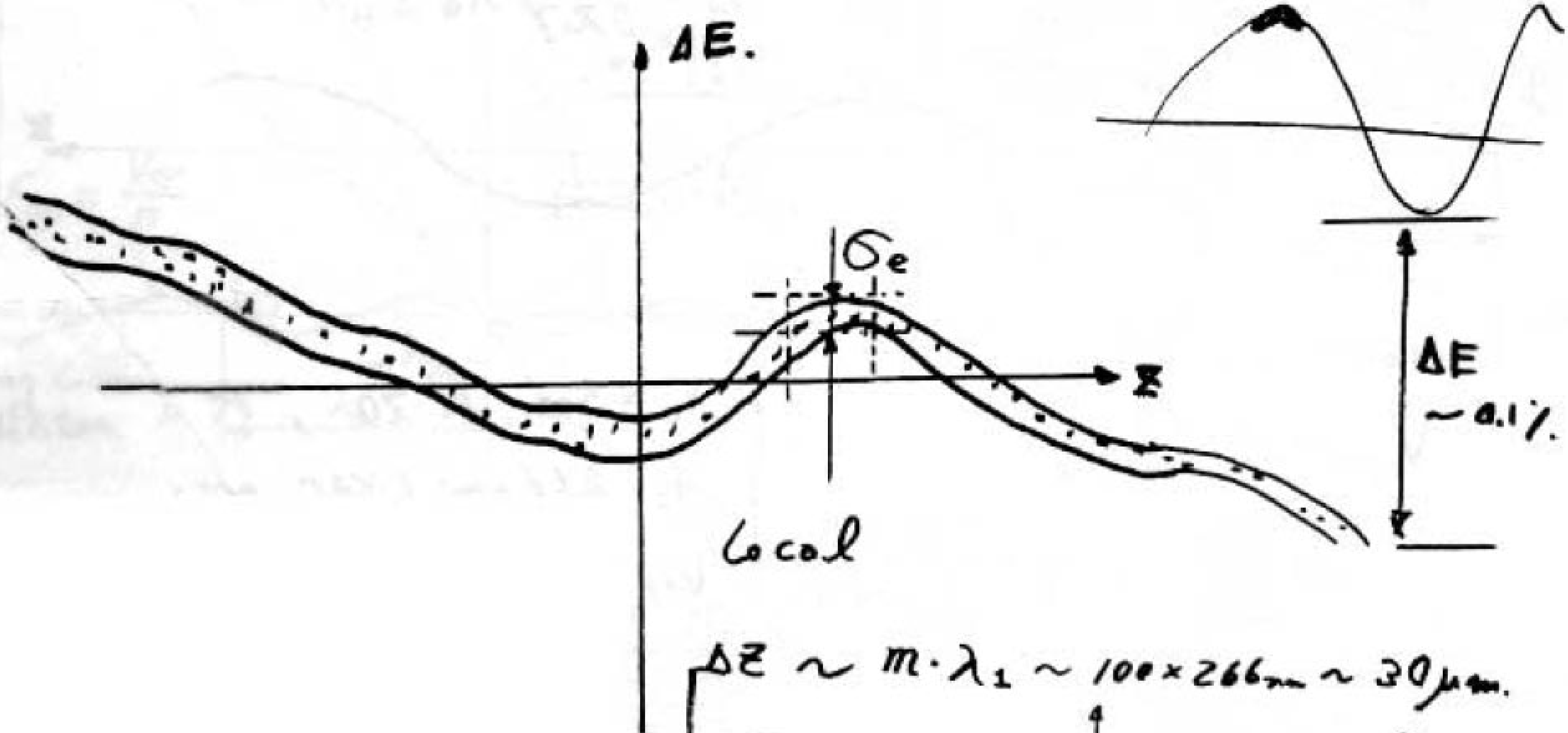
System Diagram




ε = ΔE/E
= − k_rf V_rf / E_0 · z
= − α_rf · z
ρ
ΔE / E_0
Compression
Schain
× [1 l_ch; 0 1]
− λ_1/4 + l_ch (λ_1/4 α_rf +
ΔE/E
λ_1/4 α_rf + ε_op
ε_op = V_op / E_0
1/α_rf σ_e/E_0
z
−λ_1/4
Seeding Laser Modulation
λ_1
λ_e/π
× m
(m = 1/4)
+σ_e/E
−σ_e/E
Energy Spread
1/α_rf σ_e/E_0
ρ
z

Micro-Energy Spread

$\sigma_e/E \sim 10^{-7}$ or $\sigma_e \sim 10\,eV$

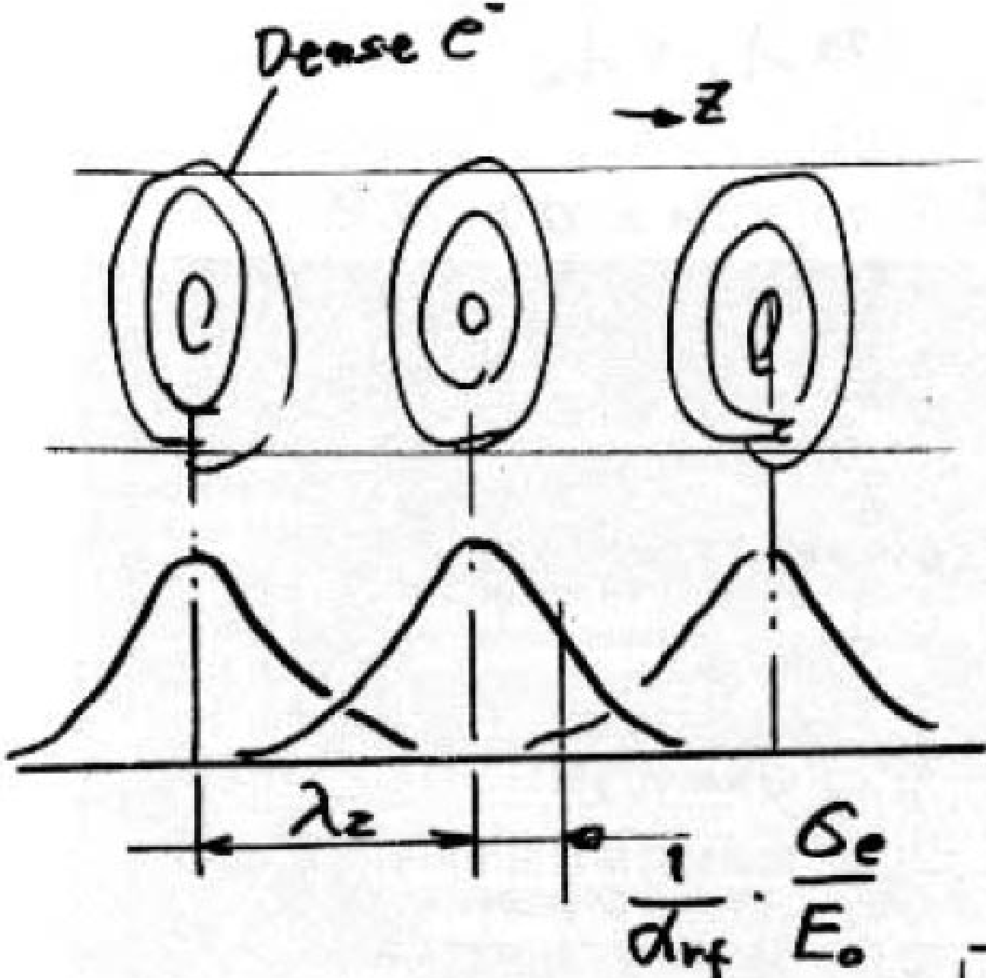


$\Delta z \sim m \cdot \lambda_1 \sim 100 \times 266nm \sim 30\mu m.$

$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{m} \sim 1\%.$

⇕ 1 mm bunch

Electron Energy Spread.



Limit

$$\sigma_e \leq \pi \cdot \frac{\lambda_z}{\lambda_{rf}} \cdot V_{rf}$$

or

$$\lambda_z > \frac{\lambda_{rf}}{\pi} \cdot \frac{\sigma_e}{V_{rf}}.$$

Example. $V_{rf} \sim 100\,MV$
$\lambda_{rf} \sim 50\,mm$

at 150 MeV

λ_z (nm)	100	50	10	
σ_e (eV)	600	300	60	3
σ_e/E	4×10^{-6}	2×10^{-6}	4×10^{-7}	2

Micro-Energy Spread Limits Shortest Wavelength

- Longitudinal spread of modulation pattern after compression due to thermal energy spread.

$$\sigma_z^* = \frac{\lambda_{rf}}{2\pi} \frac{\sigma_e}{V_{rf}} < \frac{\lambda_x}{4}$$

- Required rf voltage.

$$V_{rf} > \frac{2}{\pi} \frac{\lambda_{rf}}{\lambda_x} \sigma_e$$

$\lambda_{rf} =$ 50 mm. C-band

$\lambda_x =$ 0.1 mm. X-ray

$\sigma_e =$ 0.1 eV, thermal energy spread

$$V_{rf} > 50 \text{ MV}$$

- This is quite easy value.

Can we generate coherent X-ray at 0.1nm ?

- Need 1000 times compression.

  200 nm laser → 100 nm modulation → 1/1000 → 0.1 nm

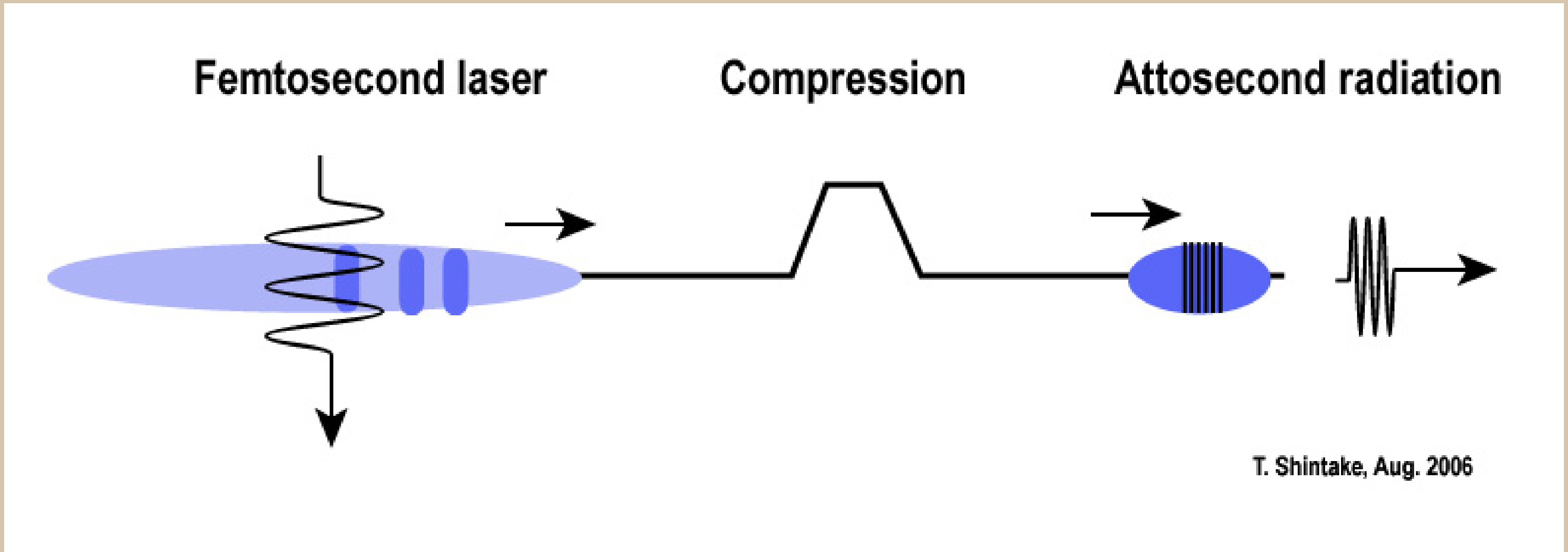
- In SCSS test accelerator, already x 800 compression has been achieved (cathode 1 A → undulator 800 A)

- 1/10 times velocity compression
- 1/100 times chicane magnetic compression (x20 at BC1, X 5 at BC2)
- Modulation depth of 1 % is good enough to seed FEL.
  - Wake field, CSR, SR, non-linear will break modulation, but, if 1 % remains, still OK.

Generation of Attosecond(10^{-18}) X-ray

- Femotosecond TiSa Laser for optical modulation

  100 femtosecond → 1/1000 times compression
  → **100 attosecond radiation**



Conclusion

- Focal point field modulates electron energy at optical wavelength.
- Thermal diffusion looks no problem. OK.
- High compression ratio will request stable power supply for rf-system.
- Seeding to X-ray FEL will be possible.

- Need beam test at VUV. SCSS test accelerator.