The Vast Light Source

~ Building the world's most powerful lasers ~

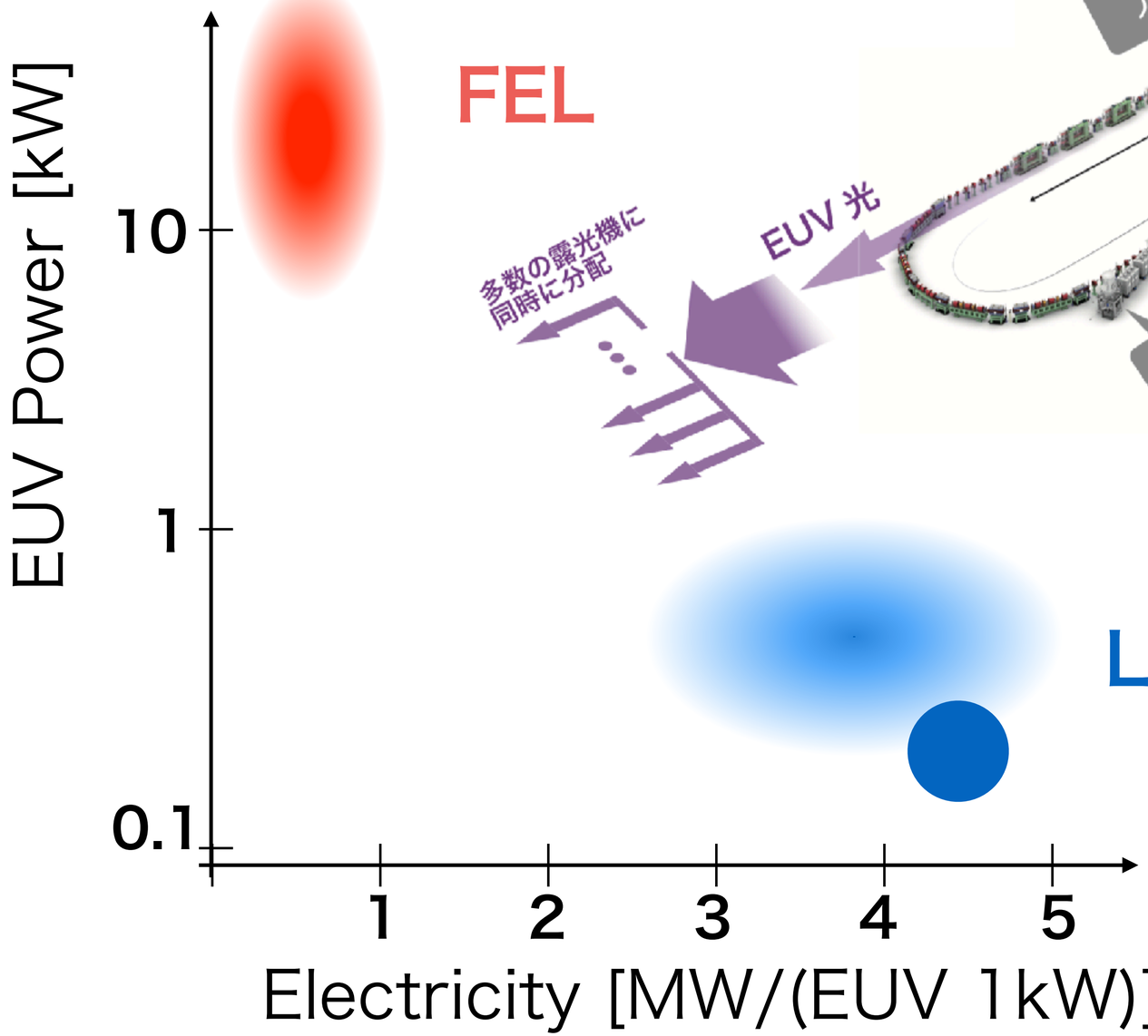
This series started since 8th workshop (2024)

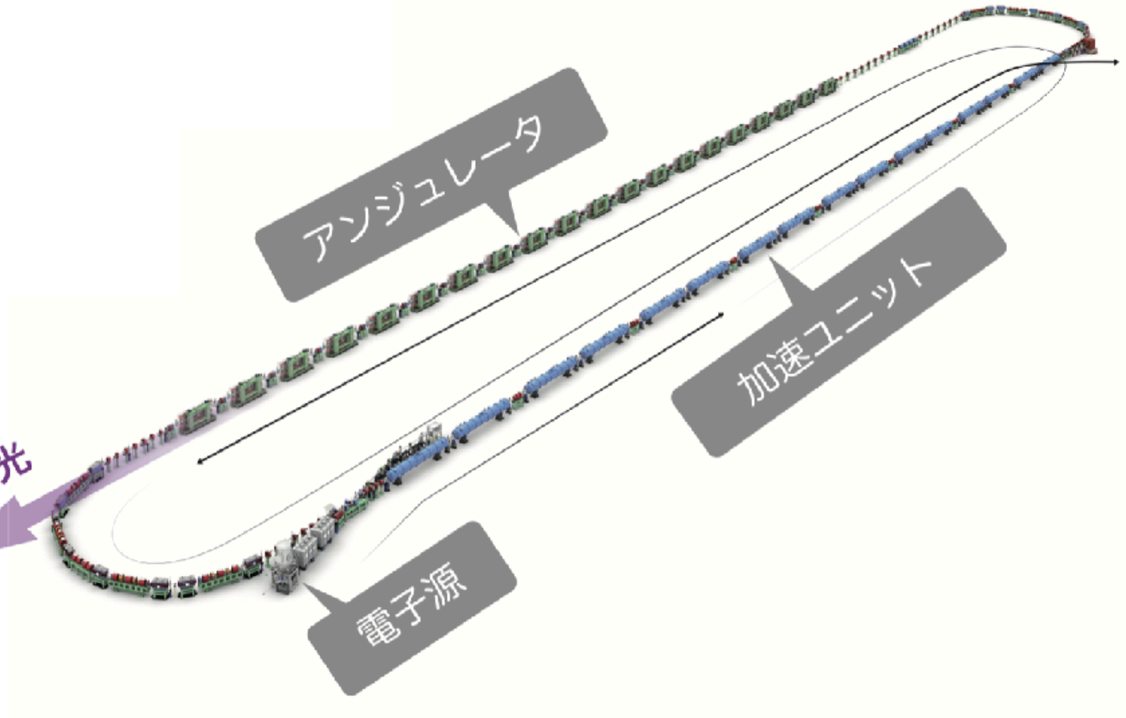
- 2024:「The Last Light Source」 (Erik Hosler)
- 2025:「The Must Light Source」(Y. Honda)
- 2026:「The Vast Light Source」
- 2027:「(The Lost Light Source ?)」

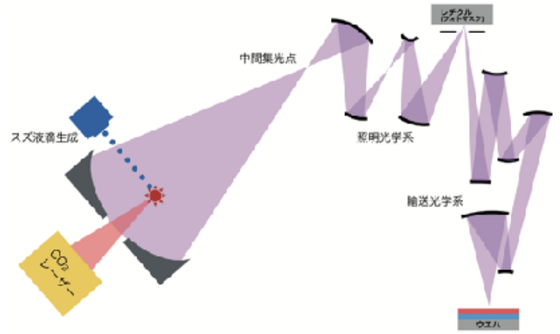
EUV-FEL WORKSHOP 2026
2026.1.28, Akihabara
Yosuke Honda (KEK)

✳ This work is supported by JST K-program Japan Grant Number JPMJKP24M2

Target of EUV-FEL







Contents

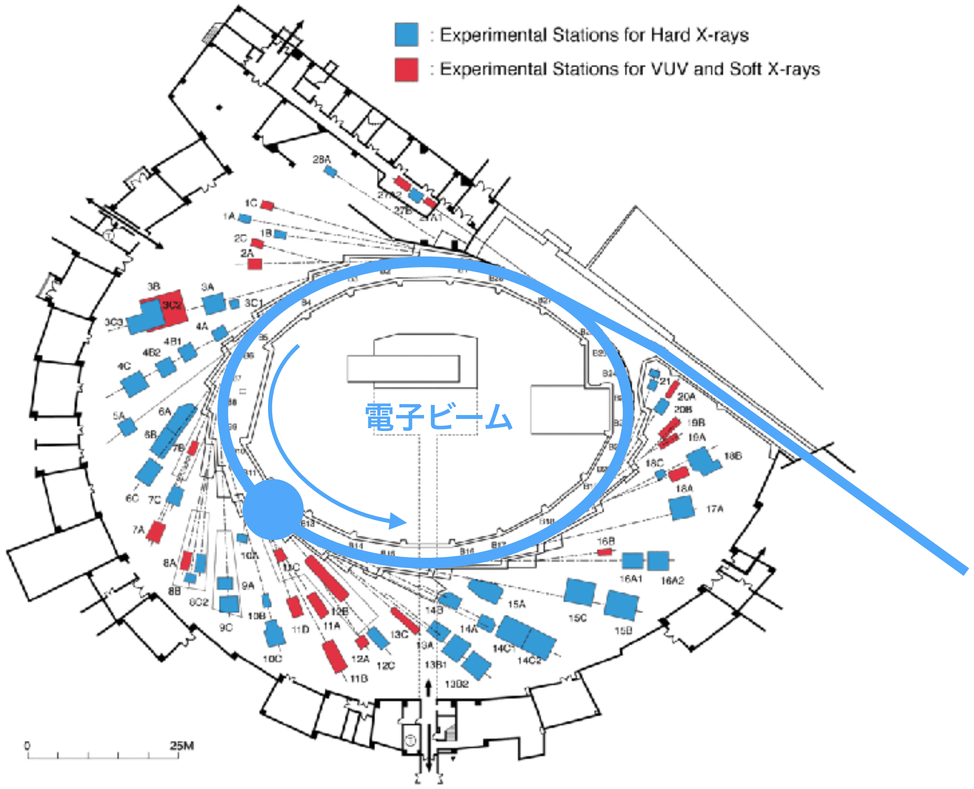
- Reviewing the Accelerator
  - Principle and necessity of FEL
  - Principle and necessity of ERL
  - Electron beam handling
- Development plan in KEK
- Summary

Contents

- Reviewing the Accelerator
  - **Principle and necessity of FEL**
  - Principle and necessity of ERL
  - Electron beam handling
- Development plan in KEK
- Summary

Synchrotron radiation light source

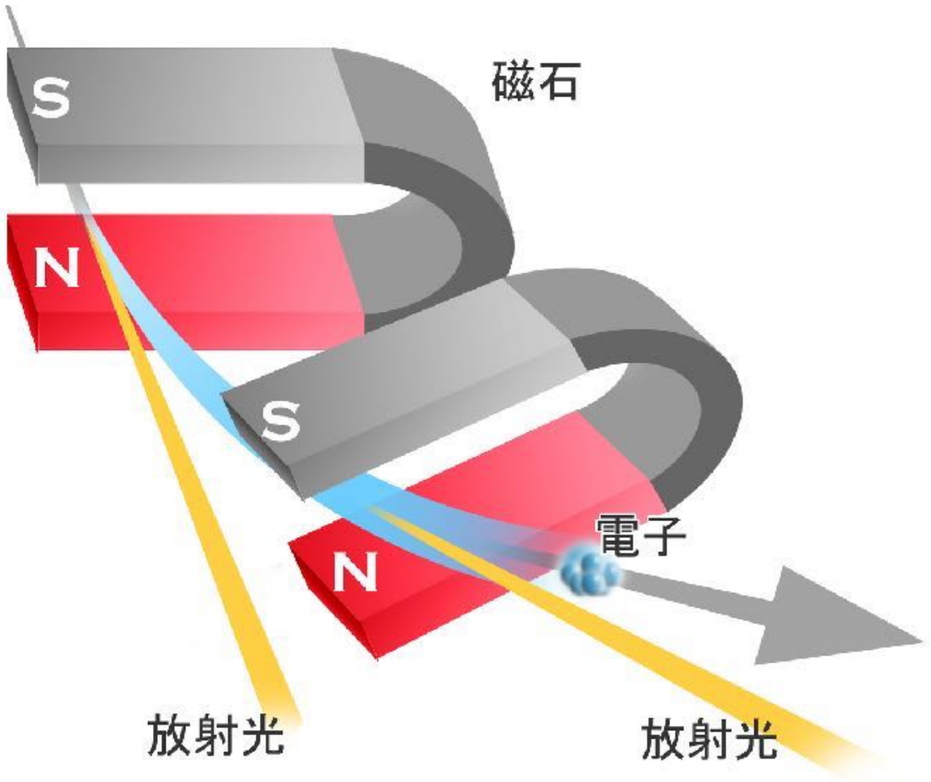
- The most established accelerator-based light source

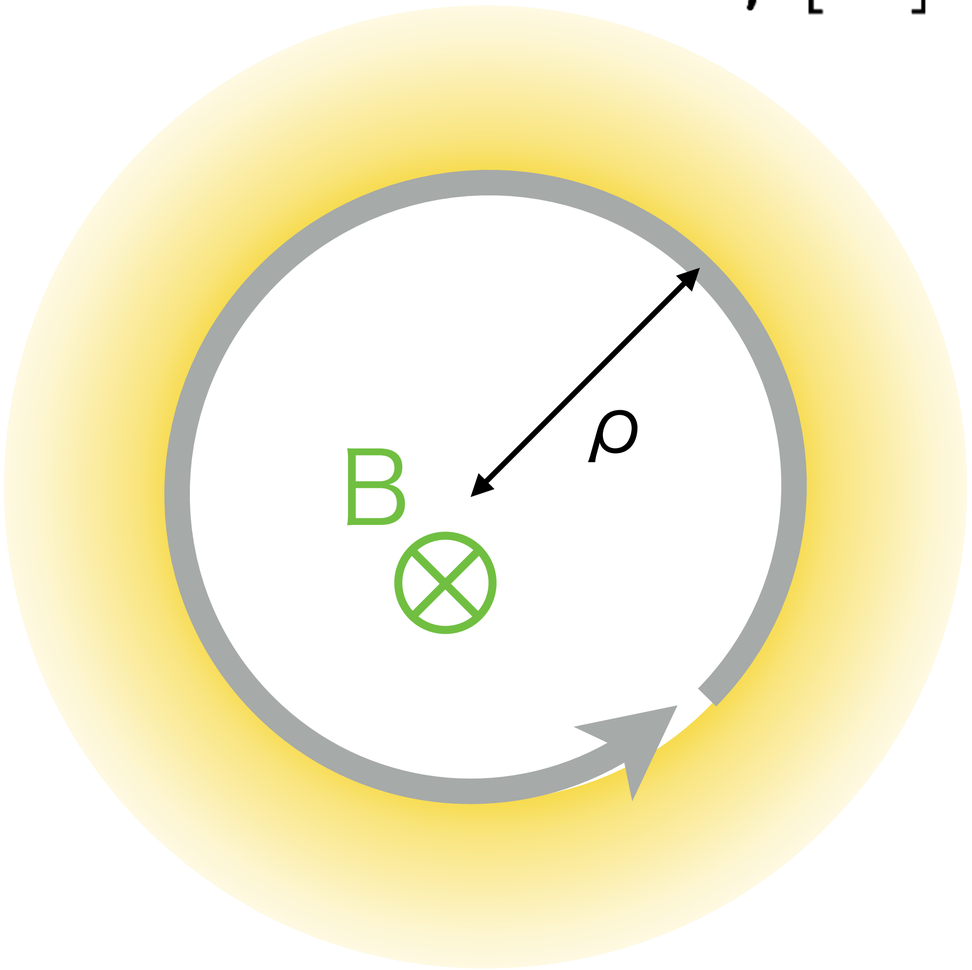


Principle of Synchrotron radiation

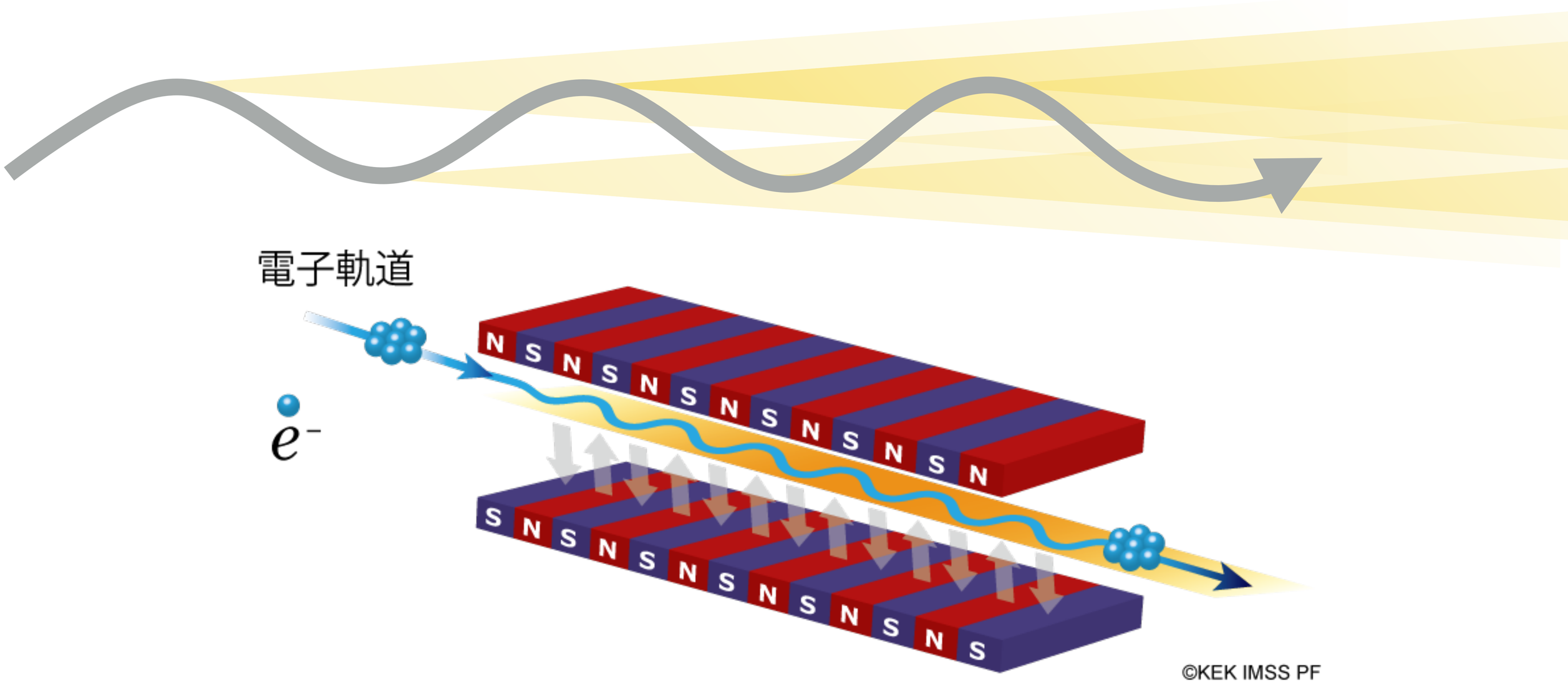
Radiation energy loss in one-turn:

$$U_0[\mathrm{keV}] = 88.5 \times \frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{m}]}$$





Undulator

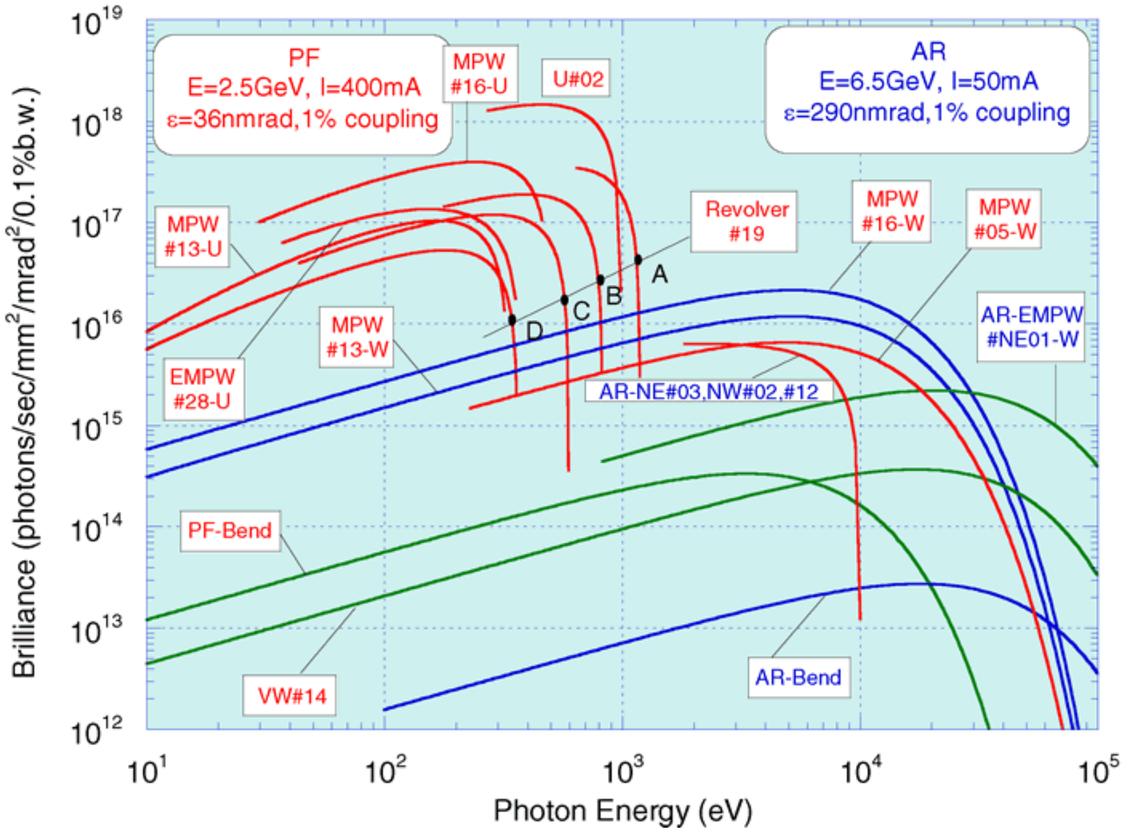


Spectrum

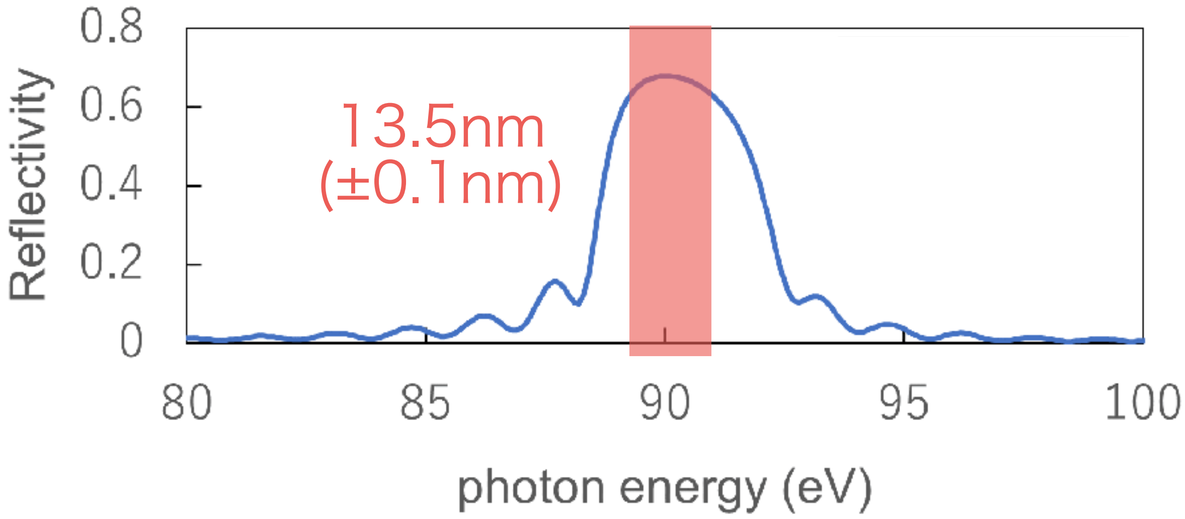
Critical energy
of the radiation spectrum:

$$\epsilon_c[\mathrm{keV}] = 2217 \times \frac{E^3[\mathrm{GeV}^3]}{\rho[\mathrm{m}]}$$

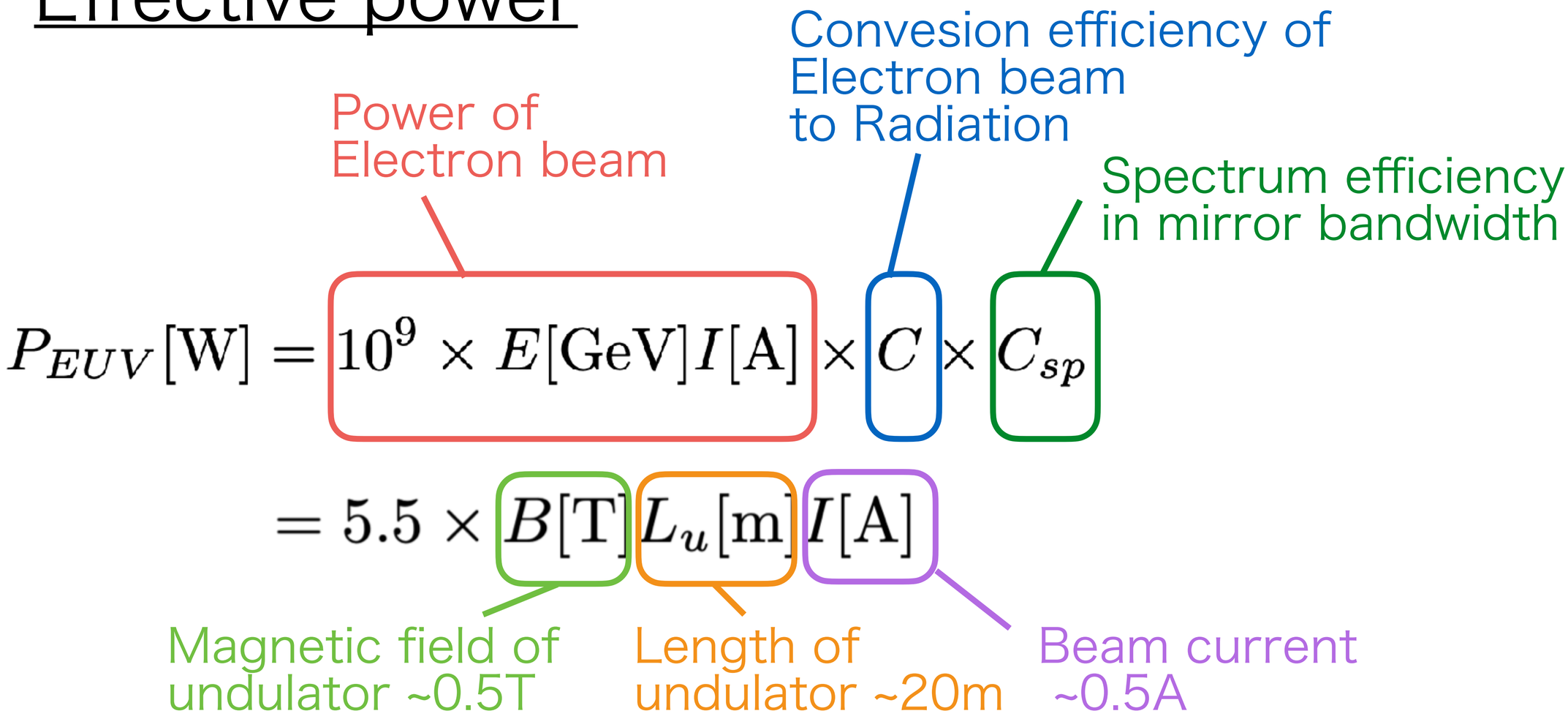
Broad spectrum
(up to the critical energy)



Bandwidth of Mo/Si mirror



Effective power



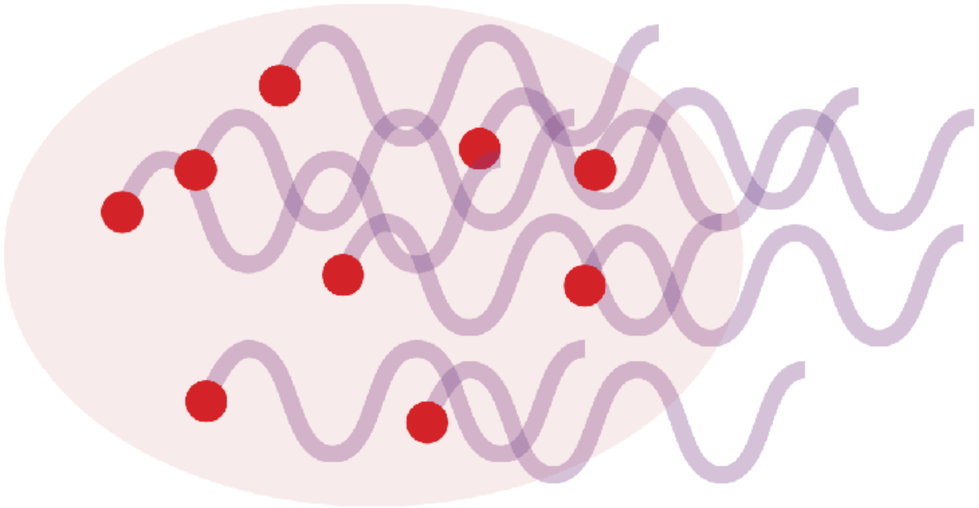
- Possible EUV power: ~30W

→ **Incoherent radiation is Not enough for EUVL**

Coherent radiation

Incoherent radiation

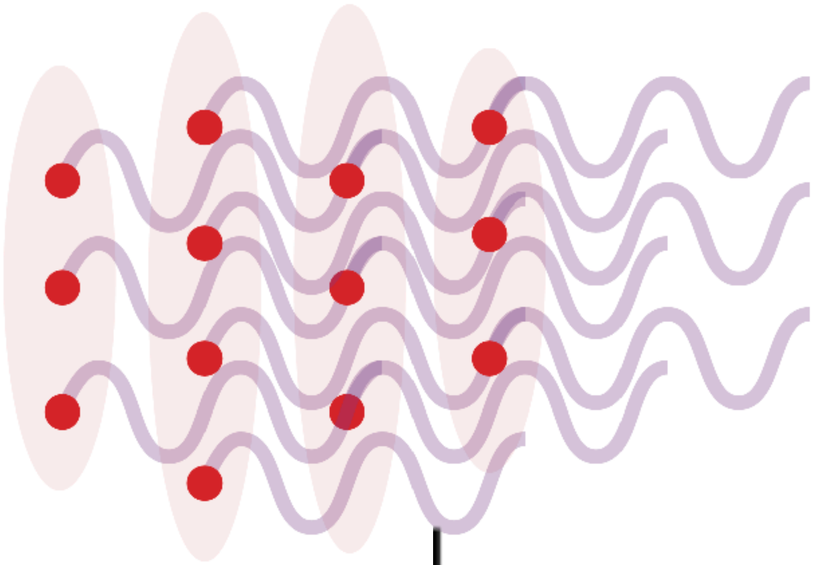
- Conventional undulator radiation



$$\sum |A|^2$$

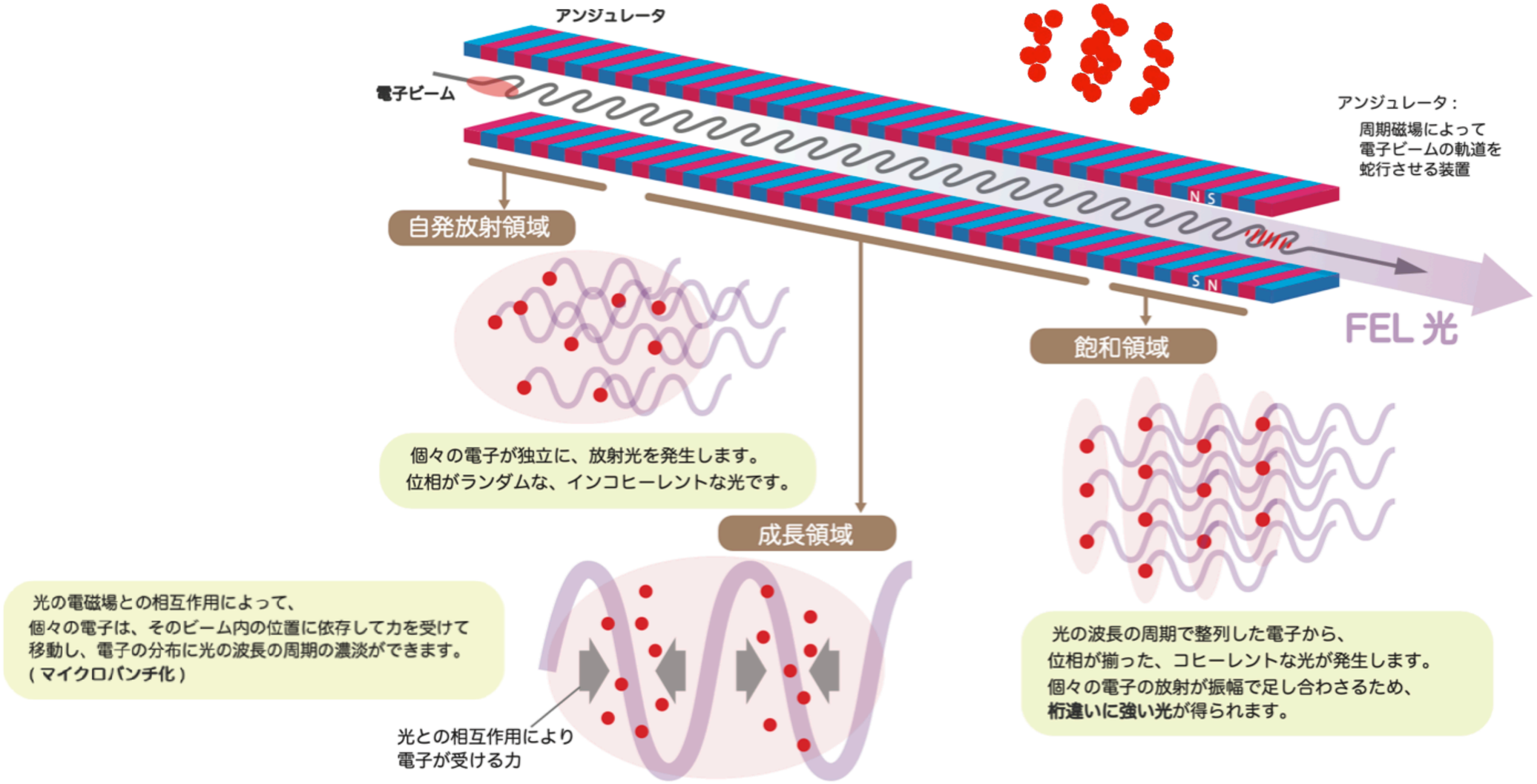
Coherent radiation

- Radiation from micro-structured beam



$$\left|\sum A\right|^2$$

Free-Electron Laser



Electron-Radiation interaction in undulator

Period of undulator

Strength of undulator

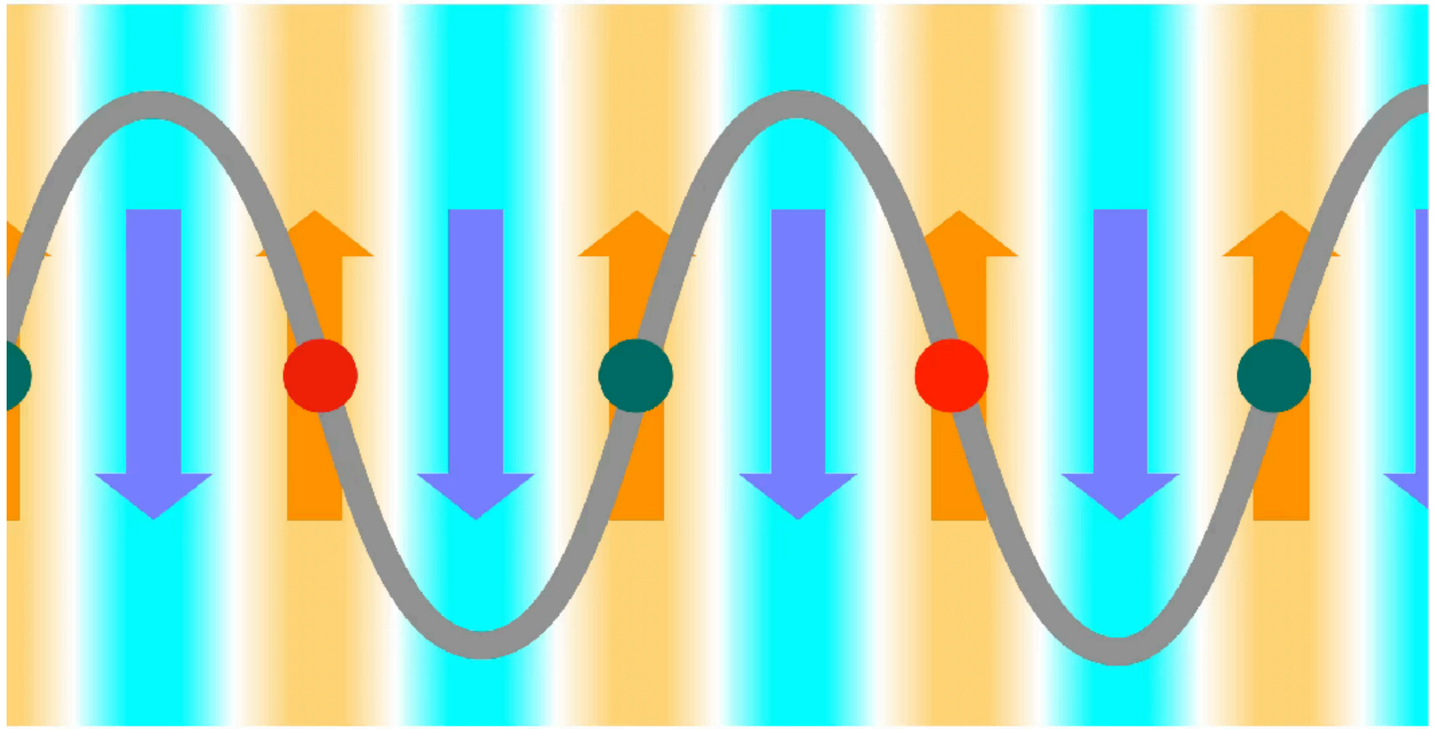
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + a_w^2)$$

Radiation wavelength

Beam energy

λ =13.5nm

Beam energy
~1GeV



Universal scaling

FEL parameter : $$\rho = \frac{1}{\gamma_r}\left(\frac{a_w}{4}\frac{\omega_p}{ck_w}\right)^{2/3}$$

- All the machine-dependent physical parameters can be normalized using ρ.

$$k_w = 2\pi/\lambda_u$$ ←Period of undulator

Undulator stength: $$a_w = \frac{e\lambda_u B_w}{2\pi m_e c}$$ ←magnetic field

plasma freq.: $$\omega_p = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}$$ ←electron density

Time and distance scaling:

$$\bar{t} = 2k_w \rho t$$ ←time

$$\bar{z} = 2k_w \rho z$$ ←distance in undulator

Radiation amplitude: $$a = \frac{e\lambda E}{2\pi m_e c^2}$$ ←electric field

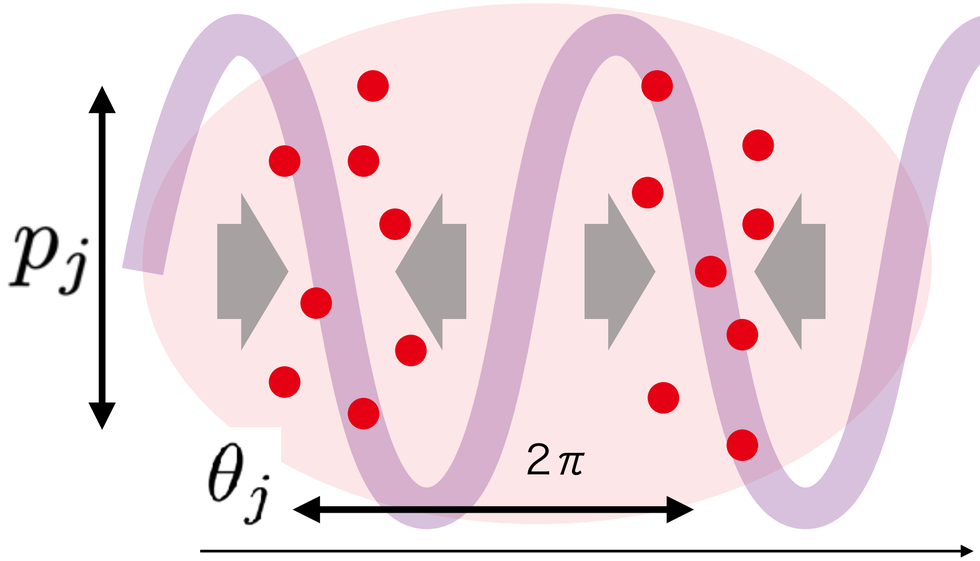
$$A = \frac{\omega}{\omega_p \sqrt{\rho\gamma_r}} a$$

Momentum scaling:

$$p_j = \frac{1}{\rho}\frac{\gamma_j - \gamma_r}{\gamma_r}$$

Equations of motion

- Describe motion of each electron in the phase-space (rest frame of the beam).



position of j-th electron

$$\frac{d\theta_j}{d\bar{z}} = p_j$$

momentum of j-th electron

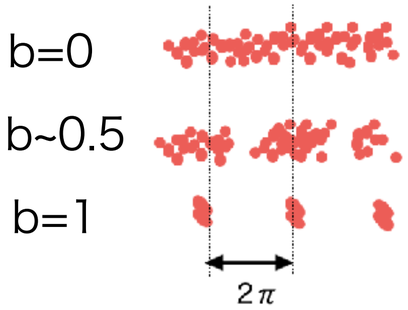
$$\frac{dp_j}{d\bar{z}} = -(A\exp(i\theta_j) + A^*\exp(-i\theta_j))$$

amplitude of radiation

$$\frac{dA}{d\bar{z}} = \langle\exp(-i\theta)\rangle + i\delta A$$

Bunching factor

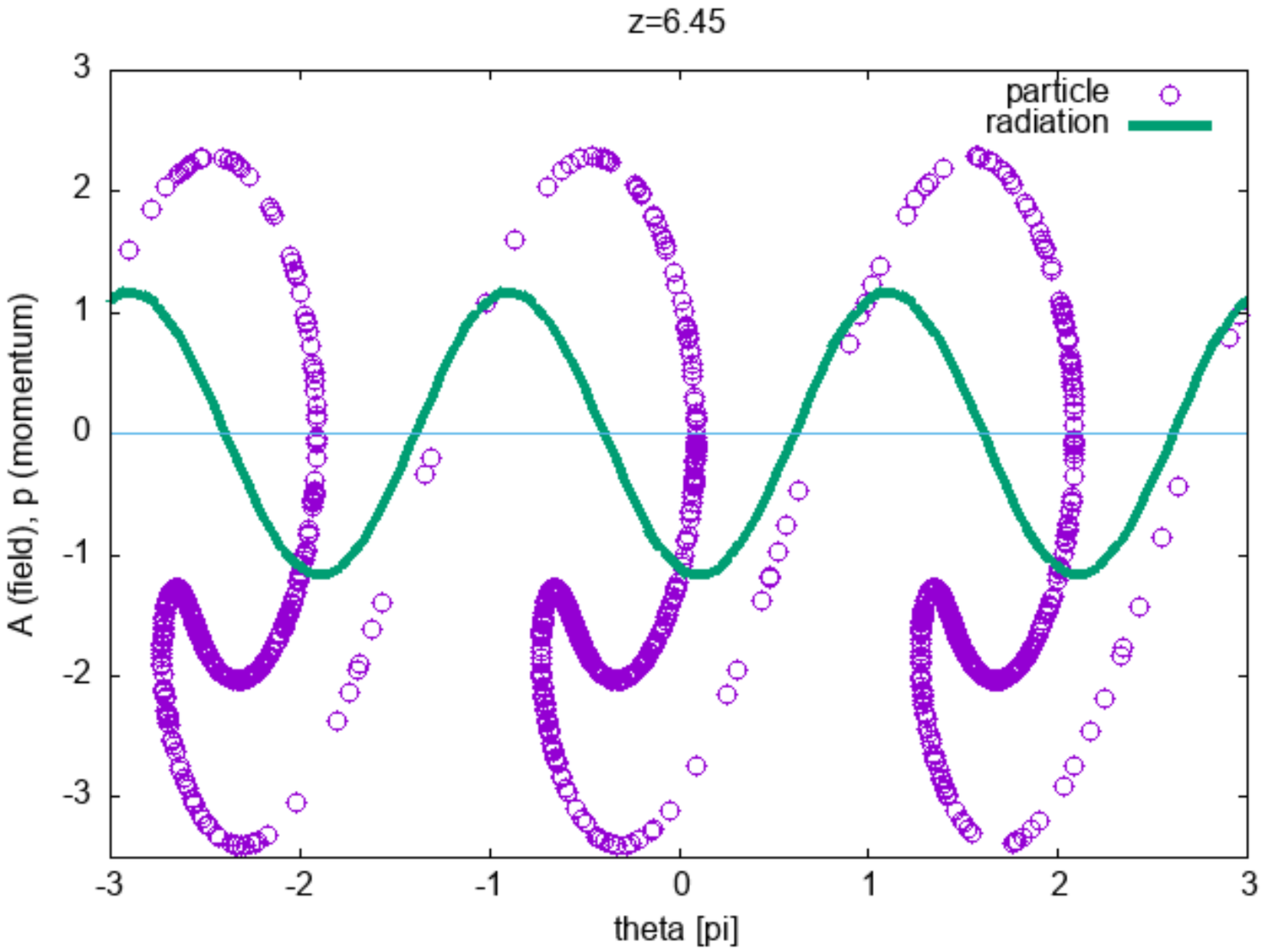
$$b \equiv \langle\exp(-i\theta)\rangle \equiv \frac{1}{N}\sum_{j=1}^{N}\exp(-i\theta_j)$$



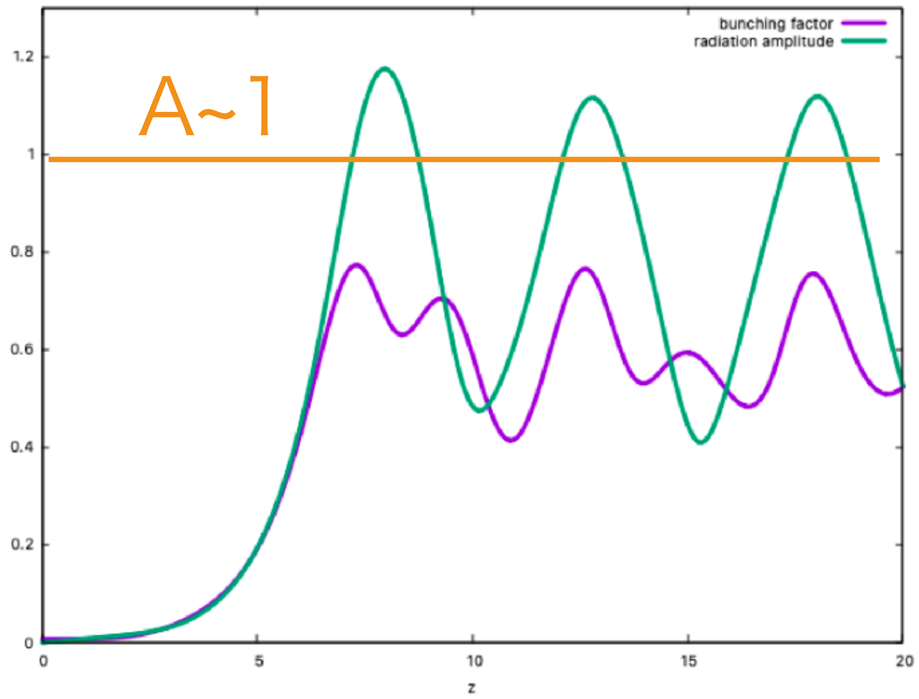
Detuning

$$\delta = \frac{\langle\gamma\rangle_0 - \gamma_r}{\rho\gamma_r}$$

Simulation



Development of A



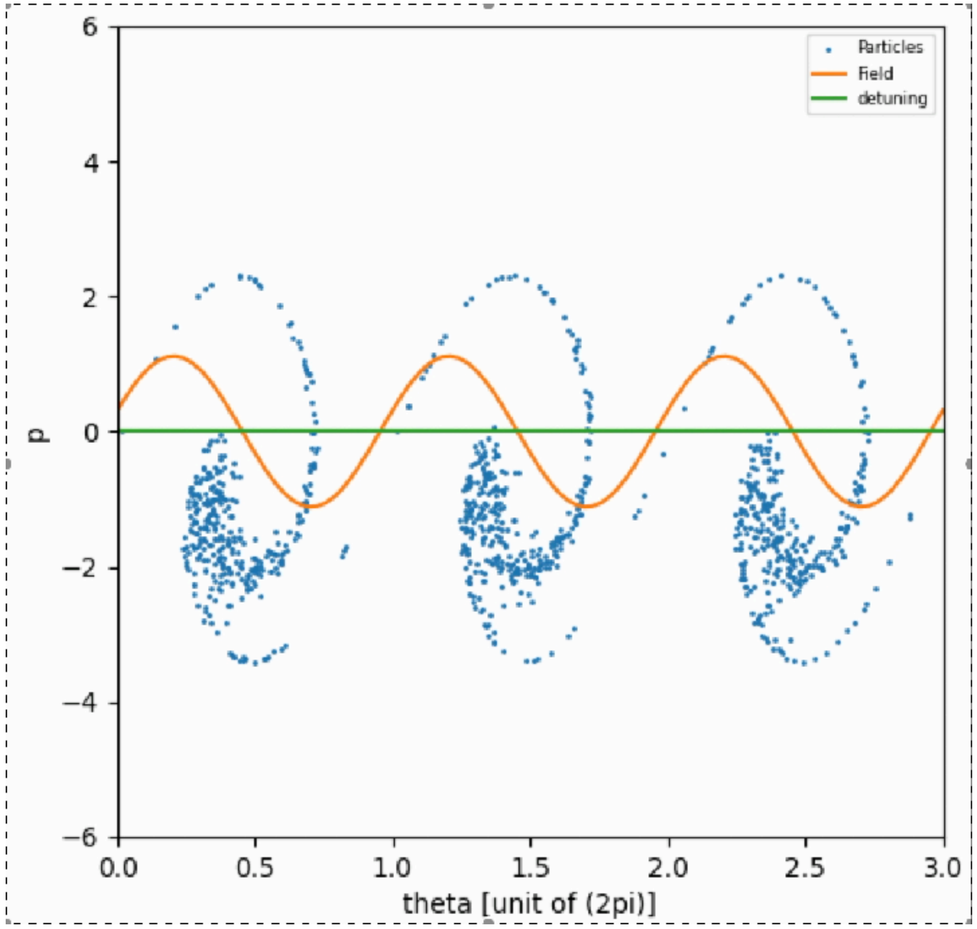
Analogy of FEL

- Similarity
  - Pendulum: Each electron in the beam
  - Pendulum motion: motion in phase-space
  - Common table: Coherent radiation

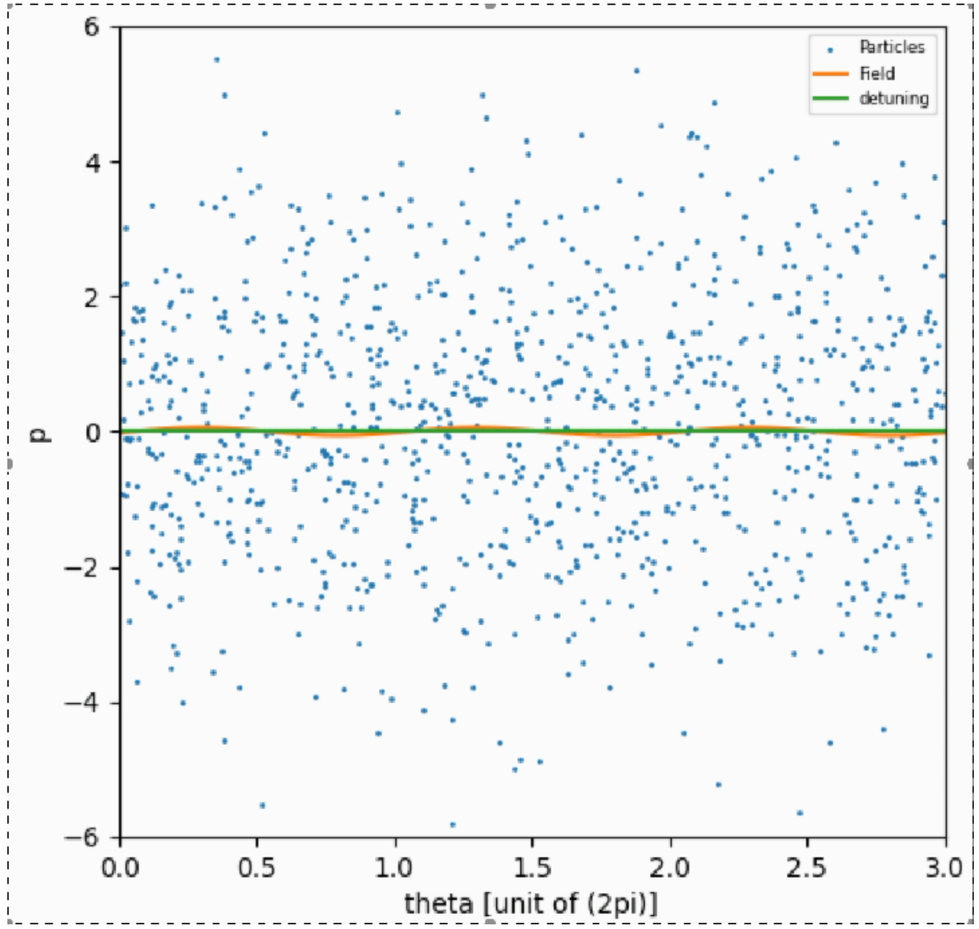
Beam quality matters

- FEL is a self-organization phenomenon in non-linear dynamics
- Small initial randomness is important for the micro-structure formation

narrow energy spread



wide energy spread



FEL T-shirts

- Photo lithography is the key technology!

Extraction efficenecy of FEL

- Identical equation
  (|A|~1 at saturation)

Radiation energy ↓ Beam energy ↓

$$\epsilon_0 |E_0|^2 = \rho |A|^2 (n_e \gamma m_e c^2)$$

ρ means conversion efficiency from electron beam to radiation

$$P_{\mathrm{rad}} = \rho P_{\mathrm{beam}}$$

(Radiation Power, Beam Power)

- In the typical case of EUV

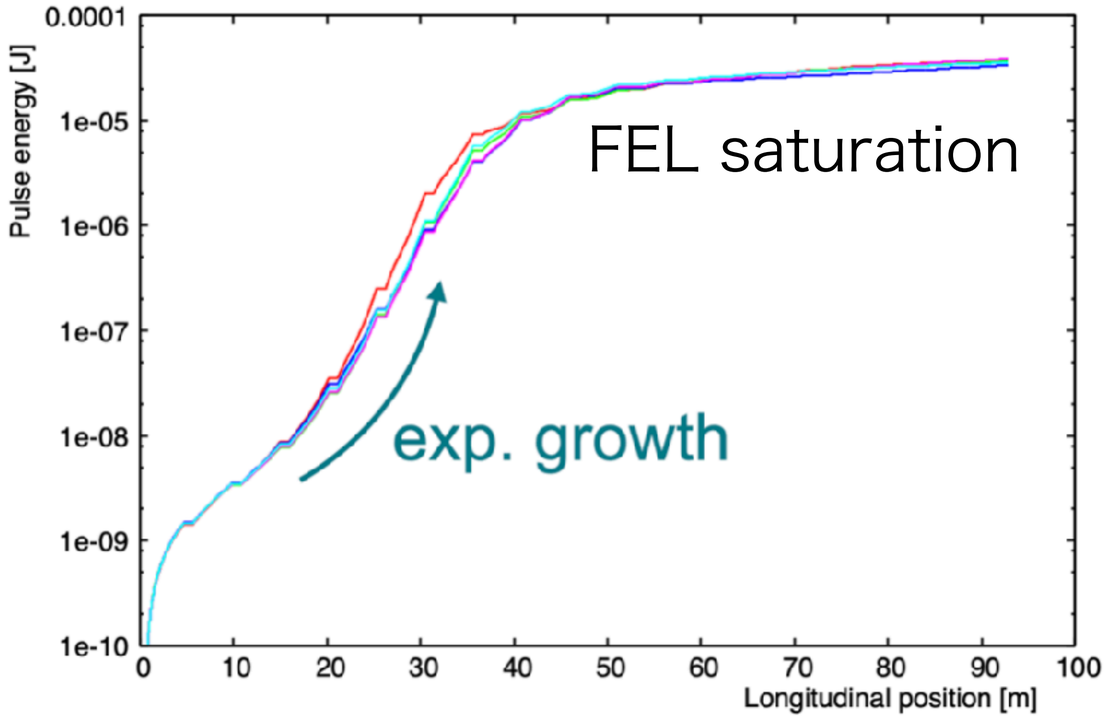
$$\rho \sim 10^{-3}$$

- 10MW of electron beam is necessary for 10kW of EUV
- 10MW = 1GeV x 10mA

Undulator length

saturation length:

$$L_{\mathrm{sat}} \sim \frac{\lambda_u}{\rho} \sim 30\ \mathrm{m}$$



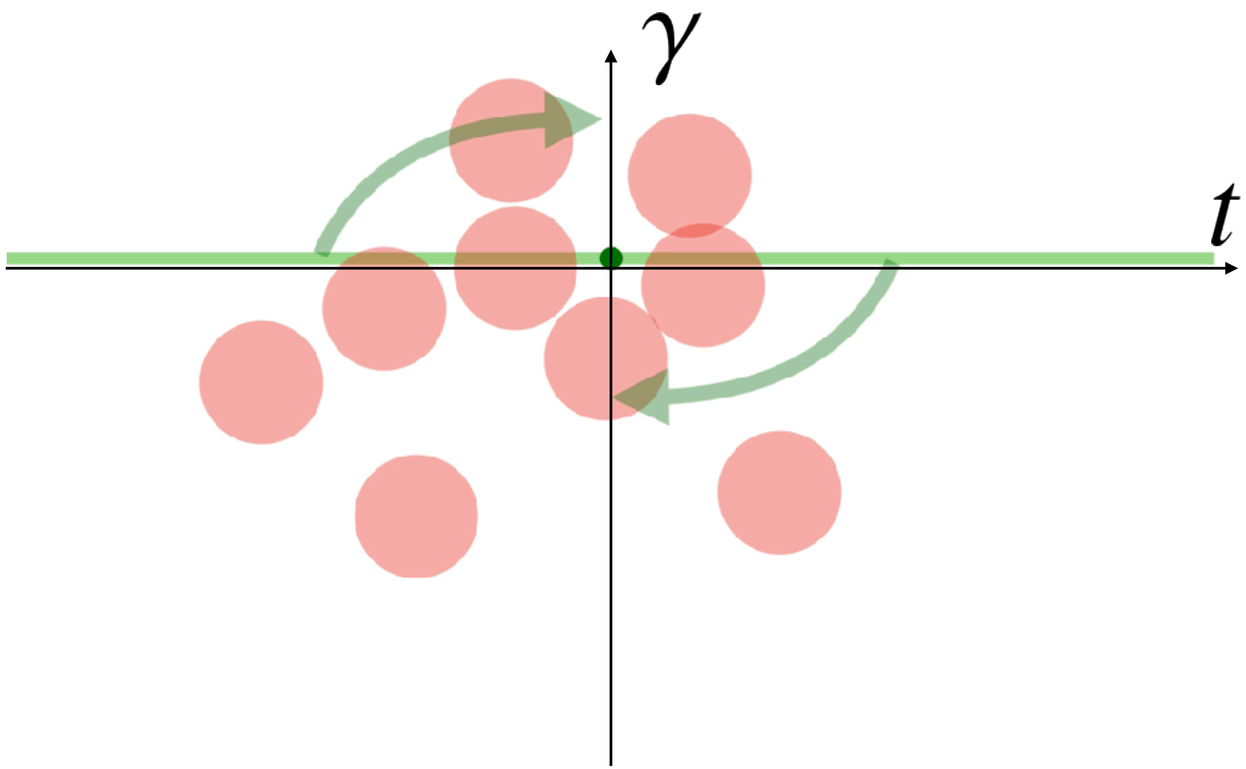
Some more power after saturation

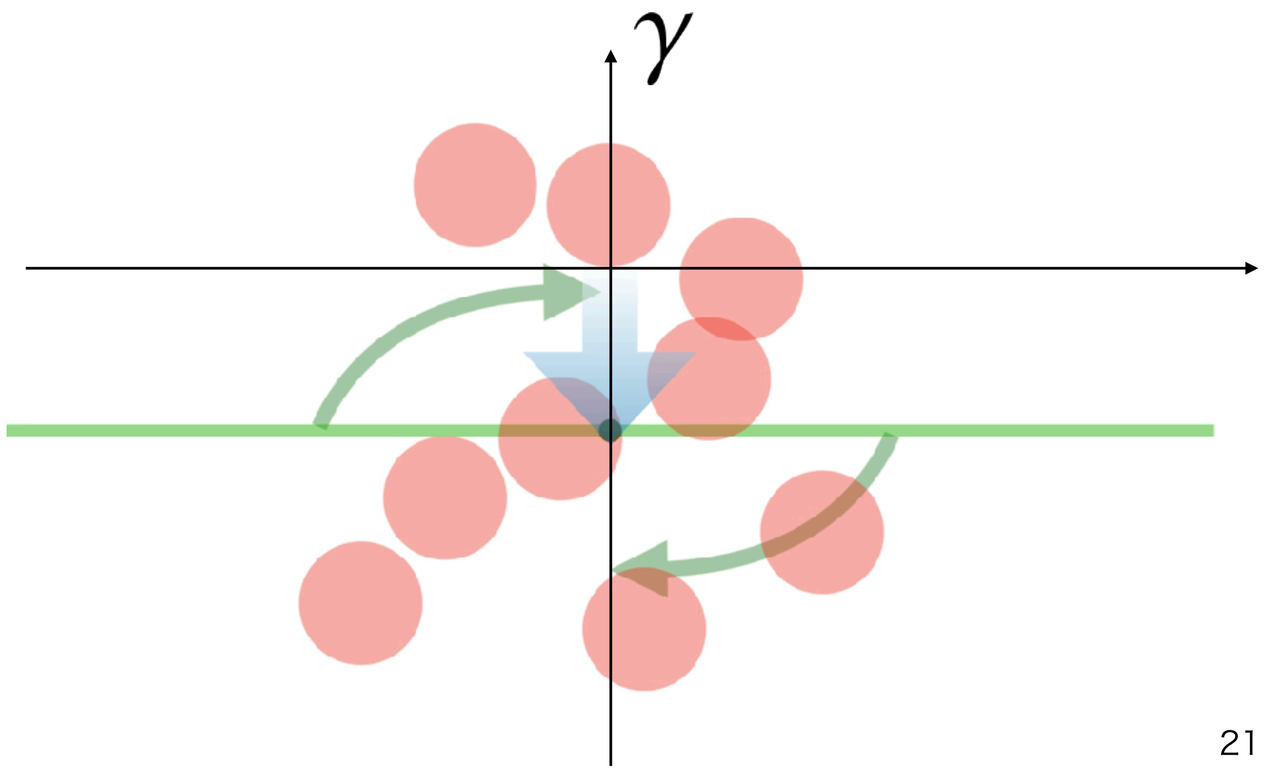
- Undulator tapering

detuning

$$\frac{dA}{d\bar{z}} = \langle \exp(-i\theta) \rangle + i\delta A$$

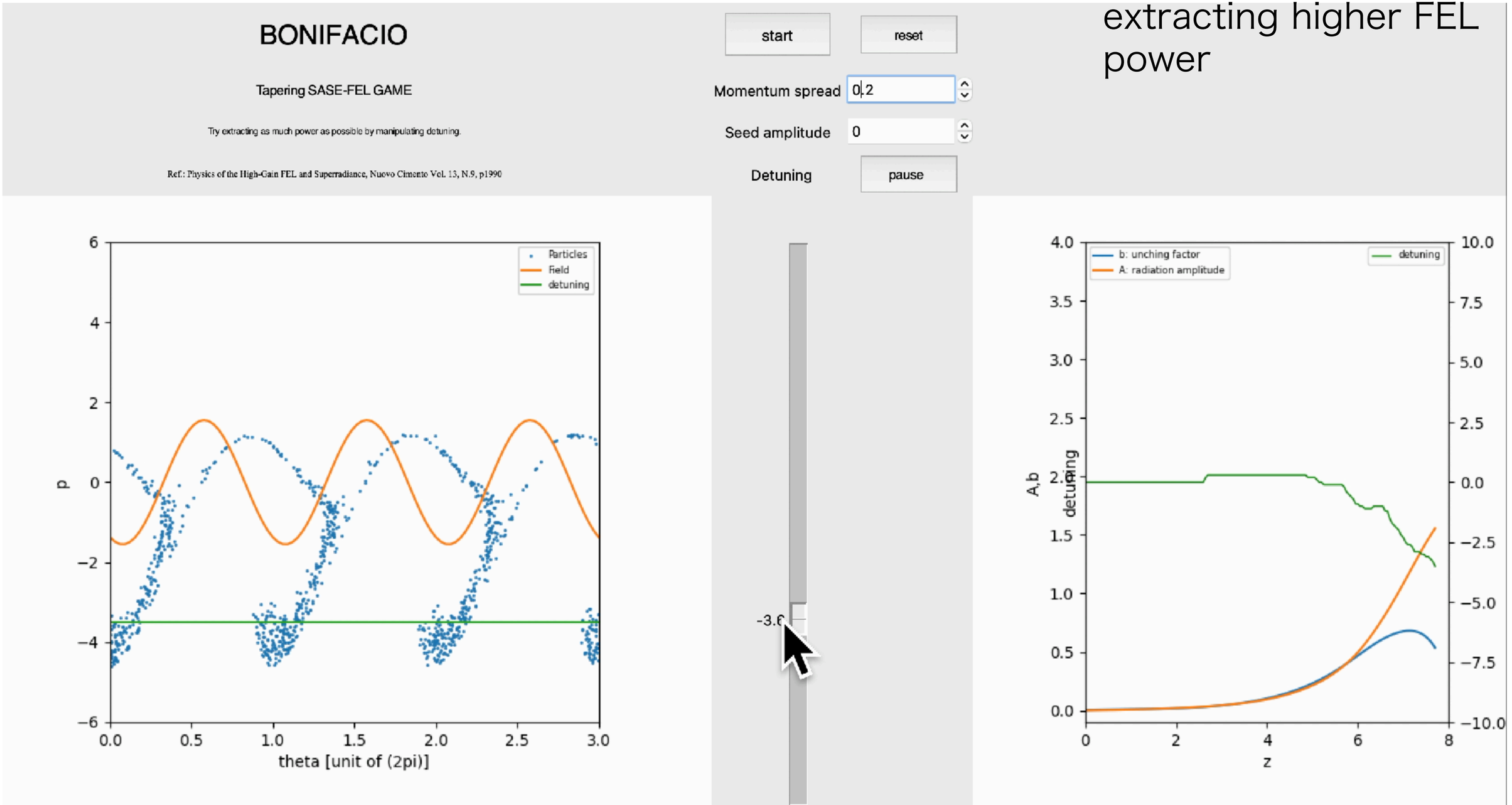
Vary undulator gap
(gradually reduce magnetic field)





Tapering SASE-FEL GAME

- Control detuning for extracting higher FEL power



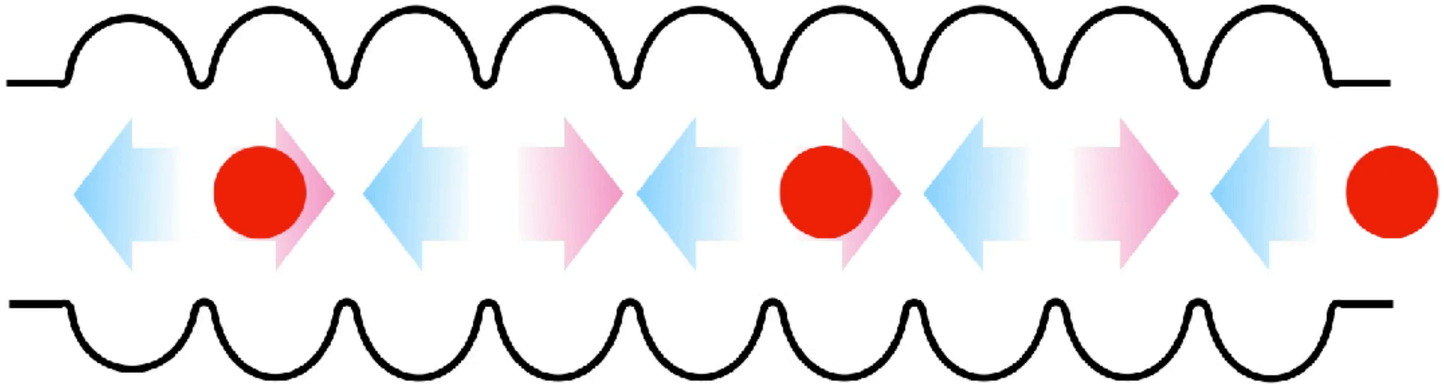
Contents

- Reviewing the Accelerator
  - Principle and necessity of FEL
  - **Principle and necessity of ERL**
  - Electron beam handling
- Development plan in KEK
- Summary

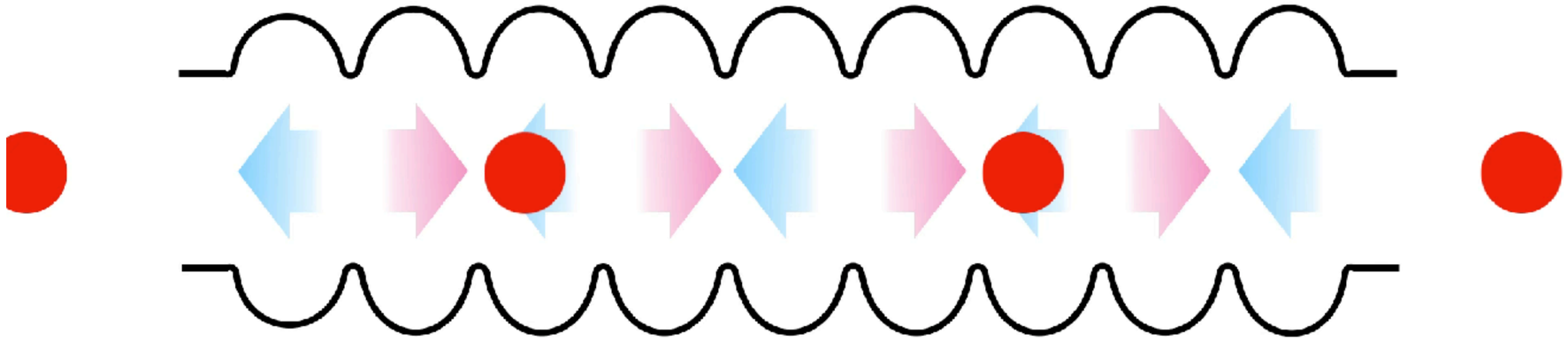
Accelerating cavity

- Same cavity can work both way accleration / deceleration

Acceleration

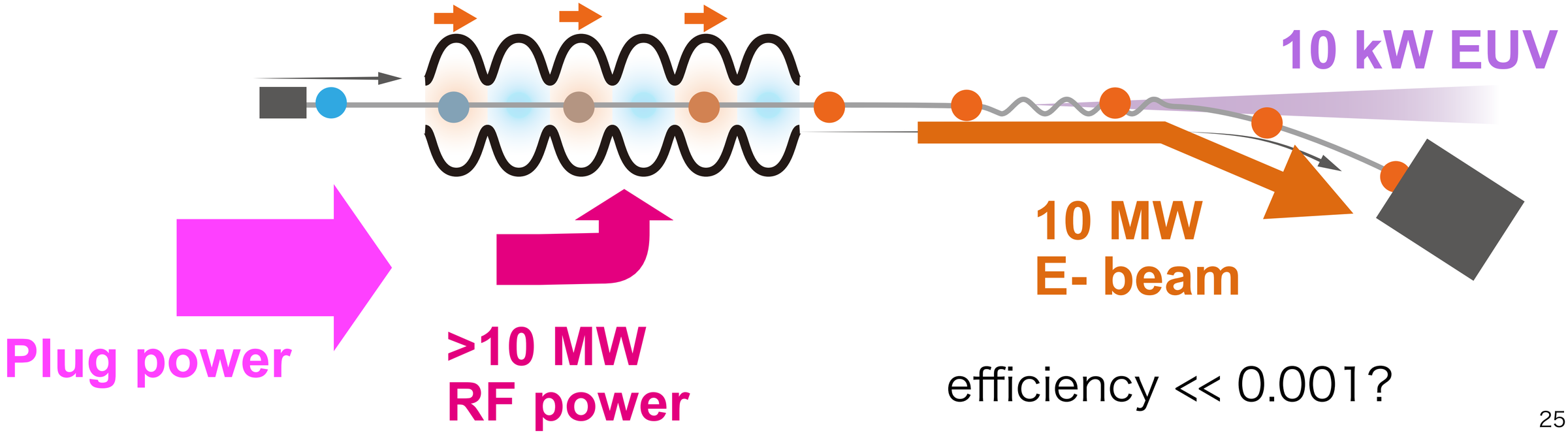


Deceleration



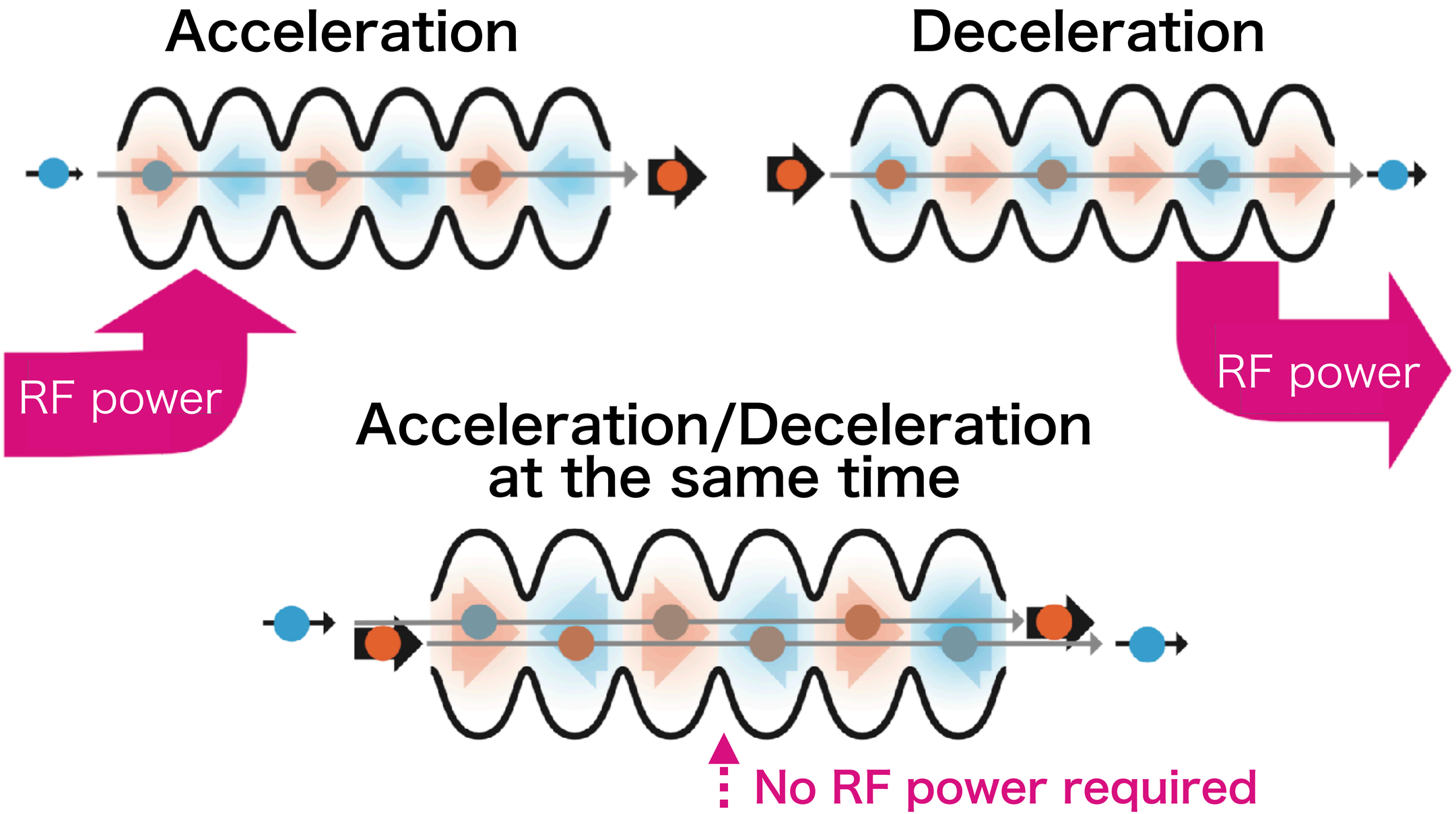
Energy Efficiency

- Conventional FEL scheme

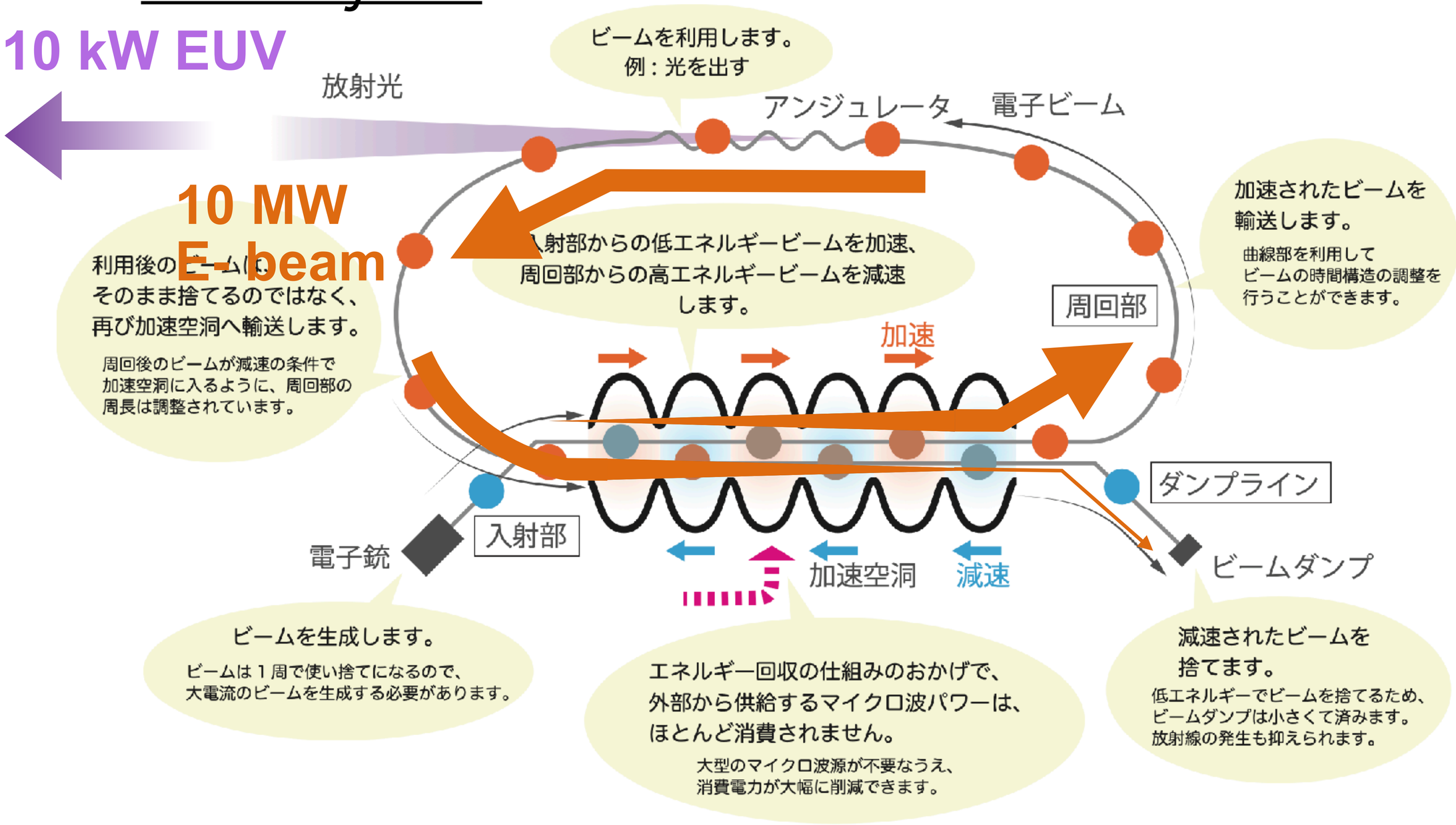


efficiency << 0.001?

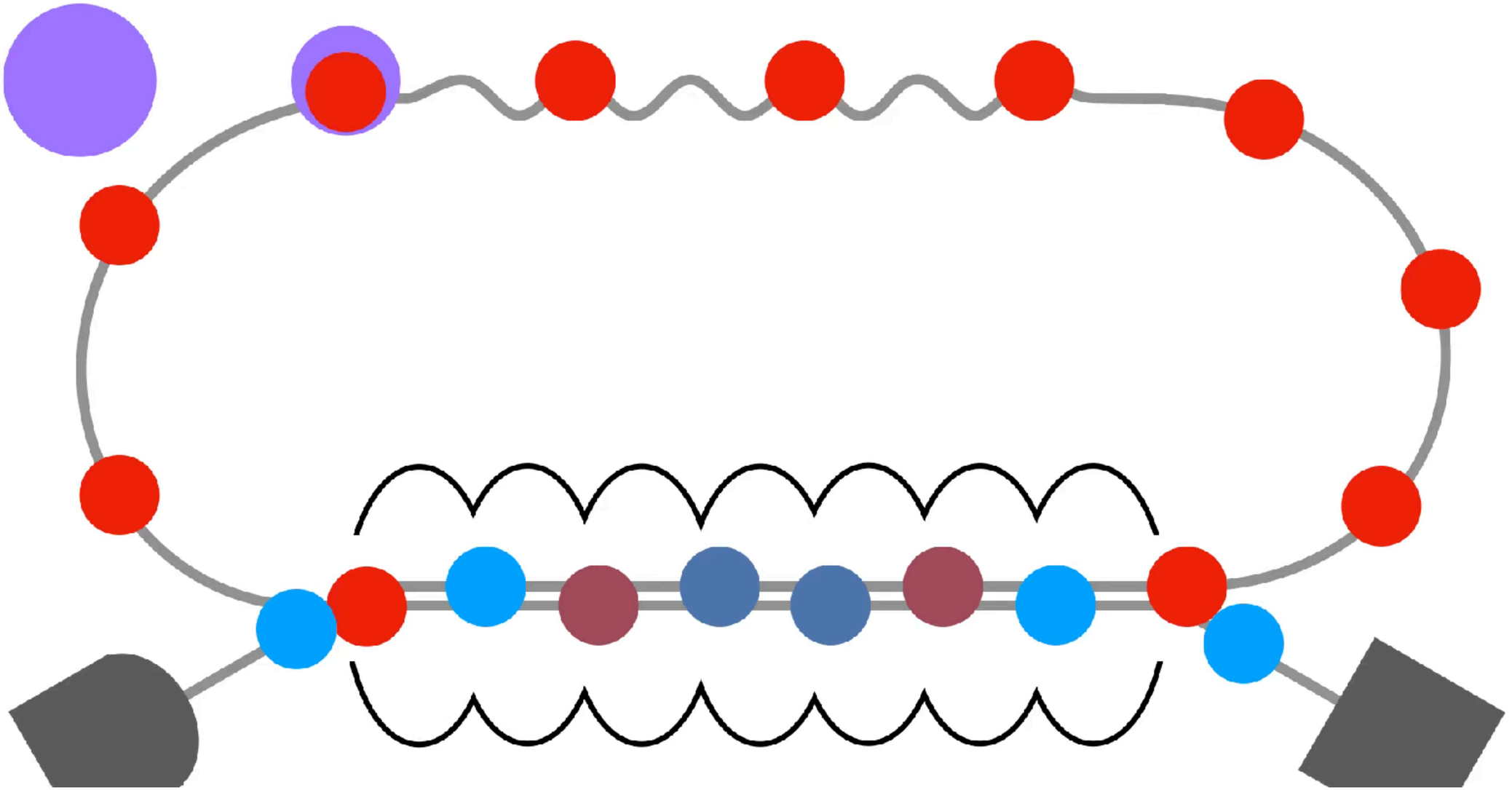
Principle of Energy-Recovery



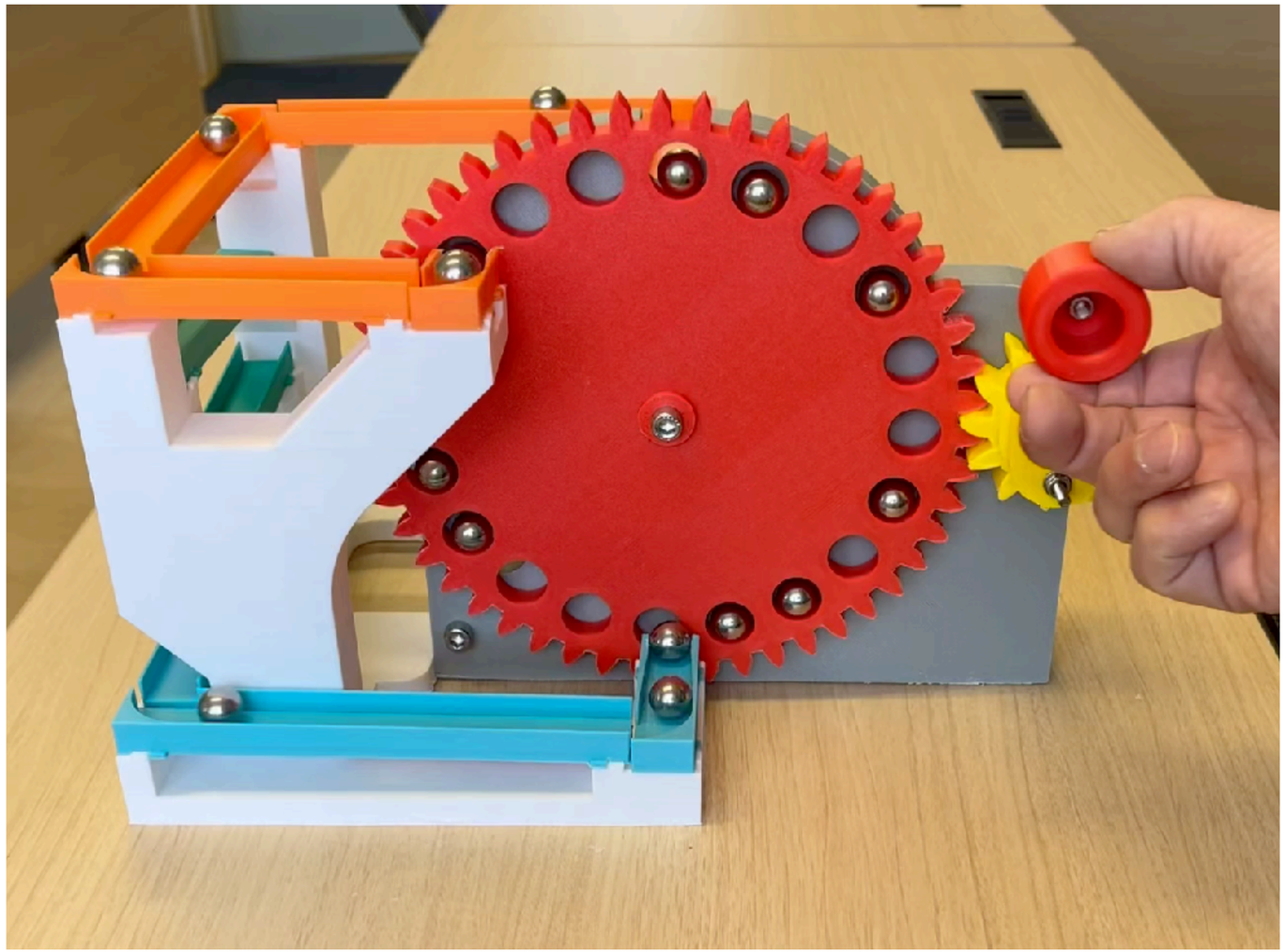
ERL layout


10 kW EUV
放射光
ビームを利用します。
例：光を出す
アンジュレータ
電子ビーム
10 MW
E-beam
利用後のビームは、
そのまま捨てるのではなく、
再び加速空洞へ輸送します。
周回後のビームが減速の条件で
加速空洞に入るように、周回部の
周長は調整されています。
入射部からの低エネルギービームを加速、
周回部からの高エネルギービームを減速
します。
加速されたビームを
輸送します。
曲線部を利用して
ビームの時間構造の調整を
行うことができます。
周回部
加速
ダンプライン
入射部
電子銃
ビームダンプ
加速空洞
減速
ビームを生成します。
ビームは１周で使い捨てになるので、
大電流のビームを生成する必要があります。
エネルギー回収の仕組みのおかげで、
外部から供給するマイクロ波パワーは、
ほとんど消費されません。
大型のマイクロ波源が不要なうえ、
消費電力が大幅に削減できます。
減速されたビームを
捨てます。
低エネルギーでビームを捨てるため、
ビームダンプは小さくて済みます。
放射線の発生も抑えられます。

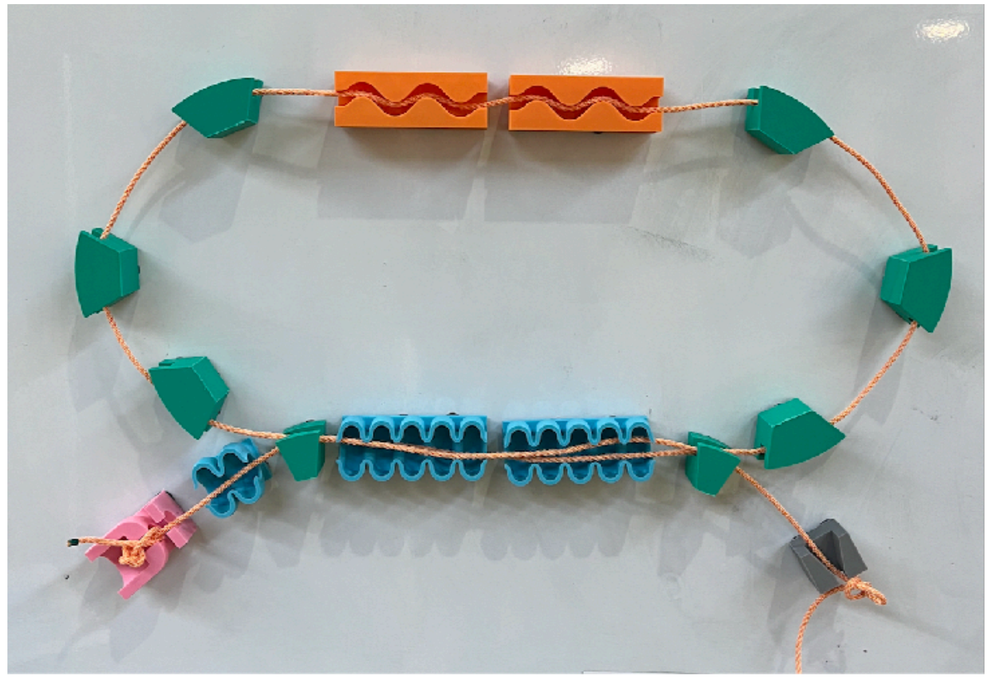
Energy-Recovery Linac (ERL)

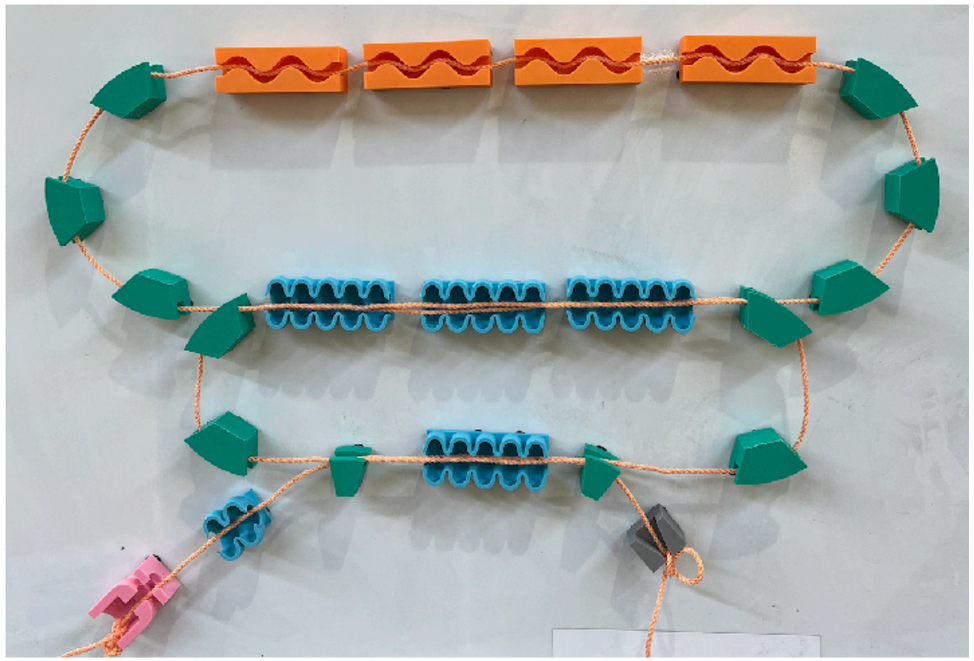


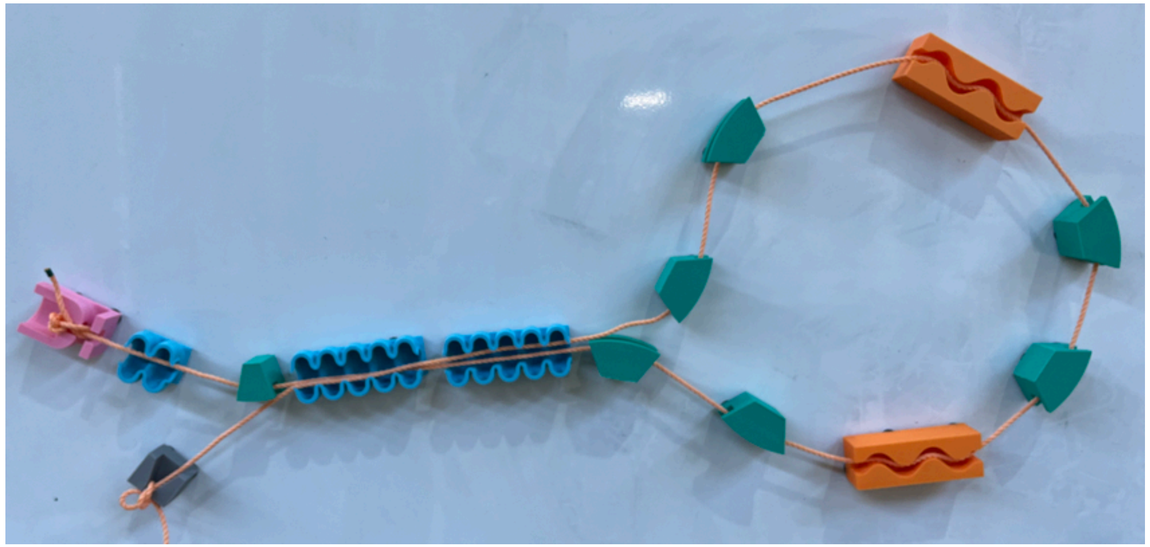
ERL Toy

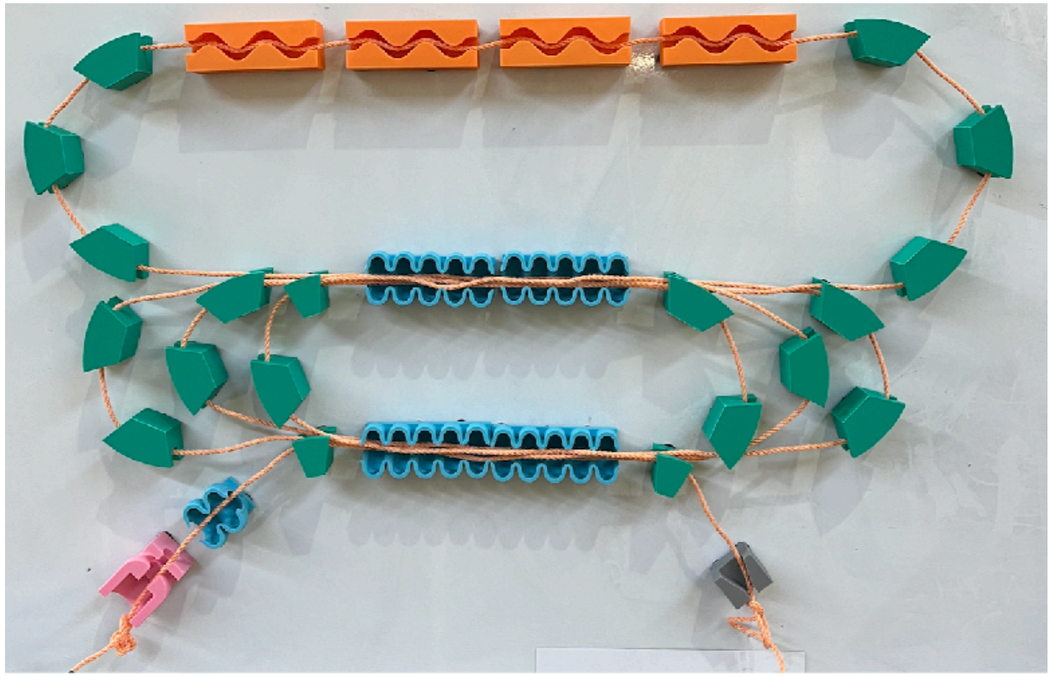


Various types of ERL

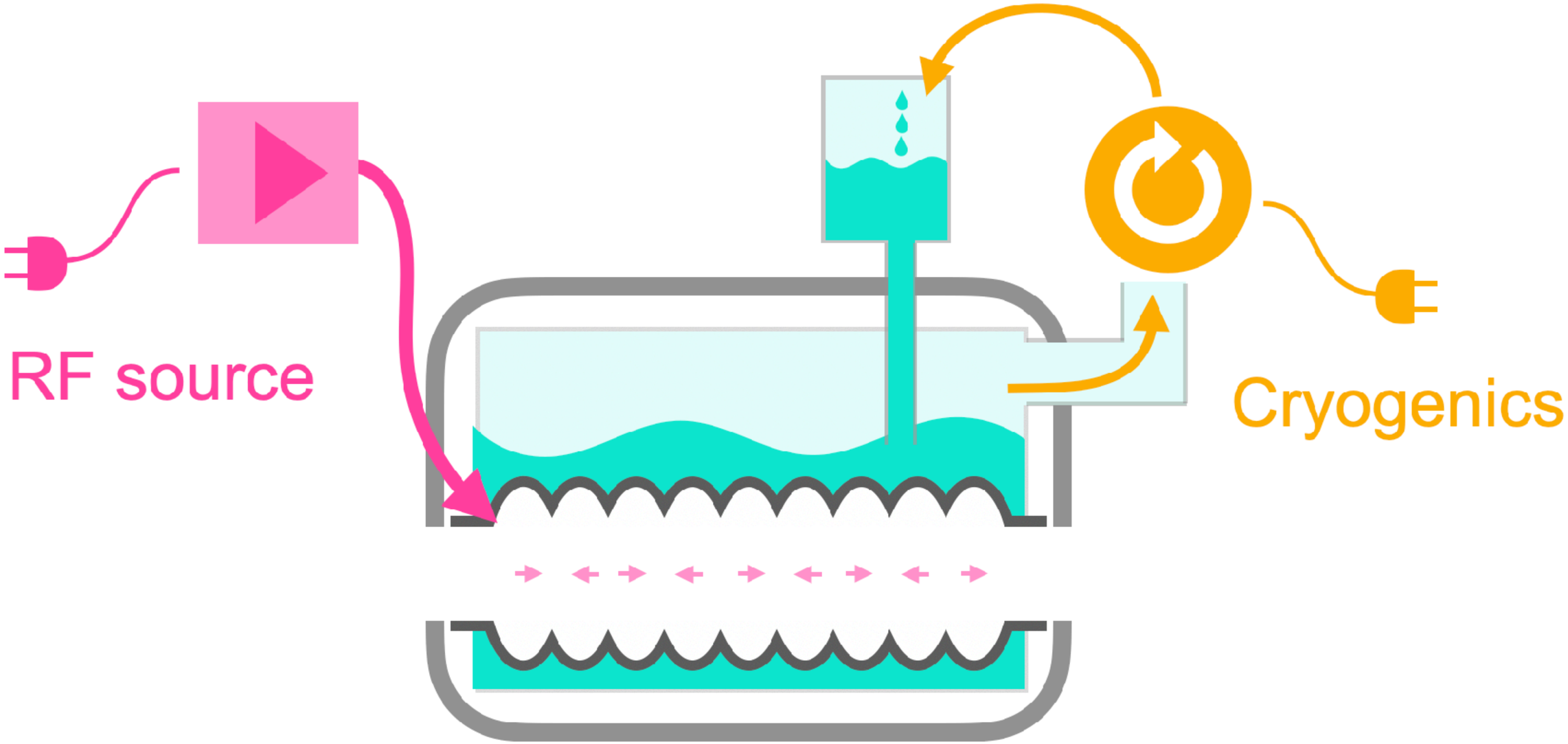








Electricity

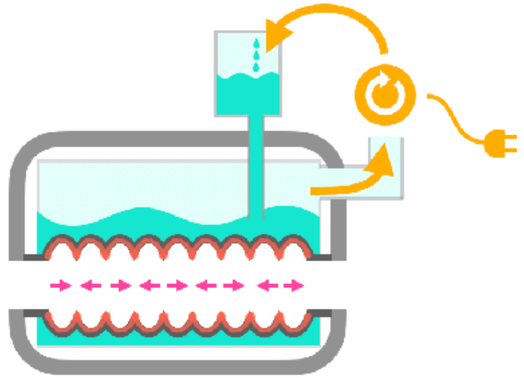


Cryo load

$$Q_0 \propto 1/R_s$$

Surface resistance of Nb cavity

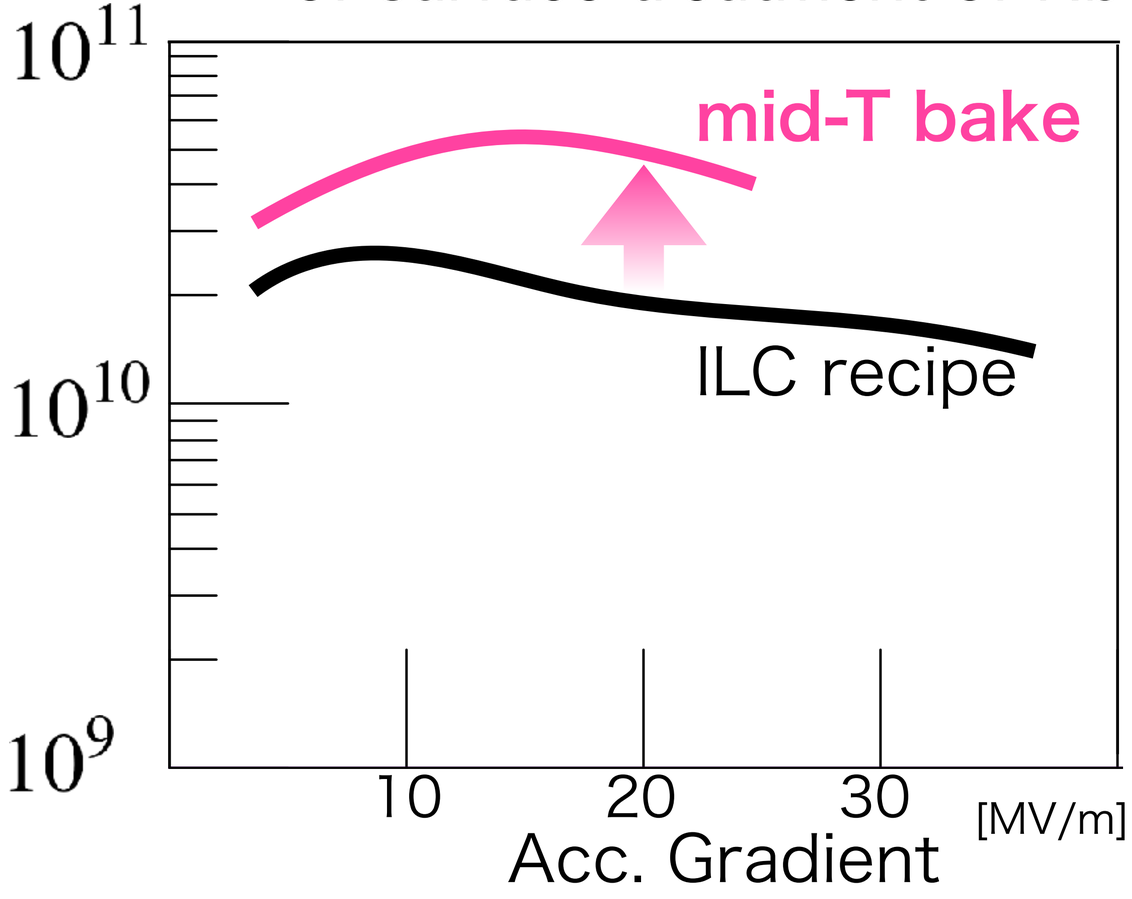
Heat load,
He evapolation



Cryo system load

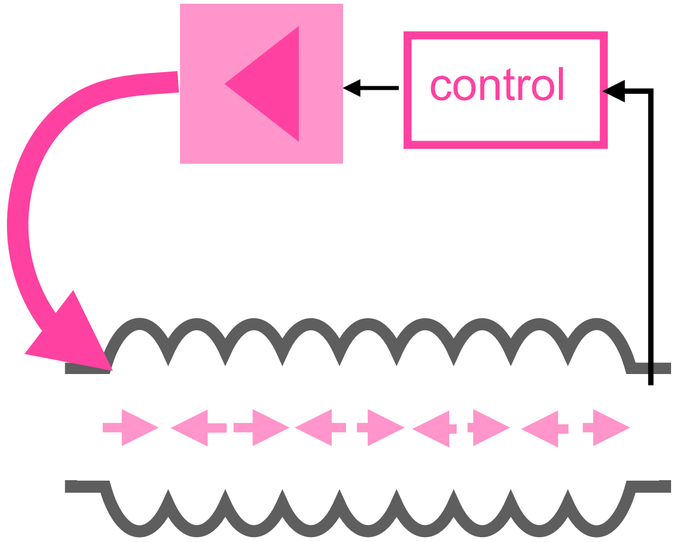
$$P_{\mathrm{Heat}} = \frac{V_c^2}{(R/Q)Q_0}$$

Recent development
of surface treatment of Nb



RF power

Q_L $\propto$ power enhancement

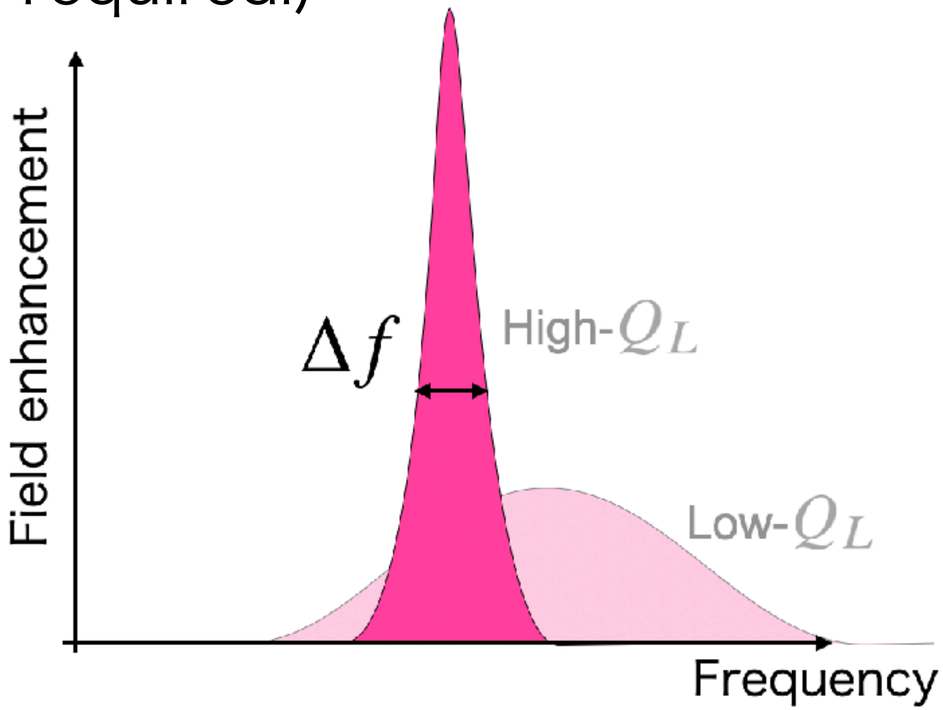


Higher power enhancement

(Control precision requiredl)

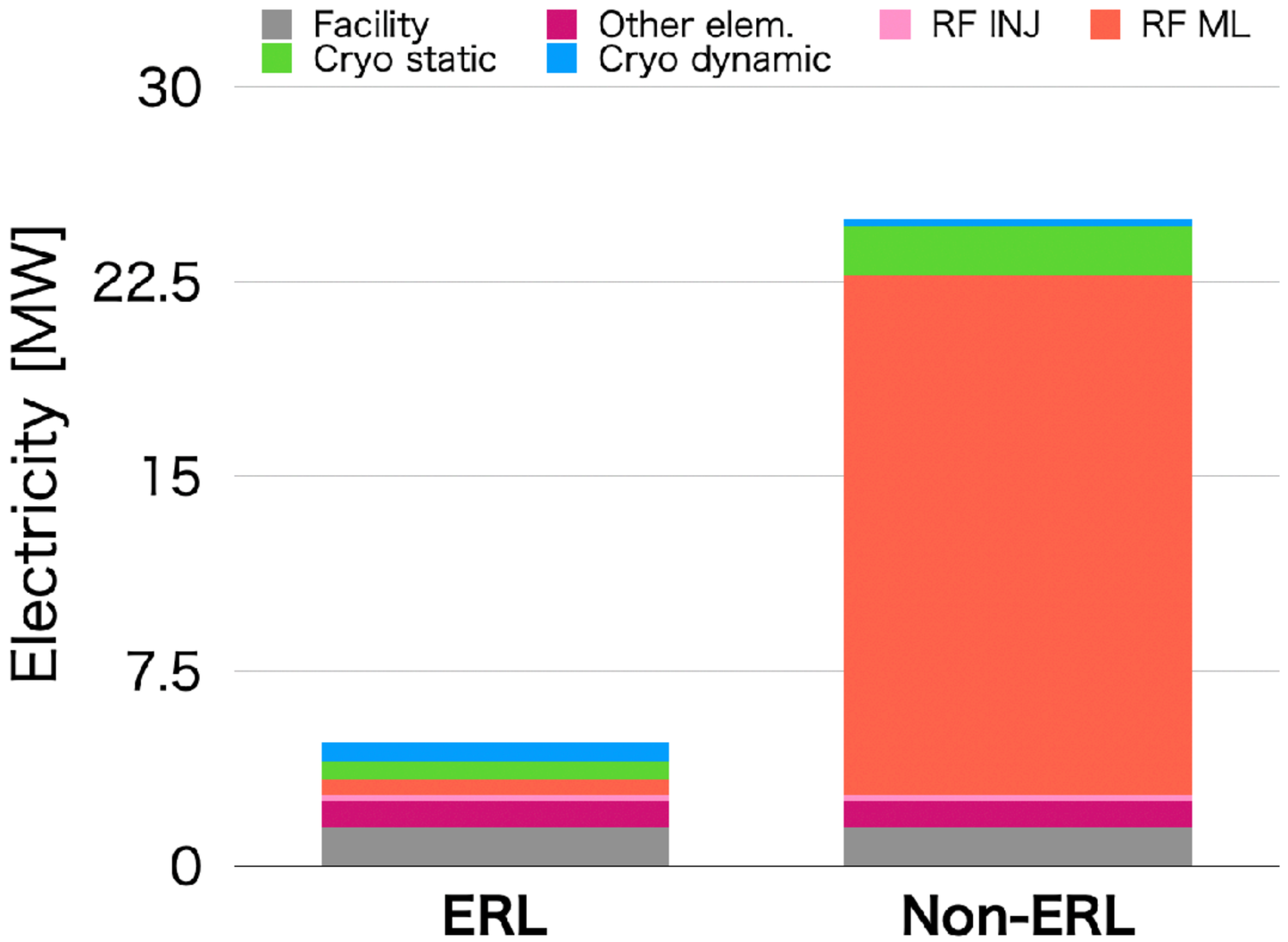
Smaller RF source

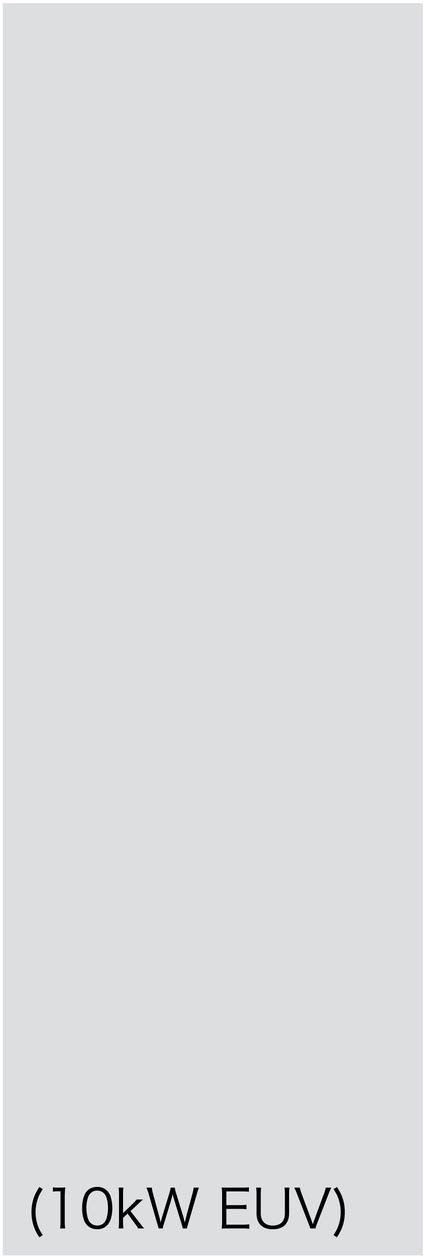
$$P_{\mathrm{RF}} = \frac{V_c^2}{4(R/Q)Q_L}$$



Necessity of ERL

- Assumption: 1GeV, 10mA class accelerator
  10kW EUV output





Contents

- Reviewing the Accelerator
  - Principle and necessity of FEL
  - Principle and necessity of ERL
  - **Electron beam handling**
- Development plan in KEK
- Summary

Beam density

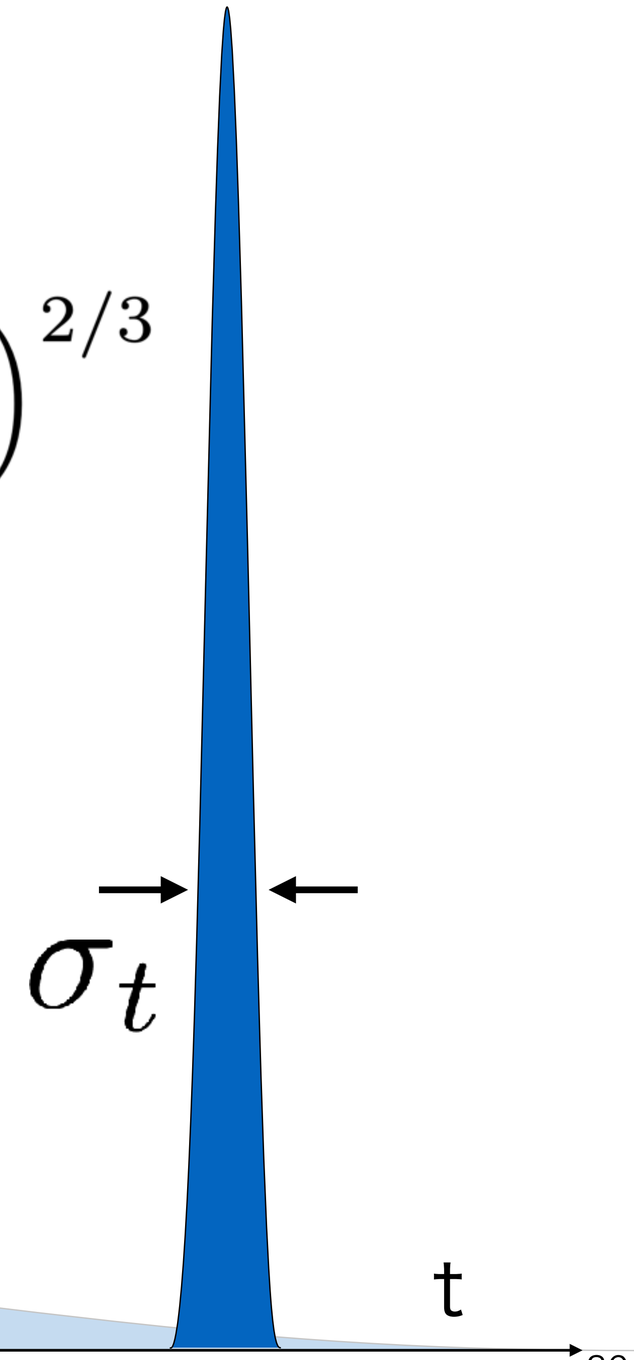
Higher ρ (conversion efficiency)

Higher n_e (electron density)

Shorter σ_t (bunch length)

$$\rho = \frac{1}{\gamma_r}\left(\frac{a_w}{4}\frac{\omega_p}{ck_w}\right)^{2/3}$$

$$\omega_p = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}$$



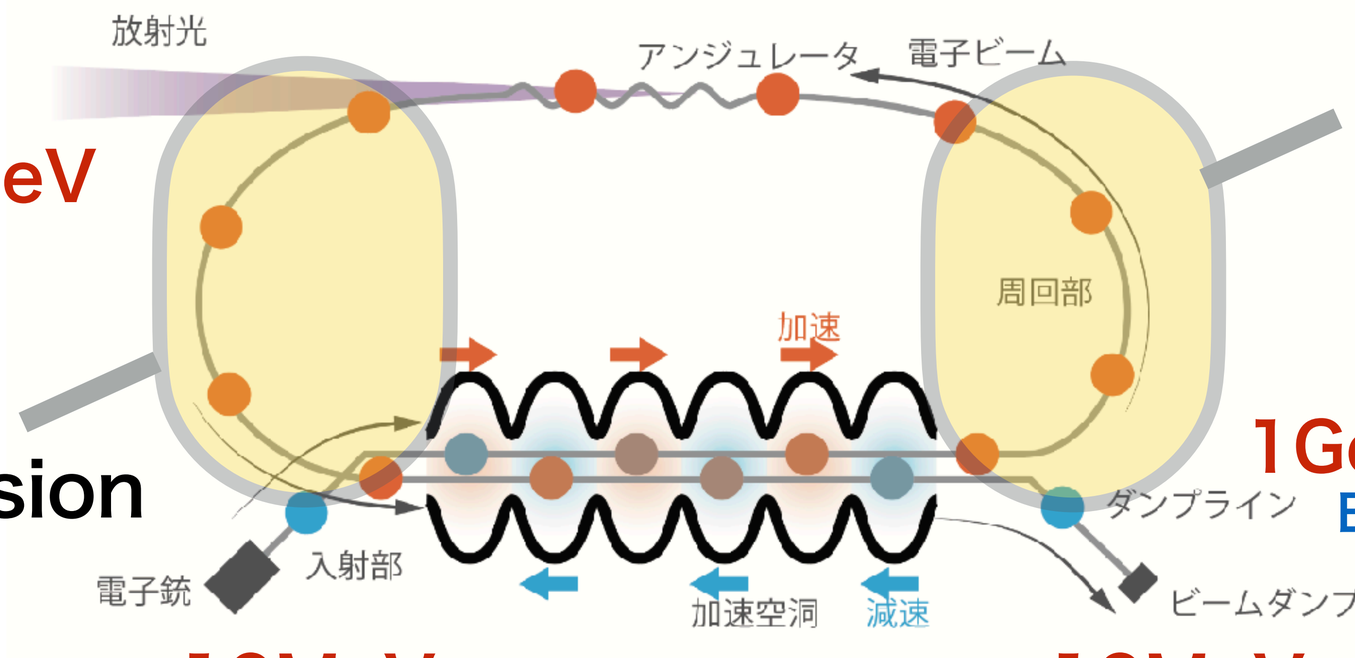
→ Bunch compression

Beam dynamics in transport

- Designing the electron beam transport optics is the key.

Energy spread >0.003

Bunch length: 50fs
Energy spread: <0.001



Bunch compression

1GeV

Bunch decompression

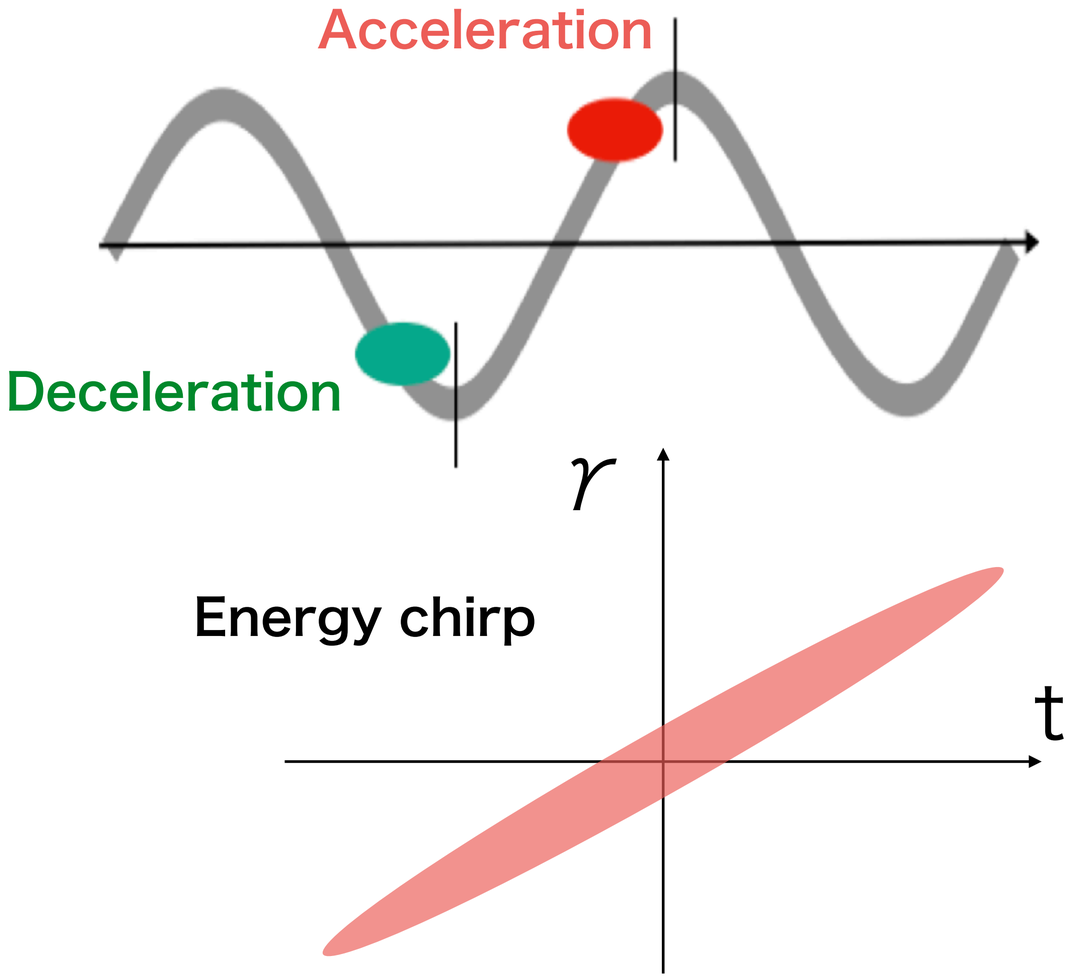
1GeV
Bunch length: 1ps

10MeV

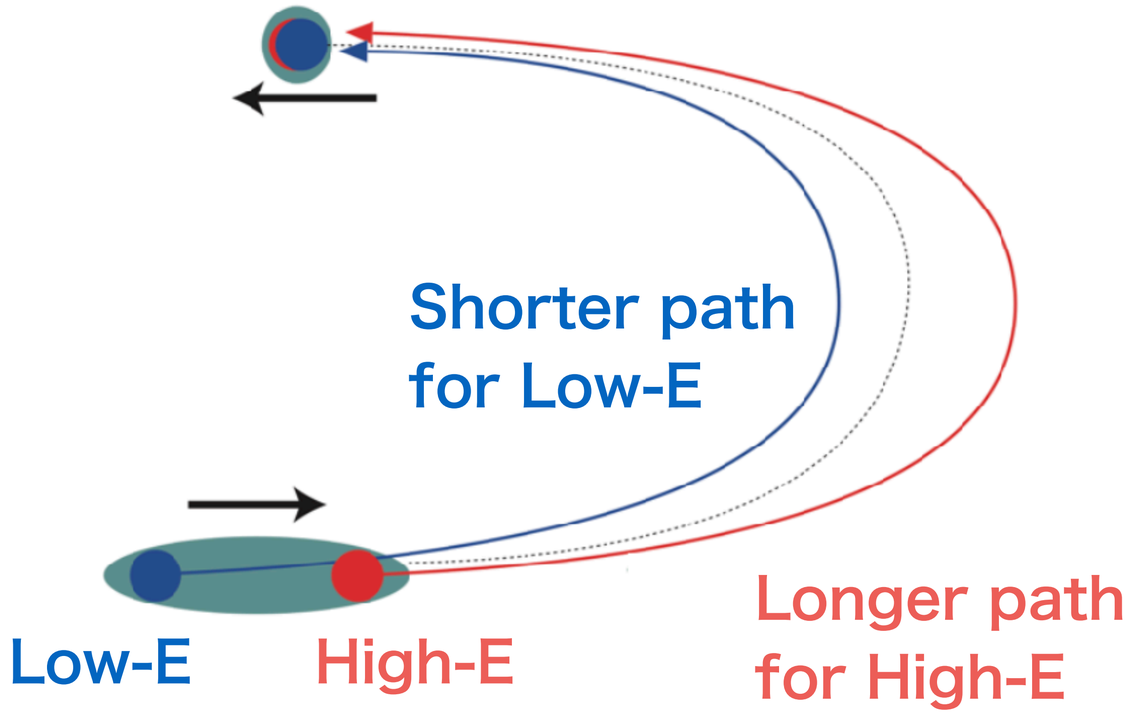
10MeV
Energy spread: <0.1

Bunch handling technique

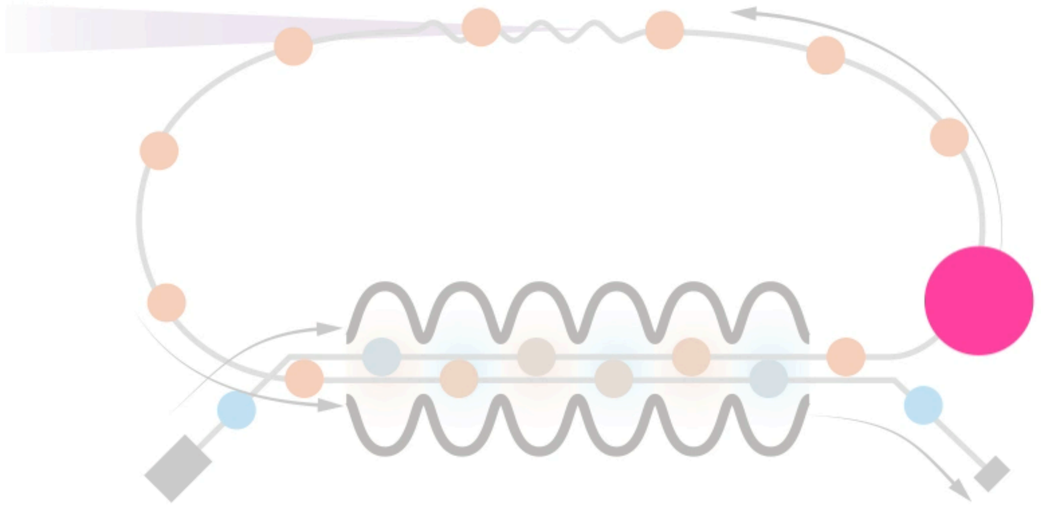
- Off-crest Acceleration/Deceleration
  - Control energy chirp

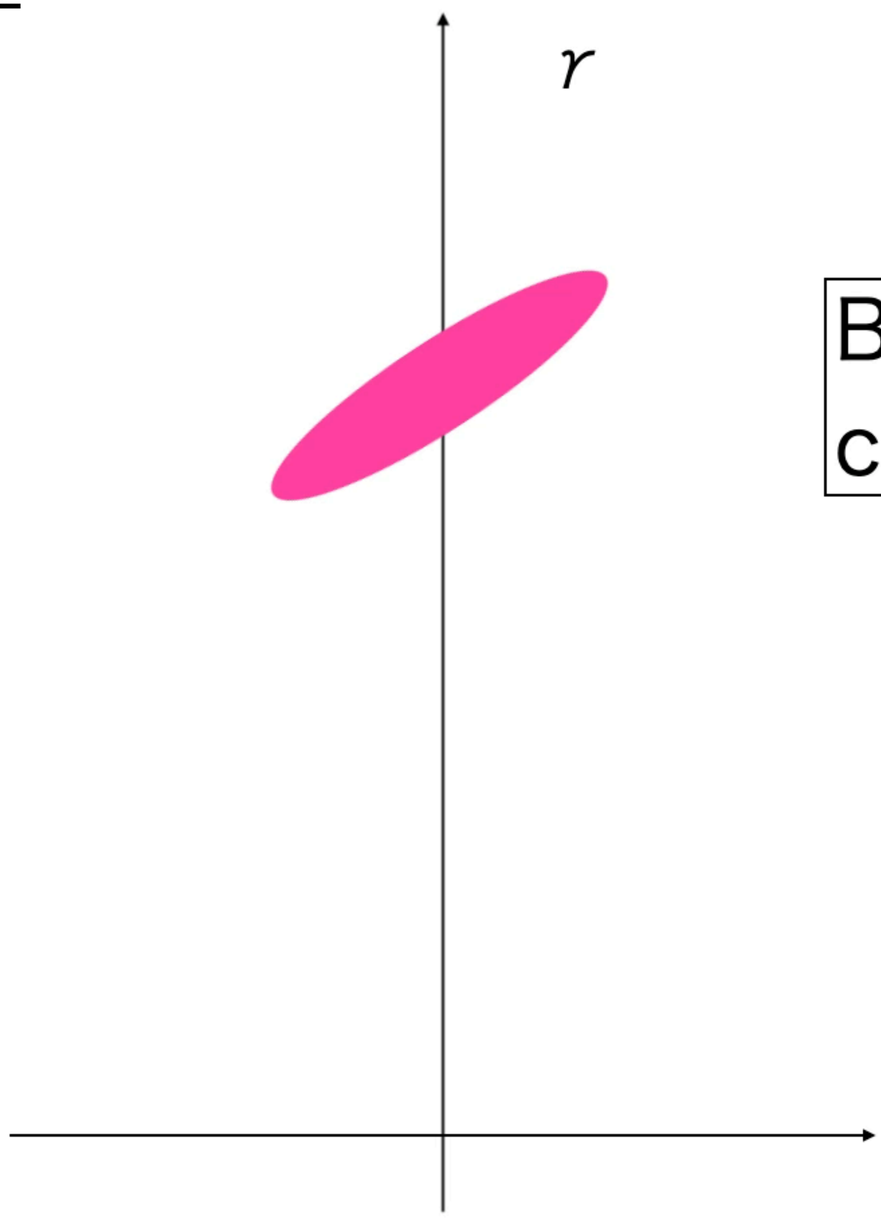


- Dispersion control in the Arc-section
  - Control path length



Bunch gymnastic





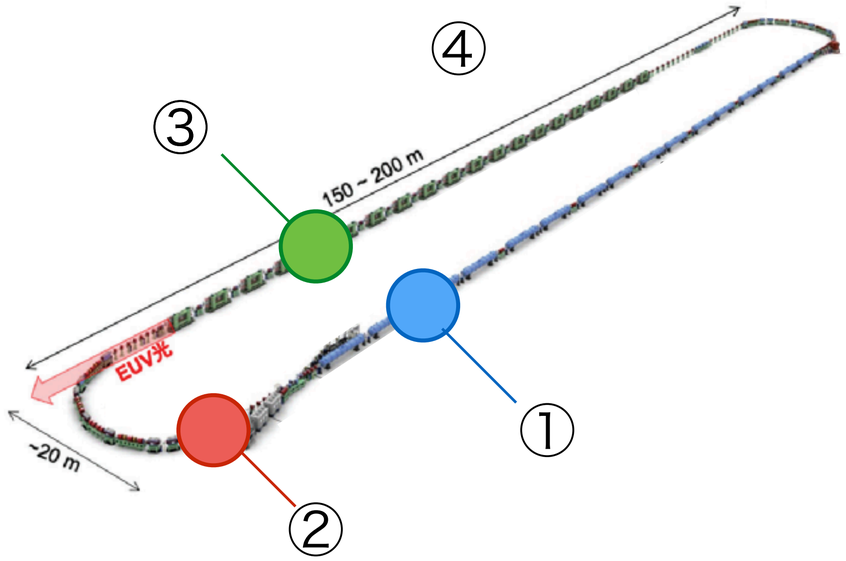
Bunch compression

Contents

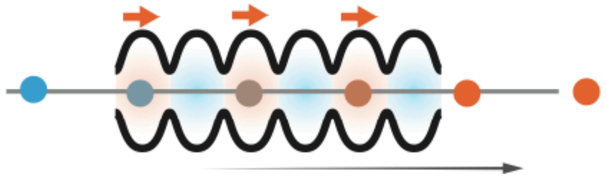
- Reviewing the Accelerator
  - Principle and necessity of FEL
  - Principle and necessity of ERL
  - Electron beam handling
- **Development plan in KEK**
- Summary

Development plan

- Establish key technologies in 5-year project

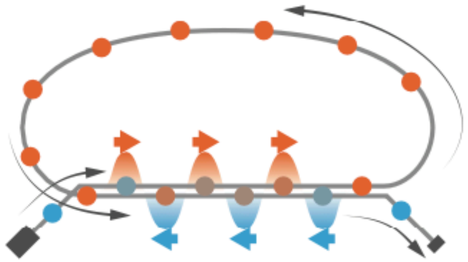


① High efficiency beam acceleration



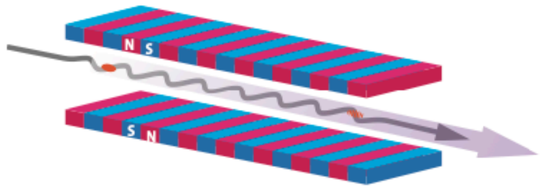
大パワービームを加速できる
超伝導加速空洞を開発します。

② High current beam operation



エネルギー回収型線形加速器の
の運転技術を開発します。

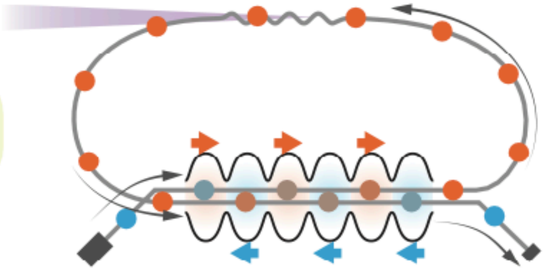
③ FEL lasing



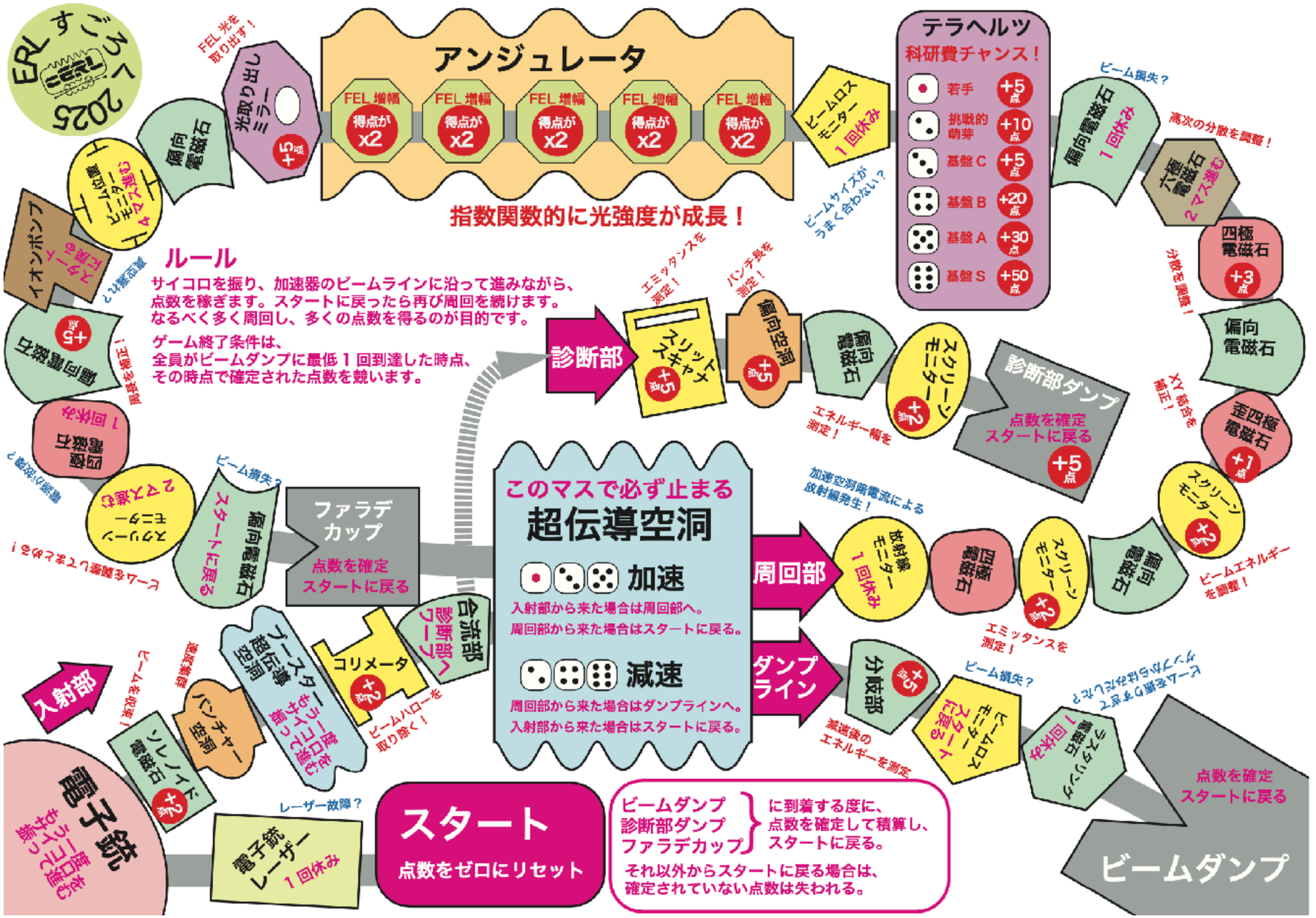
EUV 光を発生するアンジュレータと、
FEL 発振のためのビーム調整技術
を開発します。

④ Overall machine designing

上記の技術開発を踏まえて
プロトタイプ ERL 型 FEL 光源
の設計検討を進めます。



ERL-FEL Board game



Summary

- ERL-EUV-FEL is a candidate of the light source for next-generation lithography.
- By reviewing its basic principle, the followings can be understood.
  - machine parameters
  - electric power efficiency
  - key items to develop
- Development of core technologies are on going at KEK.
- Preparation of the photon beam line/ photon user (lithography) are necessary at the same time.