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DEVELOPMENT OF BEAM POSITION MONITOR USING CHERENKOV DIFFRACTION RADIATION

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OUTLINE

- ☐ Background & Motivation
- ☐ Cherenkov diffraction radiation
- ☐ Azimuthal distribution of Cherenkov diffraction radiation
- ☐ Considerations in BPM development
  - Position derivation
  - Effect of beam size
  - Intensity
- ☐ Summary

Background

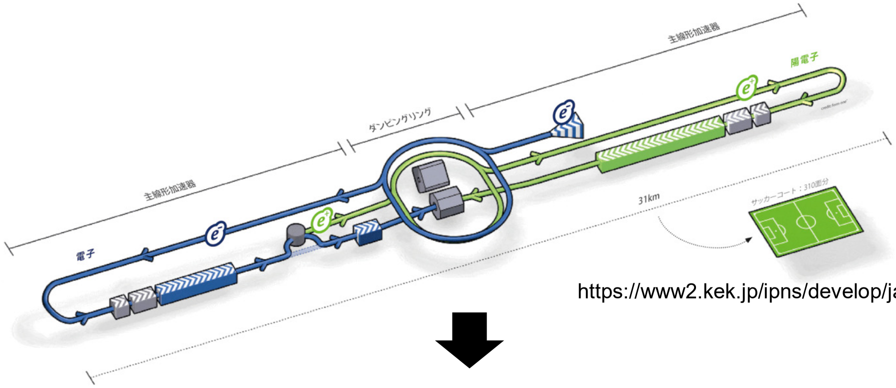
Laser-wakefield accelerators (LWFAs):

Laser-plasma acceleration

Applications
- XFEL
- Collider

Predicted maximum field strength:

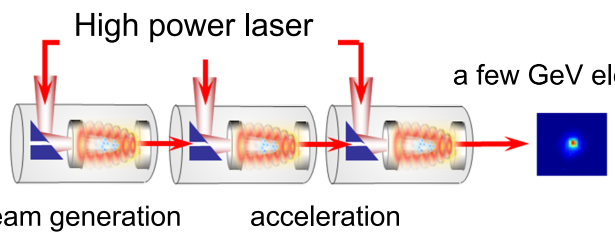
1 GeV / 1 cm = 100 GeV / m



https://www2.kek.jp/ipns/develop/ja/research/ilc/

500 GeV beam would be achieved within 500 cm

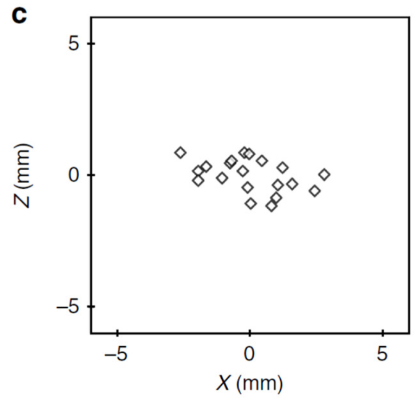
Background



ImPACT project （Sano PM）
http://www.jst.go.jp/impact/sano/

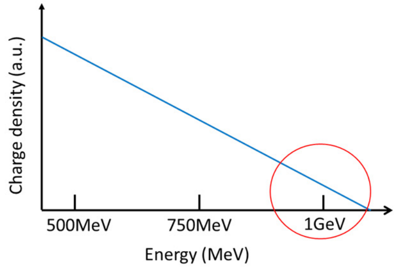
- Recently, dramatically improved their beam quality
- Small source size, Low emittance
- Large energy spread
- Still poor pointing stability
- Low beam repetition rate

Large fluctuations in beam position would be unacceptable for many beam users

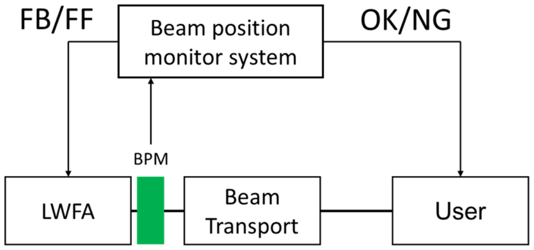


Shot-to-shot measured pointing stability

T. André et al., NATURE COMMUNICATIONS (2018) 9:1334

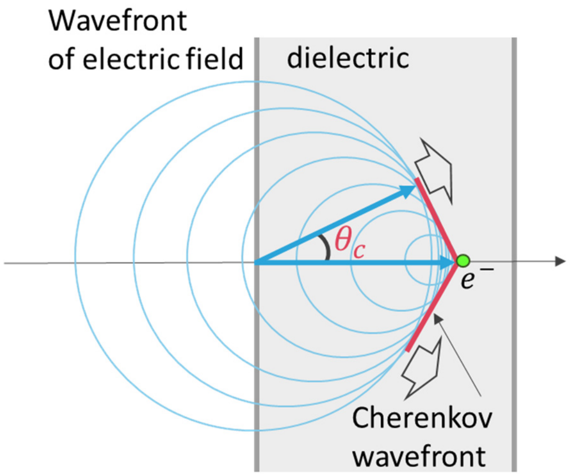


Position monitoring



Non-destructive beam monitor is required in practical use of the LWFA

Cherenkov radiation



Jelley,J.V. " Ćerenkov Radiation And Its Applications" 1958,pp.4-5

Cherenkov angle: $\boldsymbol{\theta_c}$

$$\cos\theta_c = \frac{1}{\beta n}$$

$$(\beta \simeq 1, \beta n > 1)$$

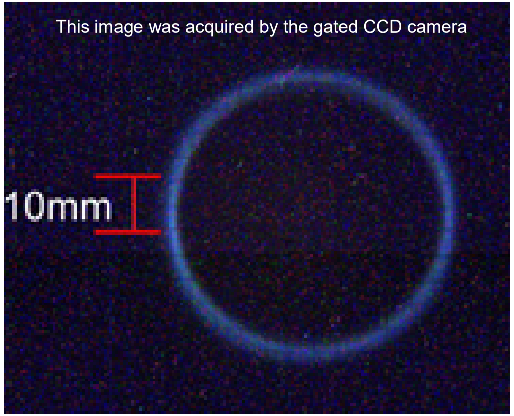
$\beta = c/v$
c : Speed of light
v : Electron velocity
n: Refractive index

Number of generated photons: N_0

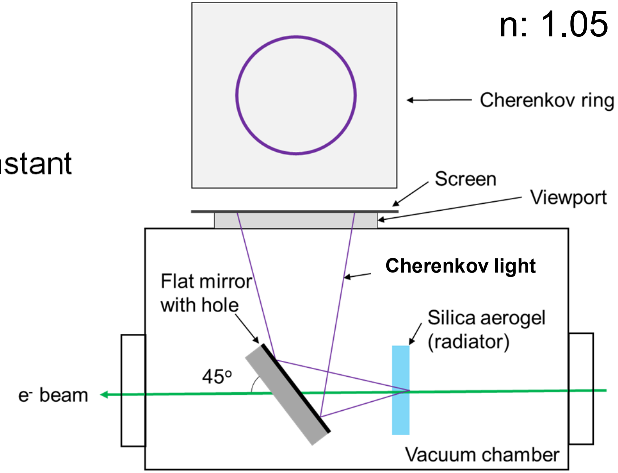
(Frank-Tamm formula)

$$N_0 = 2\pi\alpha L\left(1 - \frac{1}{\beta^2 n^2_{(\omega)}}\right)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

α: Fine structure constant
λ: Wavelength
L: Radiator length

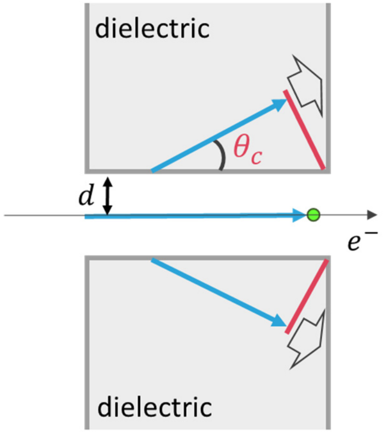


n: 1.05



Cherenkov diffraction radiation (ChDR)

Cherenkov radiation from a nearby dielectric



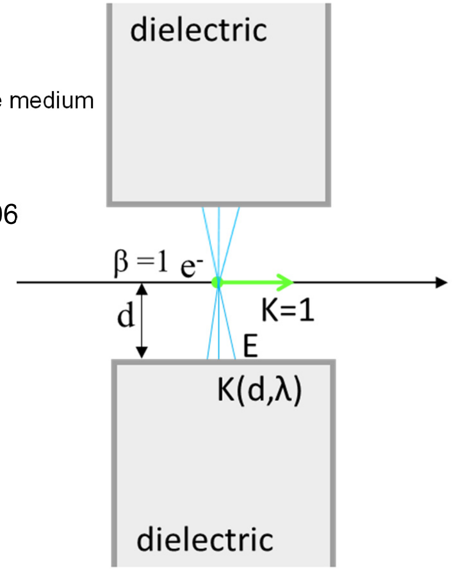
The ChDR intensity can be expressed by multiplying the intensity of ordinary Cherenkov radiation by a coupling factor, K.

- Coupling factor

$$K = exp\left(-4\pi \frac{d}{\beta\gamma\lambda}\right)$$

d: distance between the electron and the surface of the medium
γ: Lorentz factor $\gamma=(1-\beta^2)^{-1/2}$

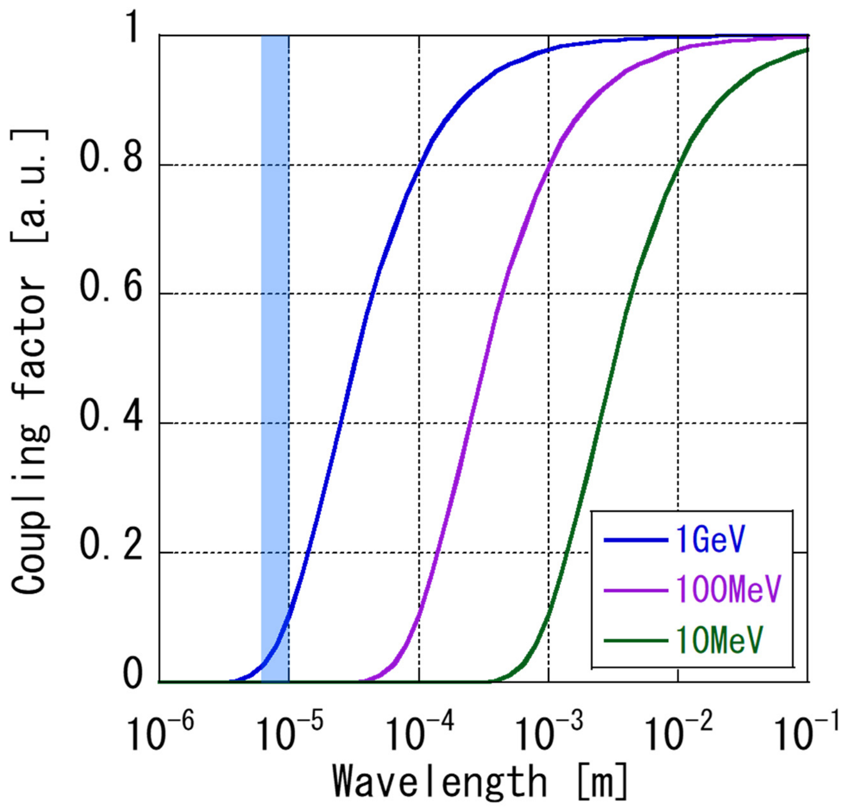
R. Ulrich, Z. Phys. 194, 180 (1966)
T. Takahashi et al., Phys. Rev. E62(2000) 8606



- Number of generated photons (ChDR): N

$$N = N_0 K$$

Characteristic of coupling factor



Variation of the coupling factor for different beam energies (d = 3.5 mm)

Large photon yield ➡ Higher K

1GeV: Infrared region

100MeV: Terahertz region

10MeV:Millimeter-wave region

d and λ have to be chosen with respect to beam energy

Azimuthal distribution of intensity

Distance d between the charged particle and surface of medium is calculated by

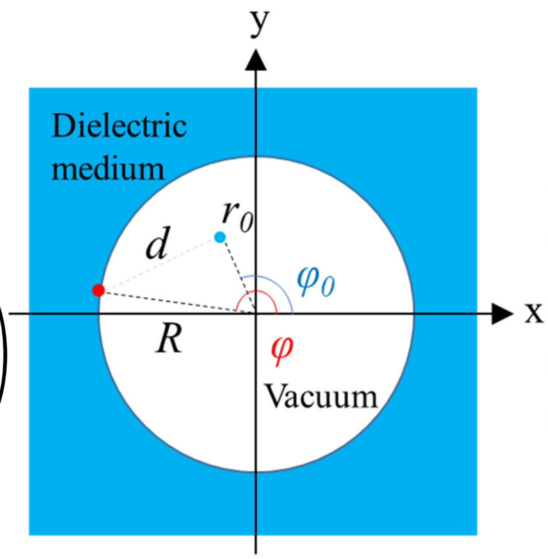
$$d = \sqrt{R^2 + {r_0}^2 - 2r_0 R\cos(\varphi - \varphi_0)}$$

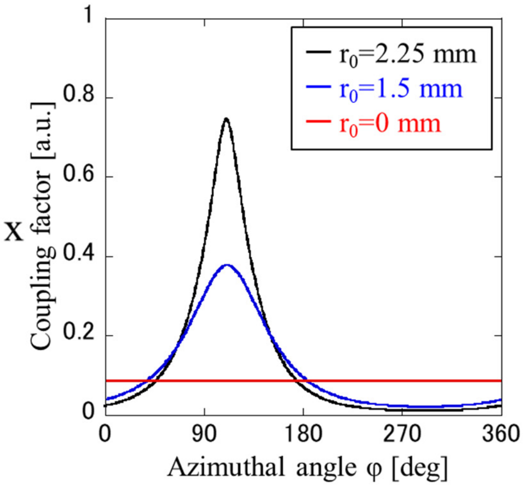
(r_0, φ_0) are the polar coordinates of the beam positon
(R, φ) are the polar coordinates of the position, which defines the intersection of the observation direction with surface of medium.

$$K(r_0, \varphi_0, \varphi) = exp\left(-4\pi\frac{\sqrt{R^2 + {r_0}^2 - 2r_0 R\, cos(\varphi - \varphi_0)}}{\beta\gamma\lambda}\right)$$

Azimuthal distribution of intensity

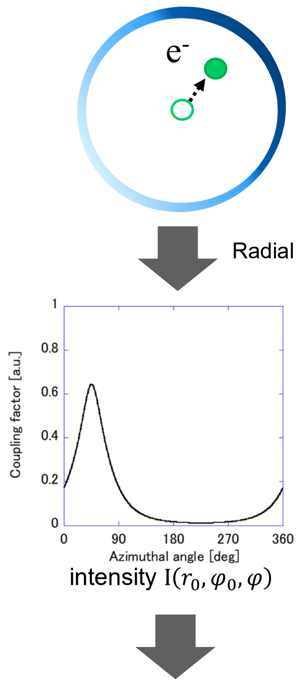
$$I(r_0, \varphi_0, \varphi) = N_0 exp\left(-4\pi\frac{\sqrt{R^2 + {r_0}^2 - 2r_0 R\cos(\varphi - \varphi_0)}}{\beta\gamma\lambda}\right)$$





Position derivation

■ Concept



intensity $I(r_0, \varphi_0, \varphi)$

Beam position (r_0, φ_0)

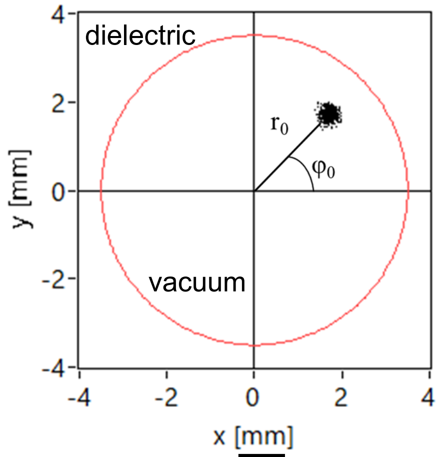
Ring image

Radial integration

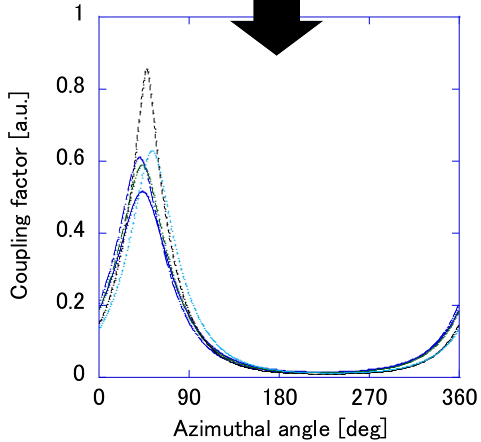
Azimuthal distribution of ChDR
&
Beam position is derived by fitting azimuthal distribution with coupling factor

Beam position

Position derivation (finite beam size)



- Beam size, σ_b:
  - Gaussian distribution
  - σ_b: 0, 25, 50, 100, 200, 300um
  - N:10000
- Beam position, r_0: 0 ~ 2 mm
- Each coupling factor is calculated from the given position of macro particles
- A total coupling factor, which is defined as the average of all the coupling factors is calculated
- Beam position is derived by fitting the total coupling factor with K(φ)



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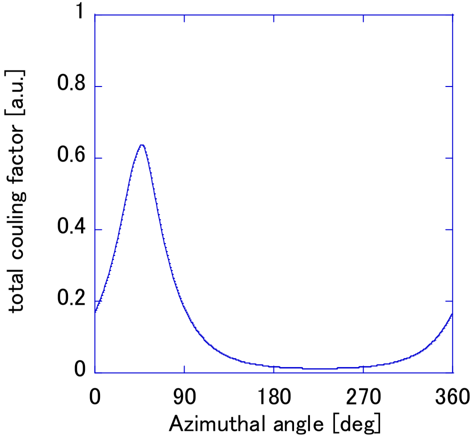
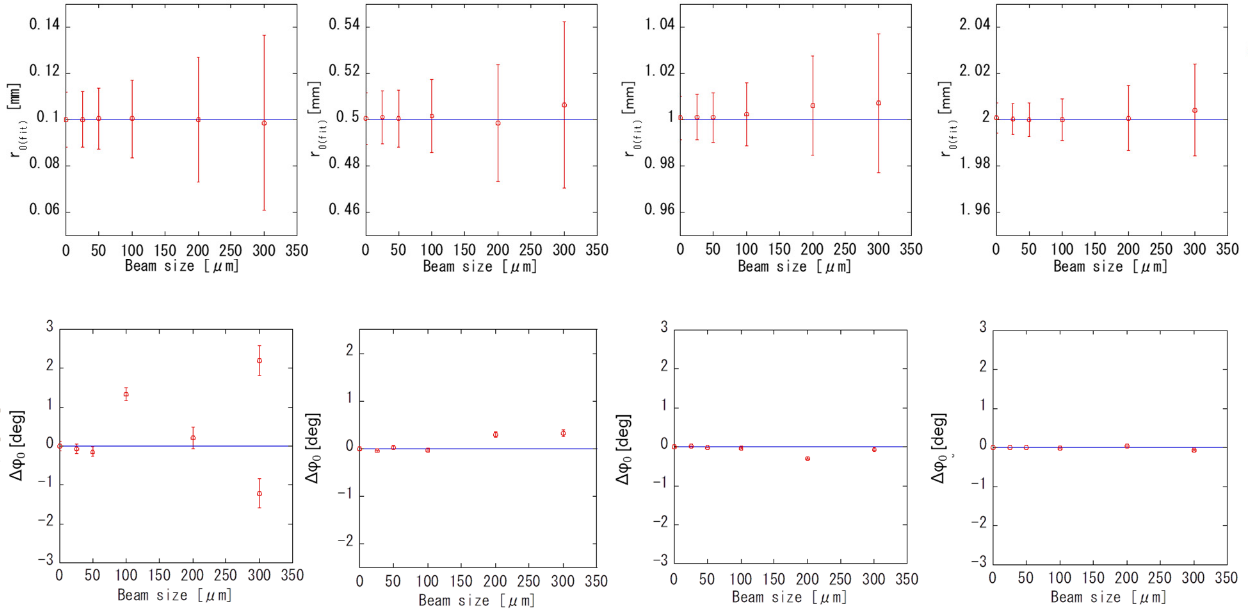


Beam position (r_0, φ_0)

Effect of beam size （Numerical simulation）

r_0 = 0.1 mm　r_0 = 0.5 mm　r_0 = 1.0 mm　r_0 = 2.0 mm



r_0:
Large beam size ➡ Large position error

Beam size should be small

φ_0:
Small r_0 ➡ Large error

※The error bars represent the fitting error

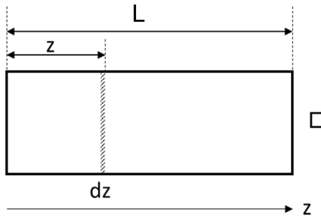
■ 1GeV beam （R: 3.5 mm, λ = 10 μm）:

$\sigma_b \leqq 100$ μm

⇒ $\Delta r_0 \cong 17$ μm

Requirement for hollow dielectric as radiator

ChDR $I(\omega)$ Intensity



$$N_0 = 2\pi\alpha L\left(1-\frac{1}{\beta^2 n^2}\right) \equiv \eta L$$

⇨ Photon yield : $\int_0^L \eta e^{(-A(L-z))} dz$

A is attenuation coefficient
z: Emission point

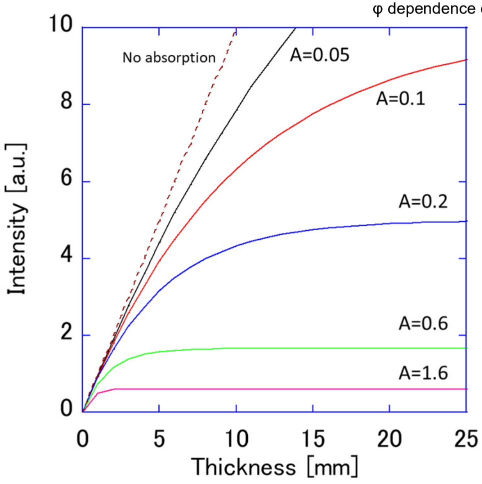
- Hollow dielectric medium
  - Large photon yield ➡ Larger n, Small absorption coefficient
  - Cherenkov angle has to be small ➡ Smaller n

Smaller absorption coefficient, appropriate refractive index

$$I(r_0,\varphi_0,\varphi) = \frac{\eta}{A}\left(1-e^{-AL}\right)\cdot exp\left(-4\pi\frac{\sqrt{R^2+r_0{}^2-2r_0R\cos(\varphi-\varphi_0)}}{\beta\gamma\lambda}\right)$$

A, and *L* have no azimuthal dependence
φ dependence of intensity comes only from coupling factor, *K*

Entire ChDR ring can be observed employing appropriate dielectric medium



Photon yields for various attenuation coefficients

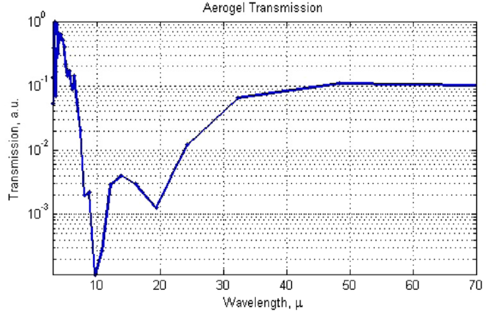
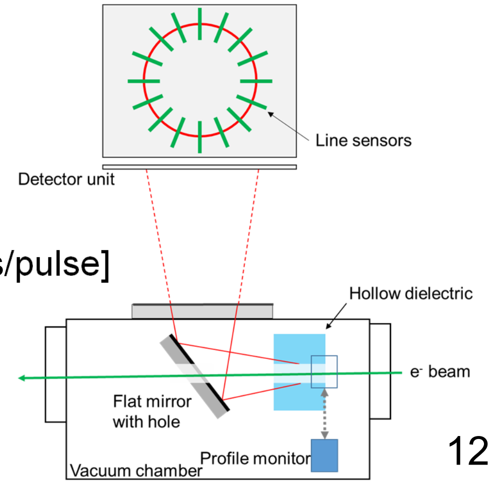


FIGURE 2. Transmission through aerogel (3.5 mm thick) of the black body radiation (1000 K) using BLIS interferometer.

n =1.008

R. Tikhoplav et al., AIP Conference Proceedings 1086, 610 (2009)

1GeV beam:
λ: 10±5 μm
10pC
t=25mm
A=0.05
➡ 5×10^8 [photons/pulse]



Summary

- Laser-wakefield accelerators have attracted much attention and have been developed actively towards practical applications worldwide.

- Single-shot and non-destructive beam monitor will provide the opportunity for effective use in practical application of LWFA.

- By measuring ChDR, single-shot and non-destructive beam diagnostics can be realized.

- The observed wavelength and the size of the hollow dielectric have restrictions related to the beam energy.

- The beam size affects the position accuracy.

- Since the observation wavelength changes depending on the beam energy, it is necessary to optimize the refractive index, thickness, and transmittance of the radiator. As a future prospect, the development of more effective radiators is considered to be an important theme.

Acknowledgement

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Thank you very much for your attention