Study of Longitudinal Phase Space Distribution Measurement via a Linear Focal Cerenkov Ring Camera


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PASJ10 5 August 2013 10:30 - 10:50
• Introduction
• Method for longitudinal phase space distribution measurement
  – Cherenkov radiation
  – Reflective optics
• Extracting beam from vacuum for measurement
  – By studying Multiple scattering of electron beam
• Conclusion
A test accelerator for the coherent terahertz source (t-ACTS) at Tohoku University has been constructed

- to generate intense coherent terahertz (THz) radiation from sub-picosecond electron bunches
- an advanced independently tunable cells (ITC) thermionic RF gun consisting of two uncoupled cavities was proposed
Introduction

- electron beam will be introduced from the RF-gun into the bunch compression system
- To obtain extreme short electron bunch production
  - proper longitudinal phase space distribution by the ITC RF-gun adjusted relative RF phases and field strengths of the two cavities
• one of diagnostic tools to measure electron energy (electron velocity corresponds to opening angle of Cherenkov light)
• **Cherenkov angle contains information of the particle energy**
  \[ \cos \theta_c = \frac{1}{n(\omega)} \beta \]

• aerogel (refractive index \( n = 1.05 \)) = radiator
• number of the Cherenkov photons can be enough to detect

\[ N = 2\pi \alpha z \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \sin^2 \theta_c \]
Linear Focal Cherenkov Ring Camera

1. $e^-$ with same Energy $\rightarrow$ photon with same Cherenkov angle

2. Special Mirror: “Turtle-back” mirror

3. Focus “same-Cherenkov-Angle photon” onto one certain Position
   “different-Cherenkov-Angle photon” gives Linear Position (focal line)

4. Streak Camera

5. directly observe longitudinal phase space distribution

novel method for longitudinal phase space distribution measurement
Special Mirror : “Turtle-back” mirror

- geometry of “turtle-back” mirror
  - Parabolic curve: reflect the photons having the same Cherenkov angle on a certain position
  - Spherical curve: designed for symmetry due to Cherenkov cone (to focus Cherenkov light on the beam axis)

Surface Eq:

\[ x^2 + y^2 - \left( -\frac{1}{2A} s^2 + \frac{A}{2} \right)^2 = 0 \]

- e.g. \( A = 60 \text{ cm} \) (this number relates to energy dependence at focal position);
  mirror azimuthal size = 36 deg (corresponds to number of photon that can be observed)
Optics for Measurement

• “turtle-back” mirror (e.g. \( A = 60 \text{ cm} \))
  – focus the photons having the same Cherenkov angle on a certain position
  – gives a focal line on the s-axis

• 2 off-axis parabolic cylinder mirrors (e.g. focal length = 10 cm)
  – transport photons outside the radiator chamber and confine again
  – focal line of 1\(^{\text{st}}\) parabolic cylinder mirror = 1\(^{\text{st}}\) focal line
  – focal line of 2\(^{\text{nd}}\) parabolic cylinder mirror = 2\(^{\text{nd}}\) focal line

• focal position on the focal line
  – energy dependence at focal position \( \sim 22.8 \text{ keV/mm} \) around electron kinetic energy of 1.870 MeV

• If entrance slit size of the streak camera \( \sim 3 \text{ mm} \)
  : electron kinetic energy range of 1.870 ± 0.034 MeV can be observed at once
Energy Resolution Factors

• Transverse emittance
  – Beam size -> radiation area -> Cherenkov ring
  – Beam divergence -> change direction of Cherenkov rad.

• Thickness of radiator
  -> Cherenkov ring

1. “turtle-back” mirror cannot focus Cherenkov Ring from same electron energy to one point
2. Direction of each electron dictates direction of Cherenkov cone which now contains information of the particle energy
Beam Transverse Emittance

- Energy dependence at focal position ~ 22.8 keV/mm
  - Its size is proportional to energy resolution by energy dependence
  - Consider 1x(standard deviation)
  - Energy resolution ~ 3.78 keV
    - about 18 \( \sigma \) corresponds to entrance slit size of the streak camera (3 mm)
    - seems satisfied

- Energy resolution ~ 5.20 keV
  - not much different from above case

To focus beam properly can enhance energy resolution
The radiator was intended to be placed outside the vacuum chamber. Beryllium thin film was proposed as a beam window. Electron beam will suffer from multiple scatterings. Root-mean-square deflection angle:

$$\theta_{\text{rms}} = \langle \theta^2 \rangle^{1/2} = \frac{21\text{MeV}}{E} \sqrt{\frac{t}{X_0}}$$

If minimum thickness of the beryllium (Be) thin film is 50 microns, (minimum) rms deflection angle is 0.105 rad or about 6 deg (kinetic energy = 1.87 MeV).
Geant4 Monte Carlo Simulation

- Geant4 can simulate the passage of particles through matter by using Monte Carlo methods
- To investigate multiple scatterings of electron beam through Be window

- significantly high deflection angle of an injected electron (through the 50-micron Be window)
  - because of Cherenkov angle (that contains information of particle energy)
- pretty high energy distribution
Multiple Scatterings of Electron Beam

50-micron Be window point-like beam (E_k = 1.87 MeV)

Its large size degrades energy resolution

Consider 1x(standard deviation)
Energy resolution \(\sim 0.55\) MeV

• multiple scatterings of the electron beam in the beryllium window degrades energy resolution
  − (position on the focal line corresponds the electron energy)
• **With** the 50-micron Be window
  – Energy resolution ~ 0.55 MeV (cannot be accepted)
    for point-like $e^-$ beam

• **Without** the Beam Window
  – Energy resolution ~ 3.78 keV (can be satisfied)
    for $e^-$ beam with normalized emittance of 0.25 mm mrad

• To extract electron beam from vacuum chambers cannot be applied for this measurement method.
• Longitudinal phase space distribution measurement via a linear focal Cherenkov ring camera has been studied.
• Numerical ray tracing combining multiple scatterings effect of Geant4 results:
  – to extract the electron beam from vacuum degrades energy resolution of measurement.
• In vacuum setup was proposed:
  – the radiator and the reflective optics should be placed inside the vacuum chamber,
    • Concerning aerogel in vacuum which is dangerous due to vaporization
  – Cherenkov light transported through a quartz window out of the vacuum to the detector
    • Concerning refraction through a quartz window and its roughness.
We would like to thank

- Mr. R. Yamazaki, Drs. M. Miyabe, and H. Kikunaga for technical assistance (Geant4)
Thank you for your kind attention