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

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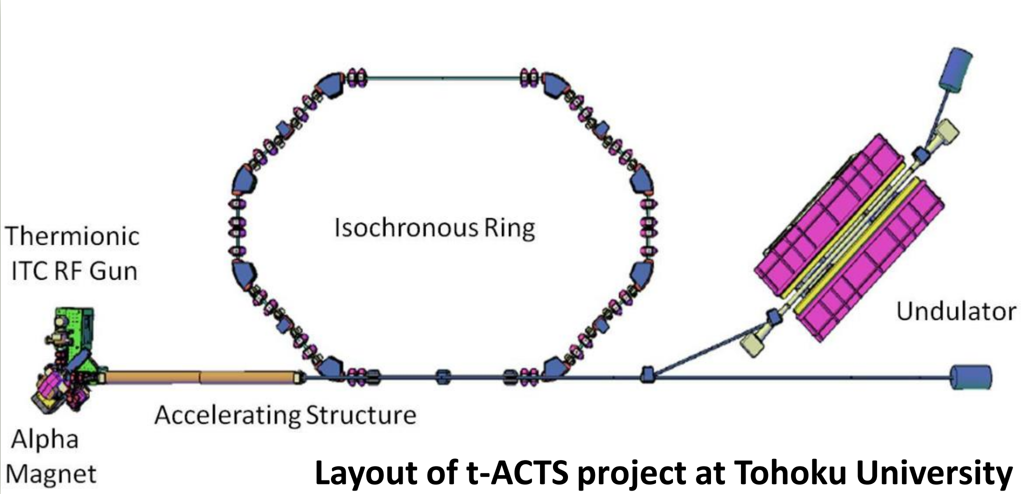
Outline

- 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

Introduction

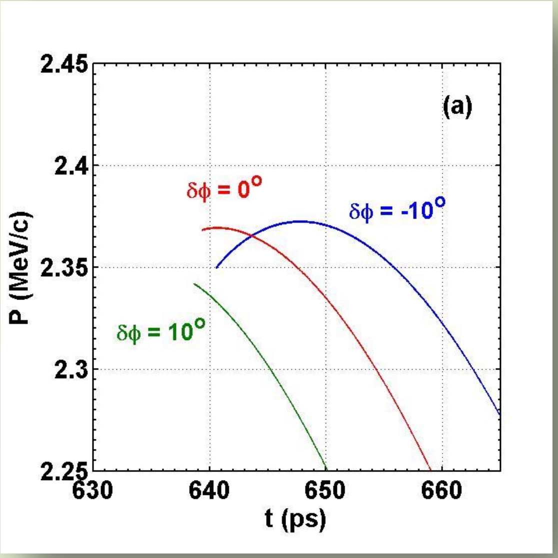
- A test accelerator for the coherent terahertz source (t-ACTS) at Tohoku University has been constructed
  - to generate intense coherent terahertz (THz) radiation from sub-picosecond electron bunches
  - an advanced independently tunable cells (ITC) thermionic RF gun consisting of two uncoupled cavities was proposed



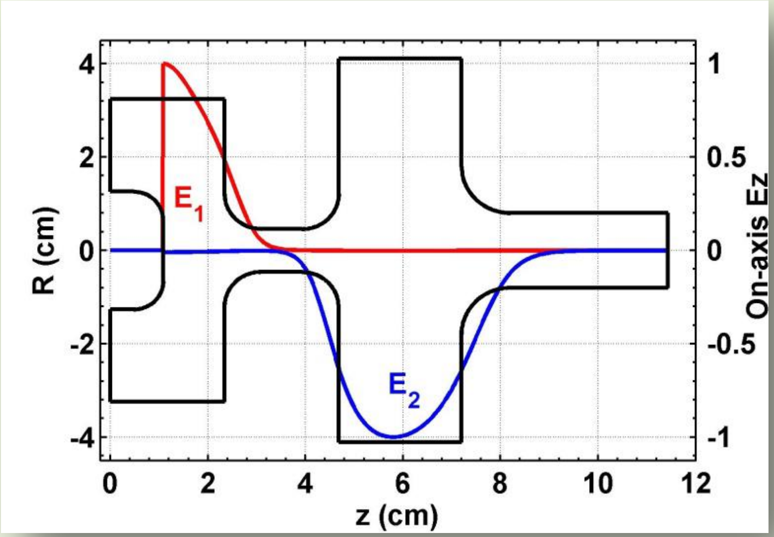
Layout of t-ACTS project at Tohoku University

Introduction

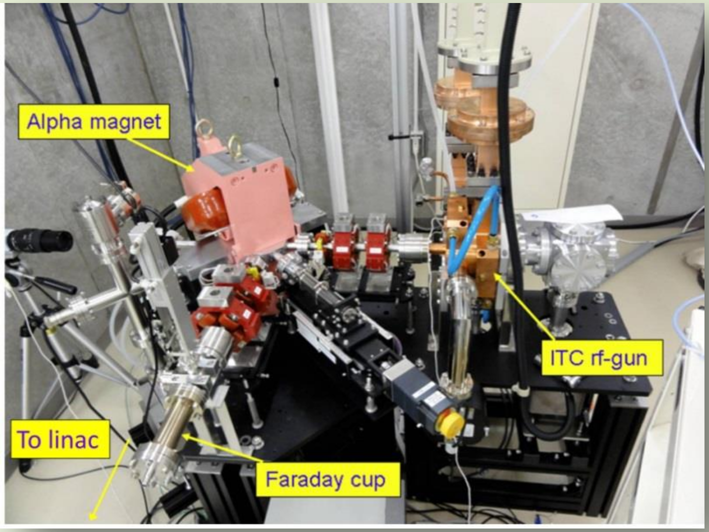
- electron beam will be introduced from the RF-gun into the bunch compression system
- To obtain extreme short electron bunch production
  - proper longitudinal phase space distribution by the ITC RF-gun adjusted relative RF phases and field strengths of the two cavities



longitudinal phase space (phase dependence)



Cross-section view of the ITC RF gun



Injector part for t-ACTS

Cherenkov Radiation

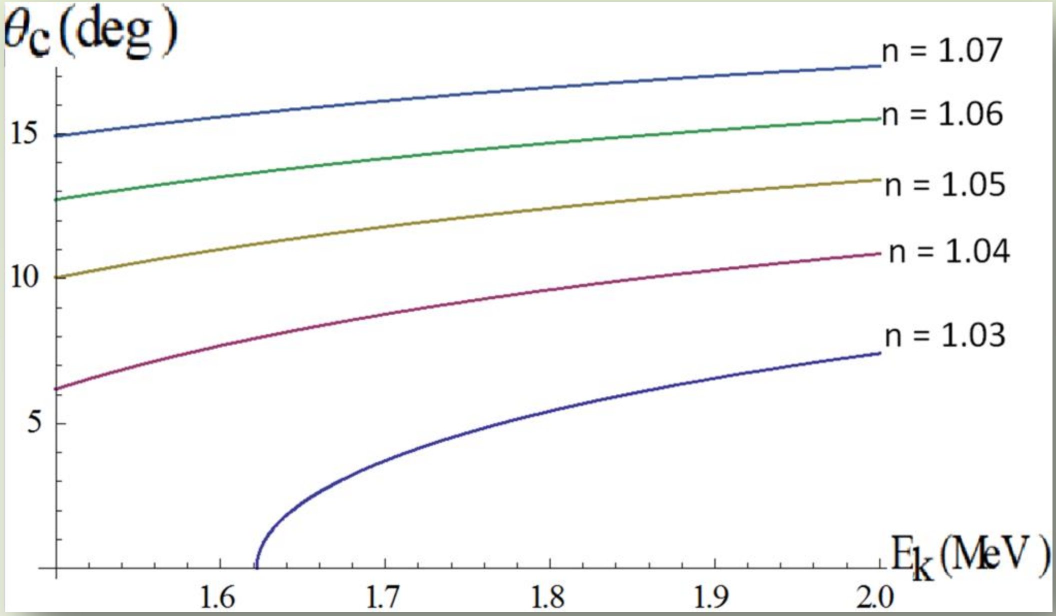
- one of diagnostic tools to measure electron energy
  (electron velocity corresponds to opening angle of Cherenkov light)
- **Cherenkov angle contains information of the particle energy** $\boxed{\beta > 1/n(\omega)}$

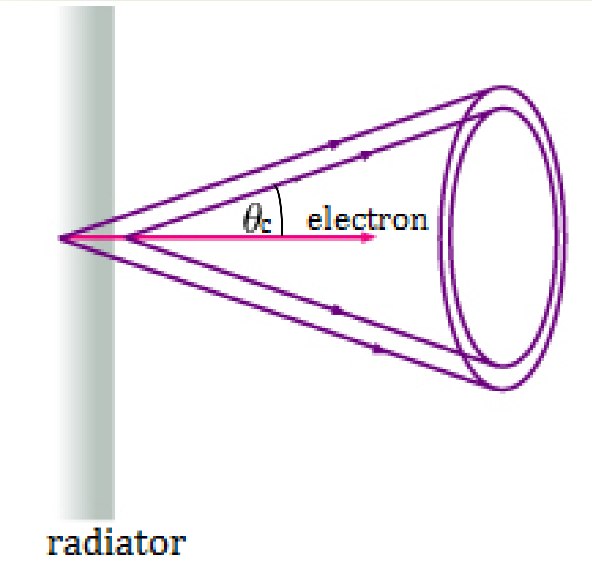
$$\boxed{\cos\theta_c = 1/n(\omega)\beta}$$

- aerogel (refractive index *n* = 1.05) = radiator

$$\boxed{N = 2\pi\alpha z(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})\sin^2\theta_c}$$

- number of the Cherenkov photons can be enough to detect





Linear Focal Cherenkov Ring Camera

novel method for longitudinal phase space distribution measurement

1

- e^- with same Energy -> 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

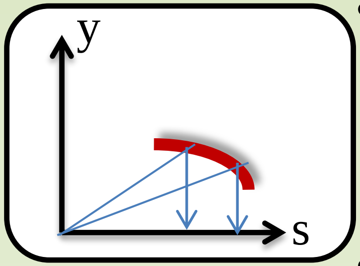
- Streak Camera

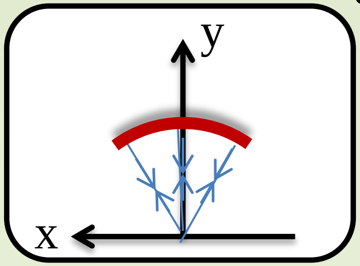
5

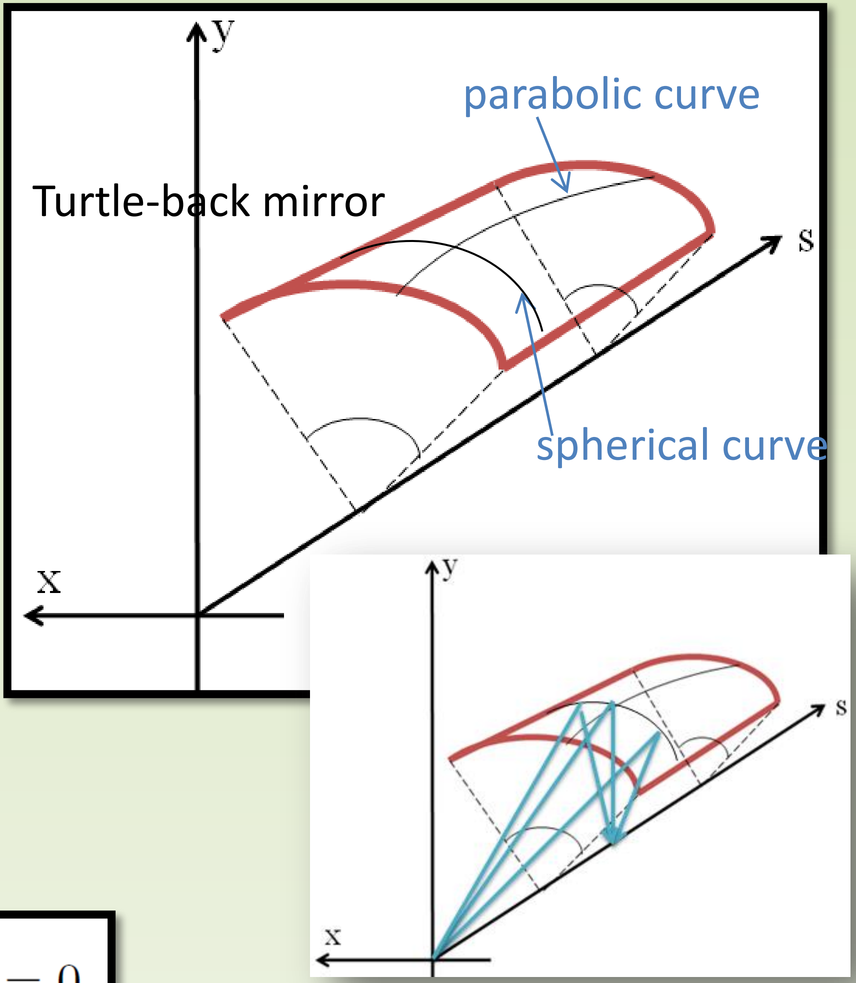
- directly observe longitudinal phase space distribution

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)



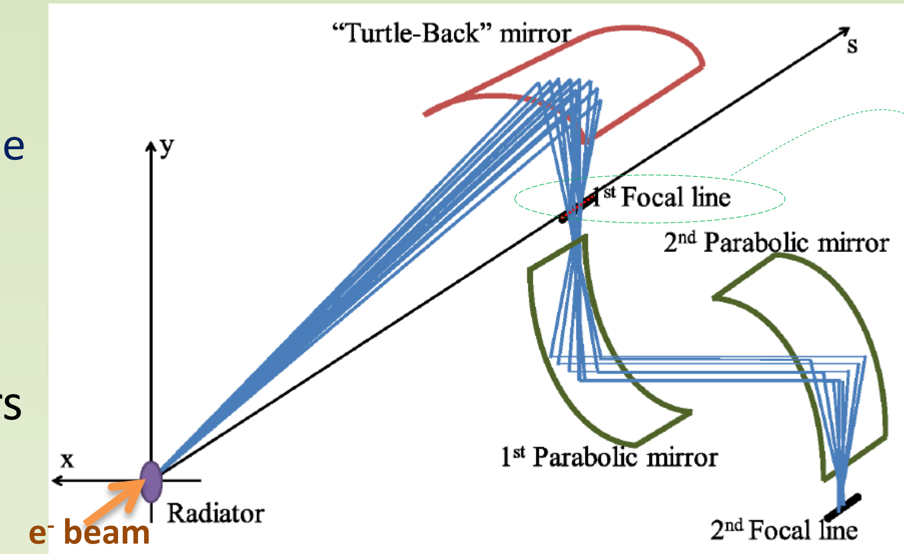




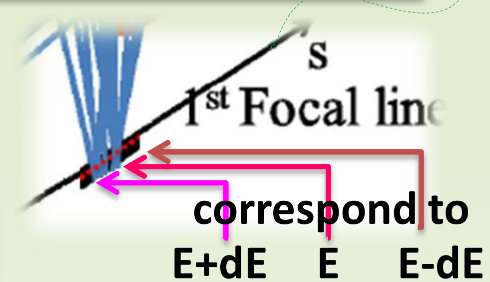
- Surface Eq: $$x^2 + y^2 - (-\frac{1}{2A}s^2 + \frac{A}{2})^2 = 0$$ A = 2x(focal length of parabolic curve)
  - e.g. A = 60 cm (this number relates to energy dependence at focal position); mirror azimuthal size = 36 deg (corresponds to number of photon that can be observed)

Optics for Measurement

- "turtle-back" mirror (e.g. A = 60 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 1st parabolic cylinder mirror = 1st focal line
  - focal line of 2nd parabolic cylinder mirror = 2nd focal line

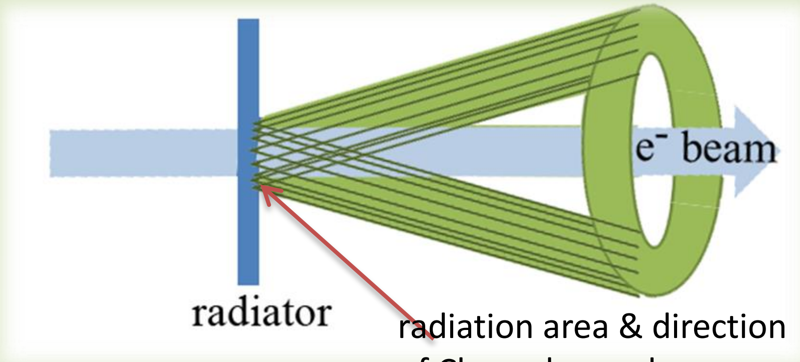


- focal position on the focal line $$s_f(\beta) = An\beta\left(1-\sqrt{1-\left(\frac{1}{n\beta}\right)^2}\right)$$
  - energy dependence at focal position ~ 22.8 keV/mm around electron kinetic energy of 1.870 MeV
- If entrance slit size of the streak camera ~ 3 mm

  : electron kinetic energy range of 1.870 ± 0.034 MeV can be observed at once

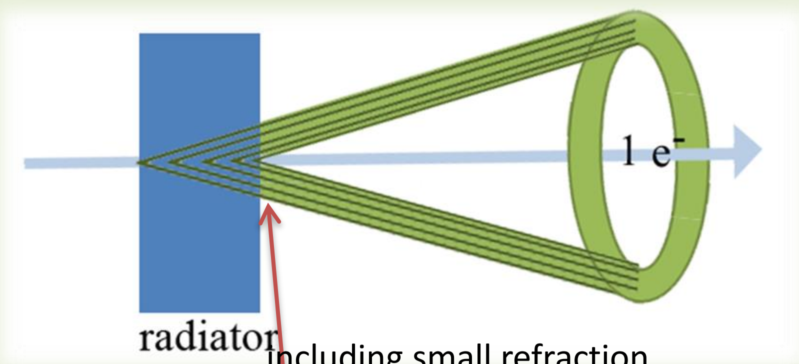
Energy Resolution Factors

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



radiation area & direction of Cherenkov rad

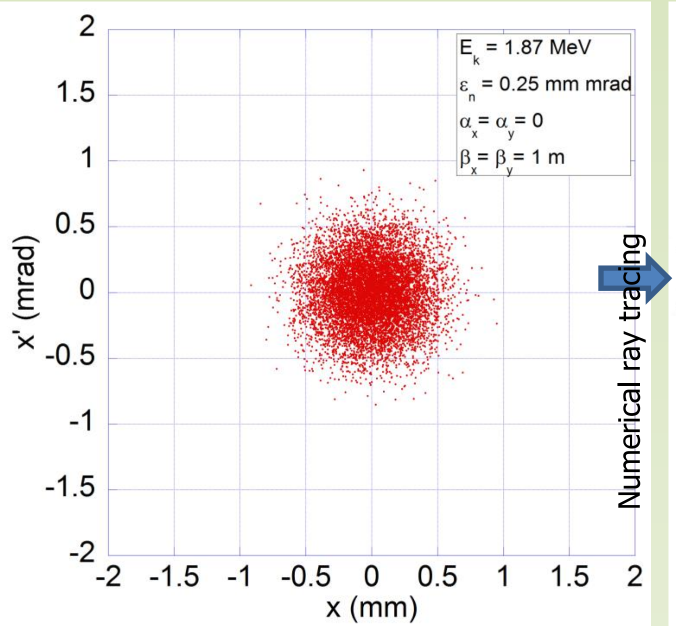
- Thickness of radiator
  -> Cherenkov ring

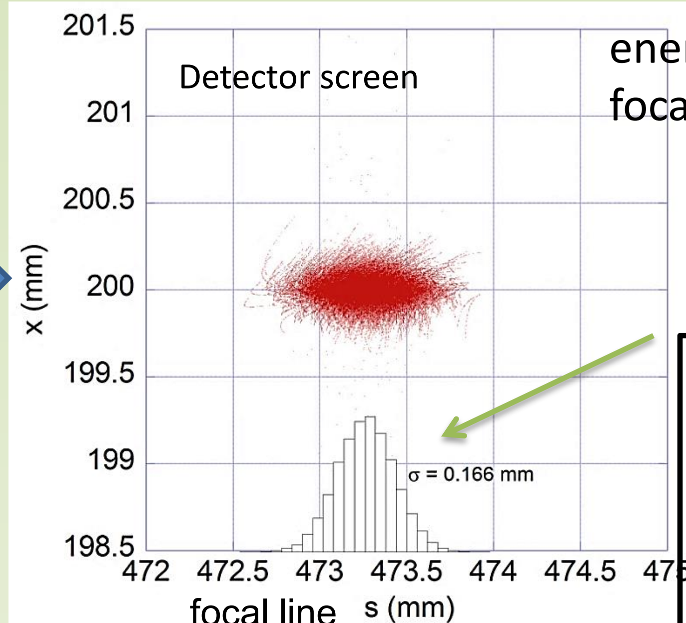


including small refraction between 2 mediums

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



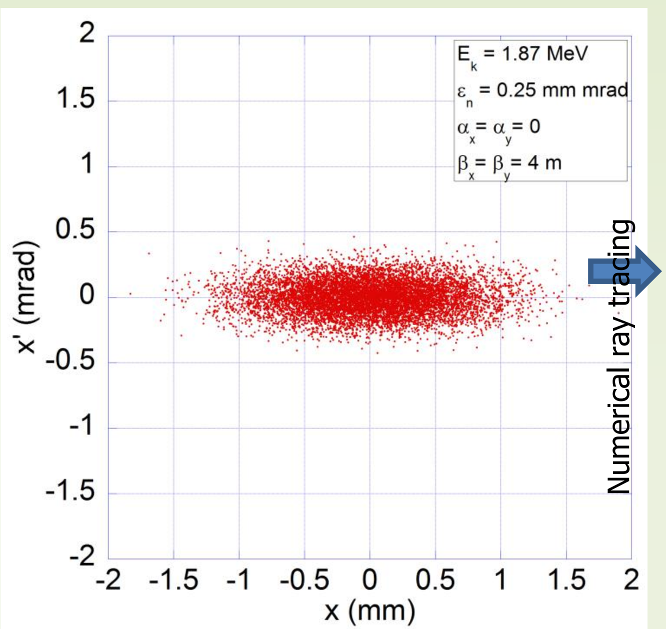


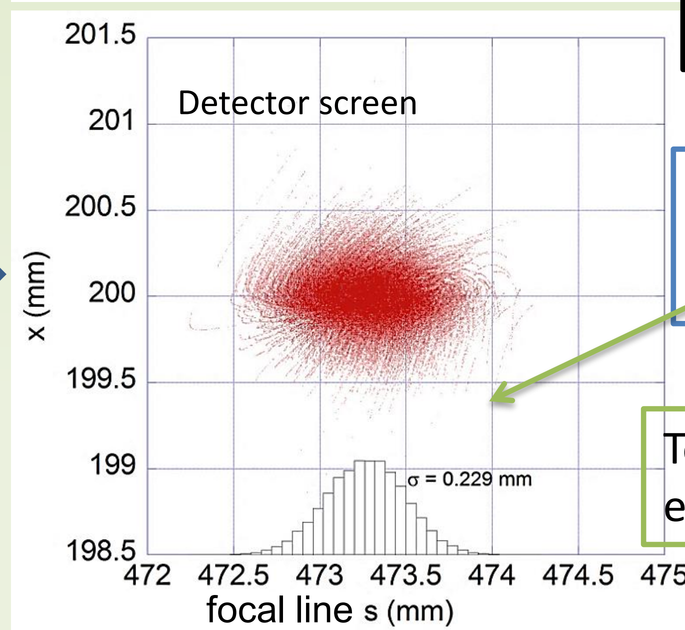
energy dependence at focal position ~ 22.8 keV/mm

Its size is proportional to energy resolution by energy dependence

Consider 1x(standard deviation)
Energy resolution ~ 3.78 keV

- about 18 σ corresponds to entrance slit size of the streak camera (3 mm)
- seems satisfied

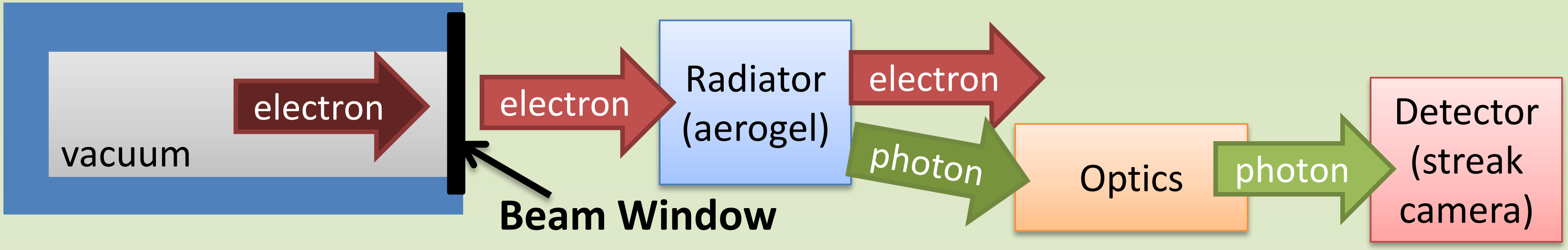




Energy resolution ~ 5.20 keV
- not much different from above case

To focus beam properly can enhance energy resolution

Extracting Beam from Vacuum for Measurement



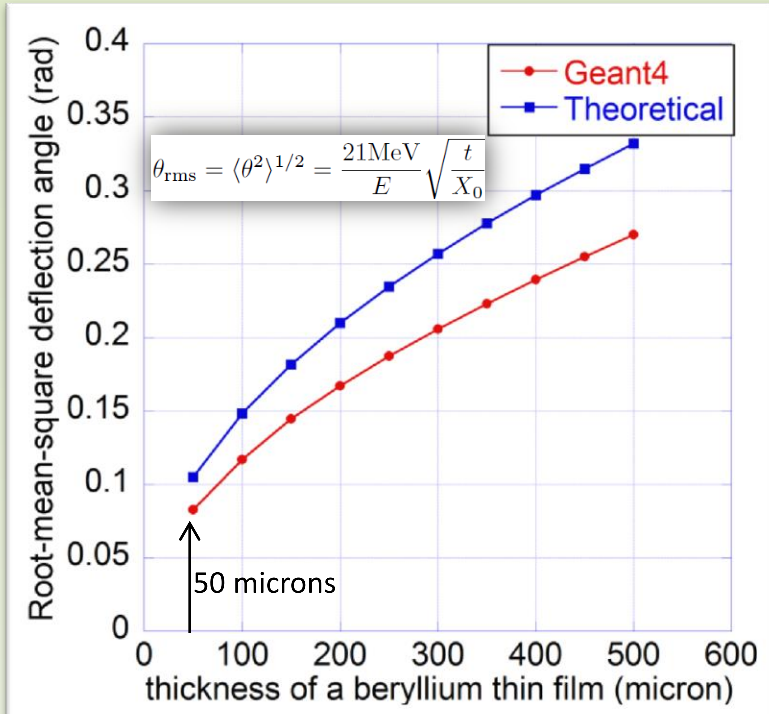
- The radiator was intended to be placed outside the vacuum chamber
- beryllium thin film was proposed as a beam window
- Electron beam will suffer from multiple scatterings
- root-mean-square deflection angle

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

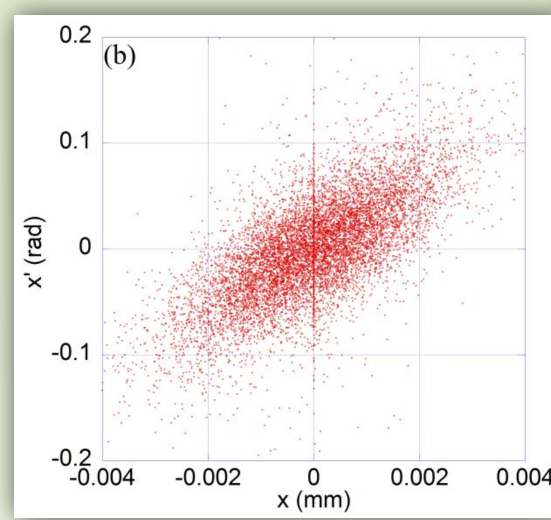
- if minimum thickness of the beryllium (Be) thin film is 50 microns, (minimum) rms deflection angle is 0.105 rad or about 6 deg (kinetic energy = 1.87 MeV)

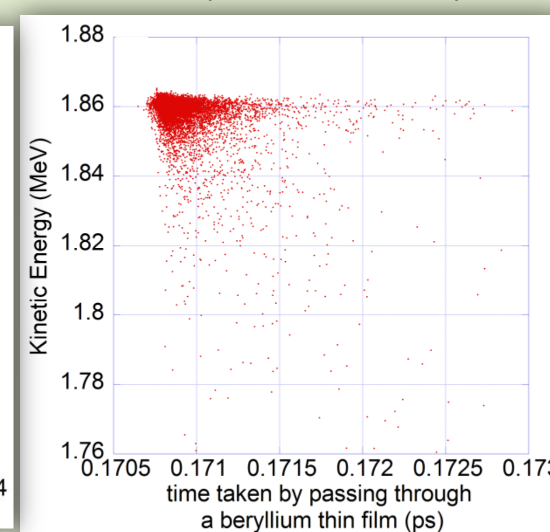
Geant4 Monte Carlo Simulation

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



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

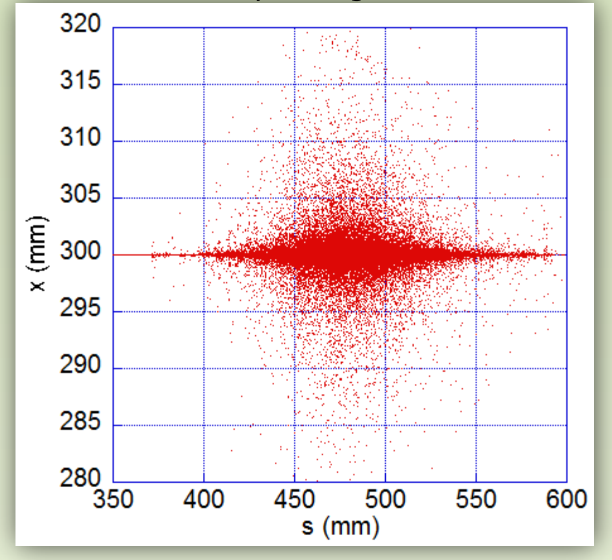




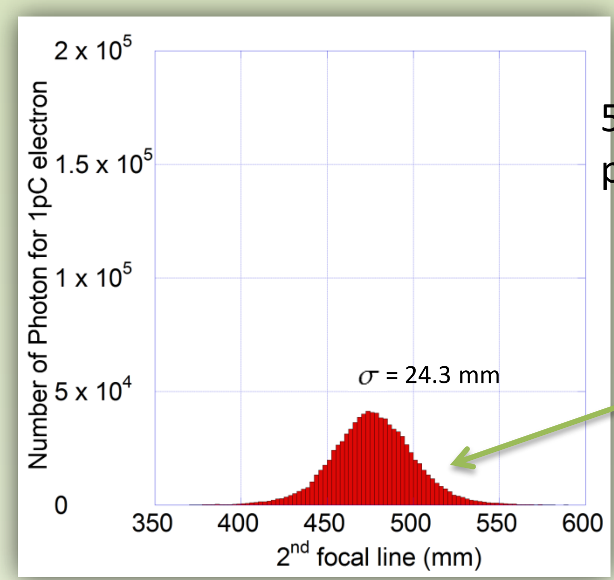
- significantly high deflection angle of an injected electron (through the 50-micron Be window)
  - because of Cherenkov angle (that contains information of particle energy)
- pretty high energy distribution

Multiple Scatterings of Electron Beam

Geant4 -> Numerical ray tracing



Detector screen



Spatial profile

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

Its large size degrades energy resolution

Consider 1x(standard deviation)
Energy resolution ~ 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)

Discussion

- 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.

Conclusion and Prospect

- 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

Acknowledgment

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Thank you for your kind attention