X-Ray Polarimetry

From the early days to an outlook for the future

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Outline

- A look to the past & tribute to Bob Novick
- The present --- electron tracking
- A view to the future

In the beginning…..

- July 1968 – Lithium-block, Thomson-scattering polarimeter flown on an Aerobee -150 rocket
  - Target was Sco X-1

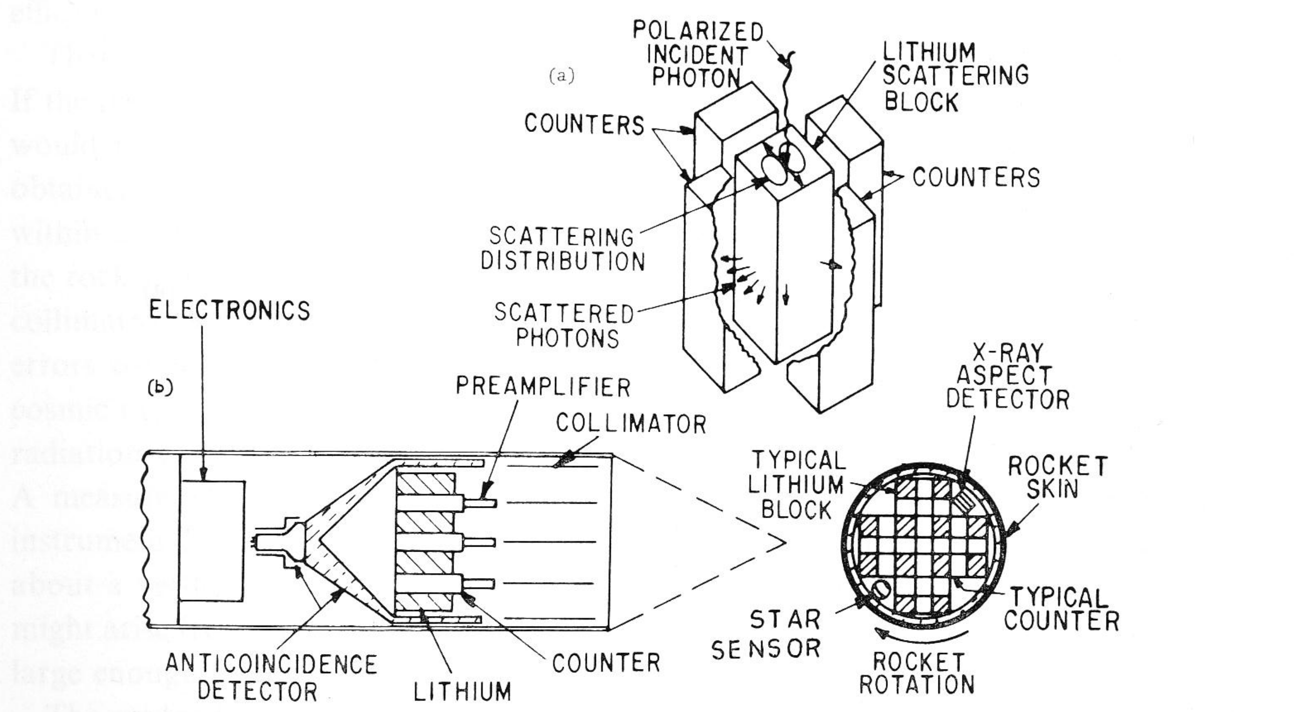


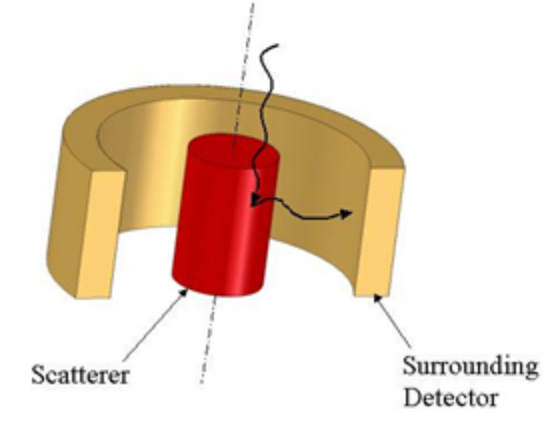
Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.

Scattering polarimeter

- Thomson cross-section illustrates the angular dependence

$$d\sigma / d\Omega = (e^2 / mc^2)^2 (\cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi)$$

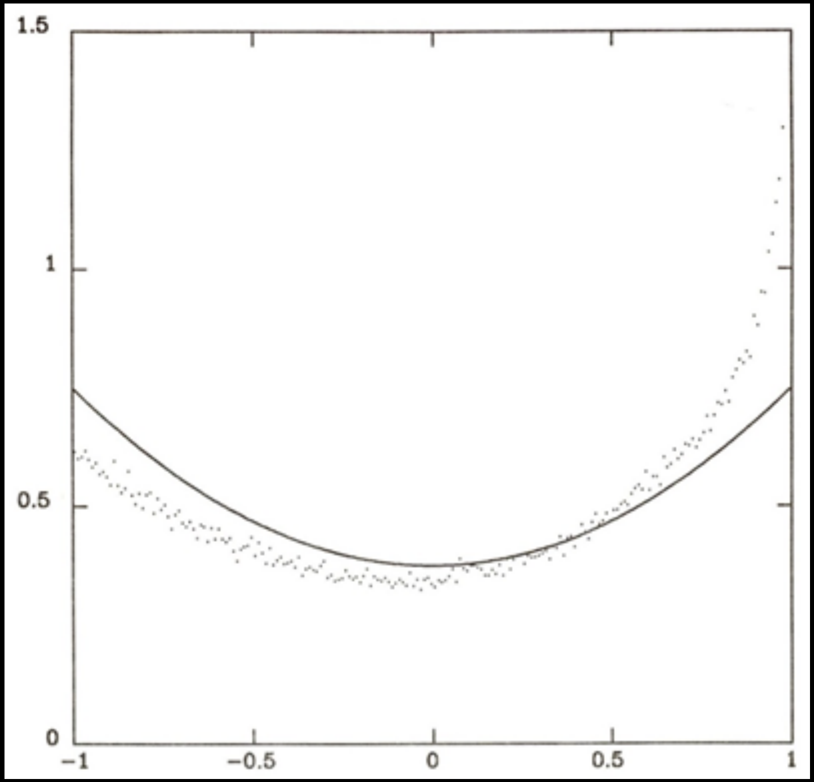
- For scattering from bound electrons one must account for both coherent and incoherent scattering and photoelectric absorption



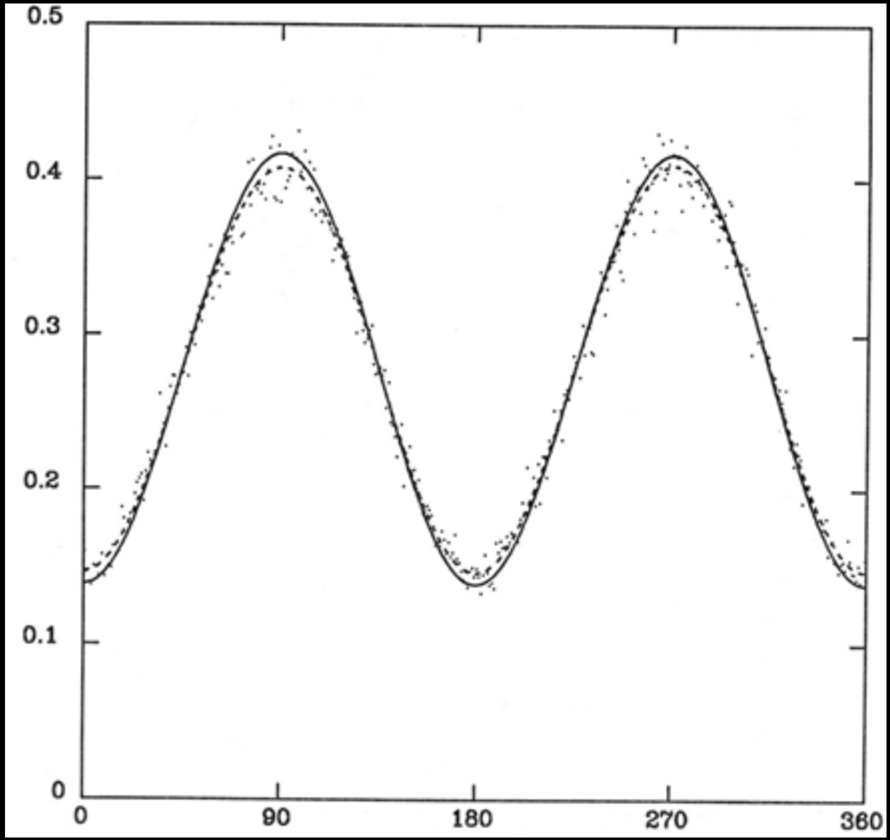
$$\frac{d\sigma_{\text{coh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \phi + \sin^2 \phi \rangle |F|^2$$

$$\frac{d\sigma_{\text{incoh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \phi + \sin^2 \phi \rangle I$$

Thompson Approximation



Cos (polar scattering angle)



Azimuthal scattering angle

Advantages

- Inherently broad band device
  - Astrophysical non-thermal spectra are characteristically broad band
  - Astrophysical diagnostics (model discriminators) may/should benefit from understanding the energy dependence

Considerations

- Scatter as much incident flux as possible
- Avoid multiple scattering
- Achieve as large a sensitivity to polarization as possible
- Collect as many scattered X-Rays as possible
- Minimize the background
- Optimize the “MDP”

$$MDP(\%) = (4.29x10^4 / M(\%))\sqrt{(R_S + R_B)} / \sqrt{R_S^2 t}$$

Disadvantage: The conundrum

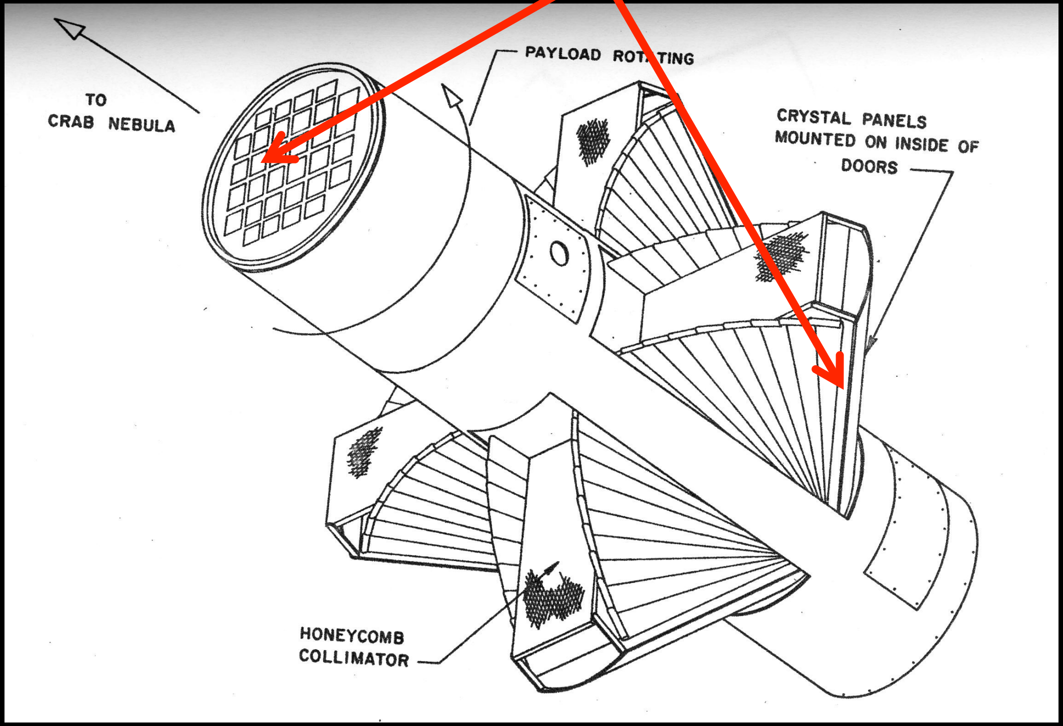
- The scattering material should be thick (deep) in order to effectively provide for interaction with all the incident photons
- The scattering material should be thin (narrow) in order to allow the scattered photon to easily escape
- Similar conundrums apply as well to other approaches to X-ray polarimetry

In the beginning….

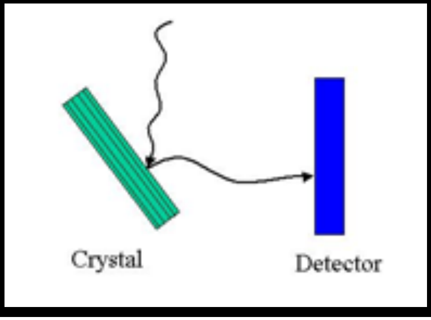
- March 1969 - Lithium-block, Thomson-scattering polarimeter flown on an Aerobee -150 rocket
  - Target was the Crab Nebula
- February 1971 Lithium-block, Thomson-scattering polarimeter and a Bragg crystal polarimeter flown on an Aerobee -350 rocket
  - Target was the Crab Nebula
- Three rockets in 21 months!

Rocket 17.09

- Two instruments in one payload!
  - Lithium scattering polarimeter
  - 4 Bragg crystal polarimeters



Crystal polarimeter



$$\frac{N}{T}=\int_0^\infty \frac{I(E')}{E'}R(E',\vartheta)A(\vartheta)dE' = I(E)A(\vartheta_B)\Delta\vartheta(E)\cot(\vartheta_B)$$

where

$$E=\frac{nhc}{2d\sin(\vartheta_B)}$$

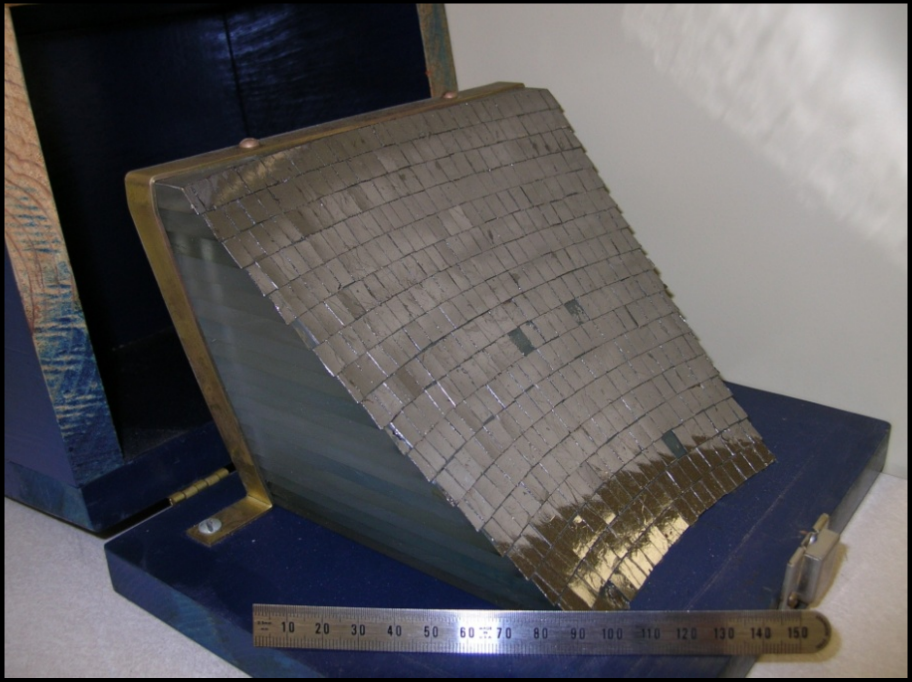
$$\Delta\vartheta(E)=\frac{N_S^2F^2r_0^2}{2\mu(E)}\left(\frac{hc}{En}\right)^3\left[\frac{1}{\sin 2\vartheta_B}-\frac{\sin 2\vartheta_B}{2}(1+\Pi\cos 2\varphi)\right]$$

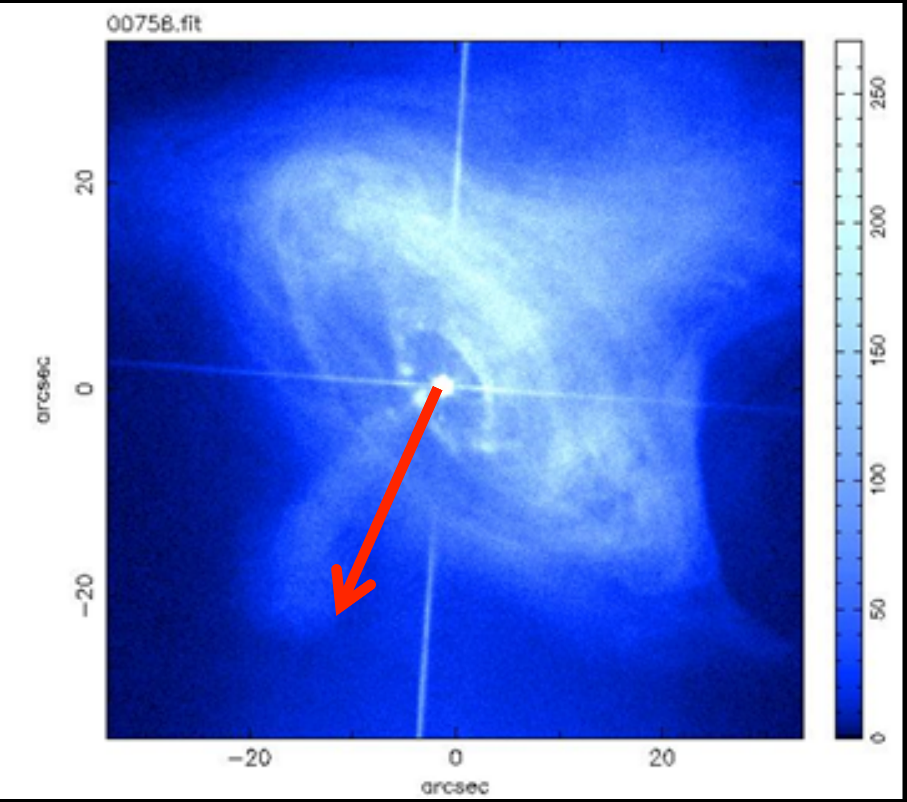
Rocket 17.09

- 1971 Aerobee 350
  - Crab detection!
    - P = 15% ± 5%
    - $\varphi = 156° \pm 10°$

On to the satellite experiment

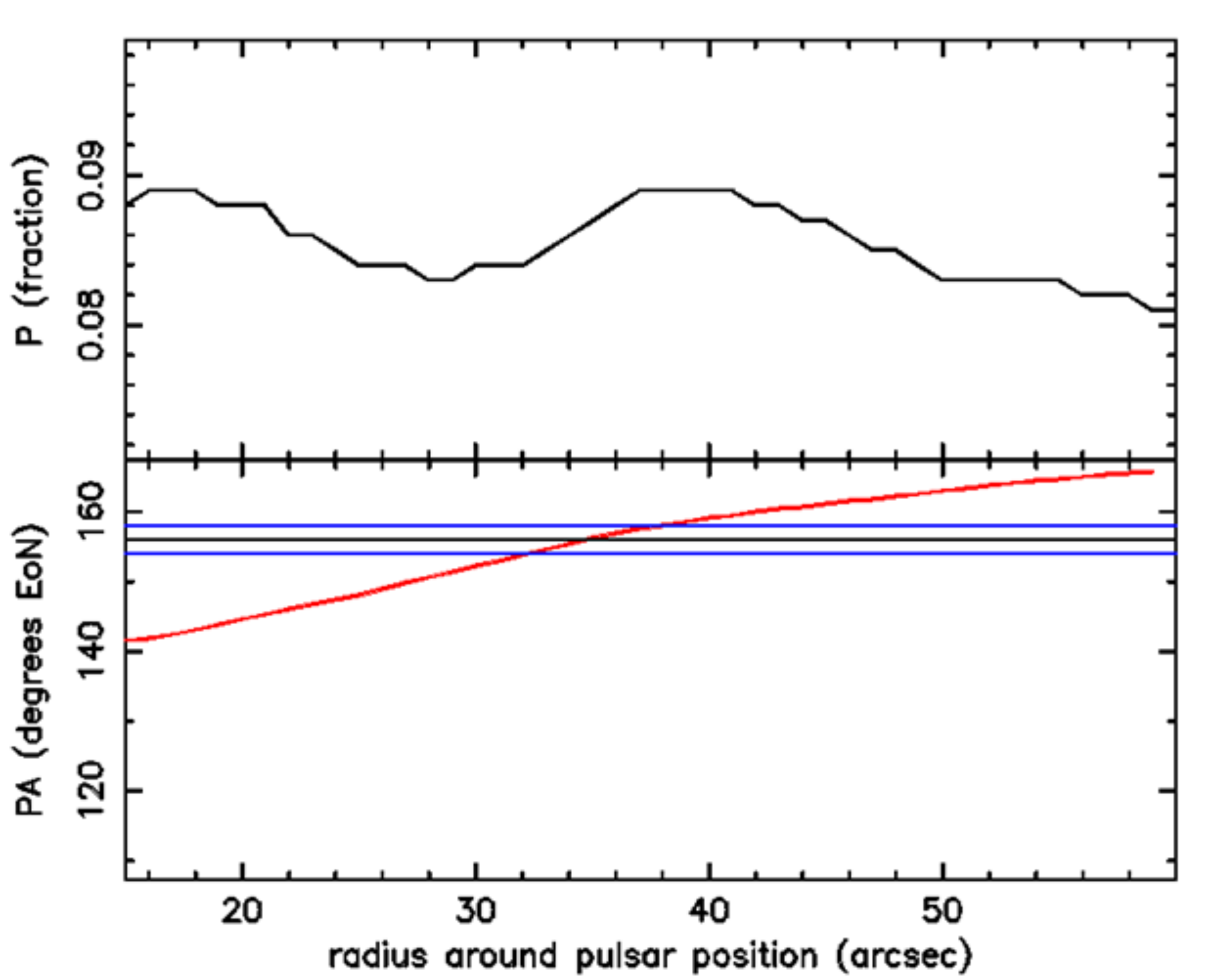
- 1975 OSO-8 crystal polarimeter
  - Precision measurement of integrated Crab Nebula polarization at 2.6 keV
    - P = 19% ± 1%
    - φ = 156° ± 2° (NNE)





Compare to modern optical results

Moran, P., Shearer, A., Mignani, R.P., et al. (2013)



1975 - 2014

- X-ray polarimeter on the original Einstein mission but descoped
  - Polarimeters amongst the first to go
- X-ray polarimeter built for the original SRG mission … which never launched
- X-ray polarimeter selected for the last NASA SMEX mission … but was cancelled

1975 - 2014

- Polarimeters don't get much observatory time
    - 60 days of observation per year (OSO-8)
    - 11 days of observations per year (SXG)

Electron-Tracking Polarimeters

- Optical Imaging Chamber
  - Austin & Ramsey 1992
- Pixelated Gas Multiplication
  - Costa et al. 2001
- Time Projection Chamber
  - Black et al. 2007

Electron-Tracking

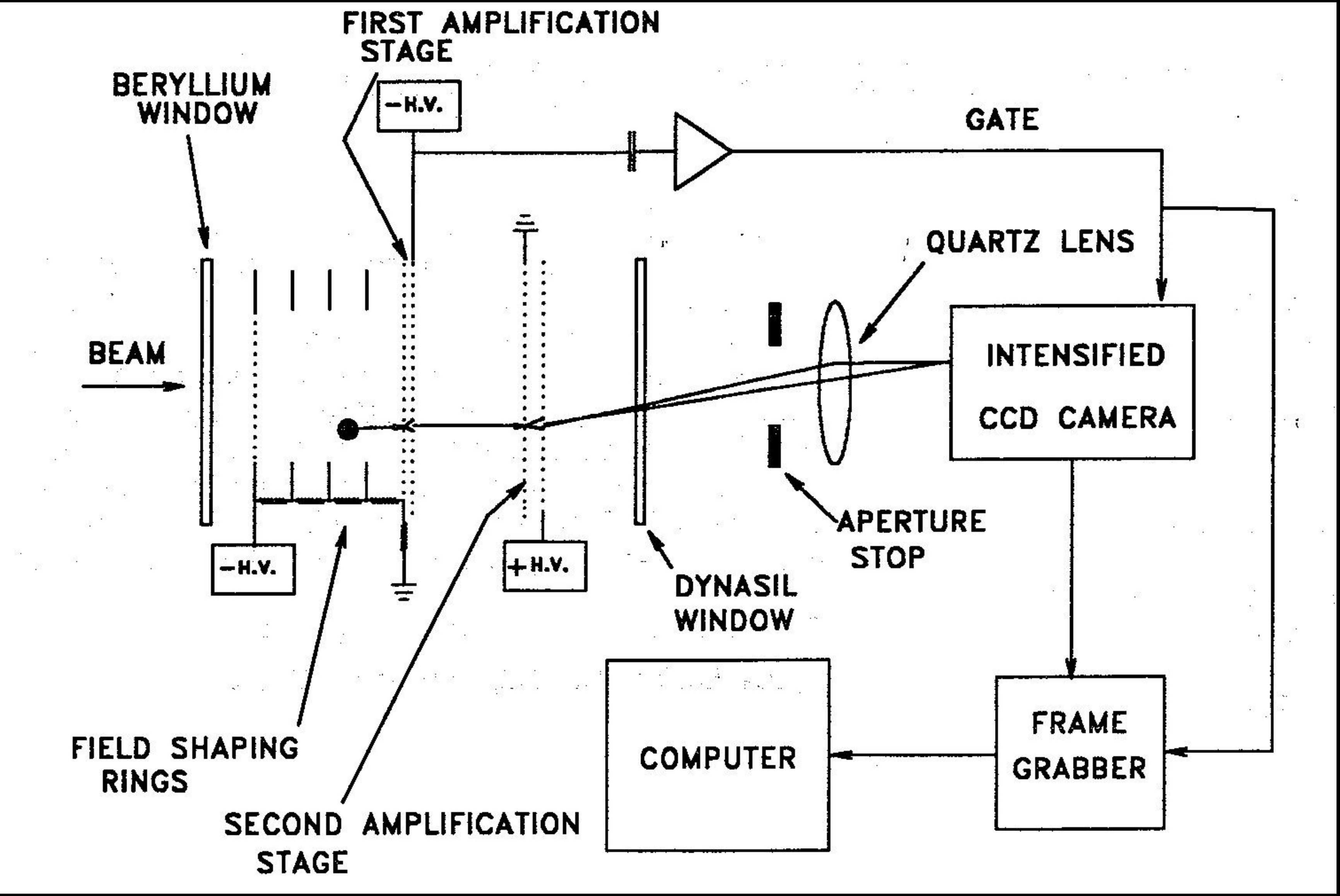
- The direction of the *initial* K-shell photoelectron is determined by the electric vector and the direction of the incoming photon

$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2} \sin^2\theta \cos^2\varphi$$

Electron-Tracking

Site of initial ionization and Auger electron cloud produced by a 54 keV photon

Electron-Tracking



Austin and Ramsey (1992)

Looking to the future

- We need to remember that X-ray polarimetry is difficult
    - One does not expect all astrophysical systems to be strongly polarized
    - Instruments typically not fully sensitive to polarization
    - Linear polarization is non-negative – i.e. one always measures something, even for an unpolarized source

Looking to the future

- X-ray polarimetry can be powerful – *especially* if accompanied by high-resolution imaging
- X-ray polarimetry typically *requires* longer observing times than imaging, spectroscopy, and timing
- **Do not rely on an observatory-class mission**
    - Won't get the needed observing time
    - Early (if not first) candidate for descoping

Finally

- Polarimetry is the study of systematic effects
  - End-to end calibration of the full system with unpolarized beams to the appropriate precision is essential!