Advances in X-Ray Scintillator Technology

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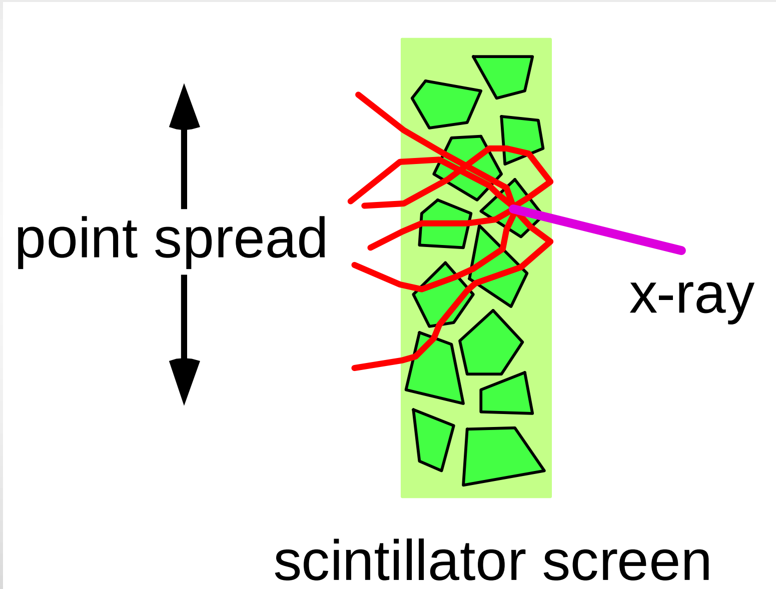
Scintillator-based imagers

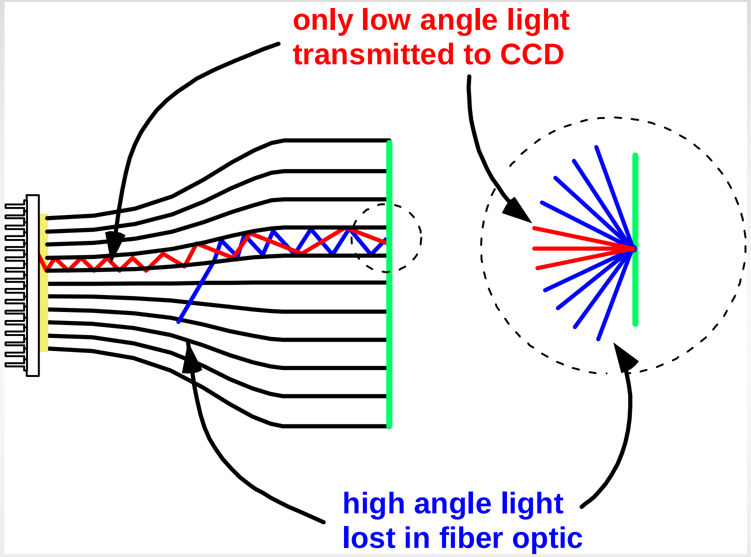
- One of the earliest techniques employed for imaging ionizing radiation
- Scintillator-based imagers remain one of the most flexible and successful techniques for x-ray imaging
  - Crystallography
  - SAXS/WAXS
  - Microtomography...
- However, conventional scintillators have significant limitations...

Limitations of conventional scintillators: point spread function

- **Point Spread Function (PSF) is limited by scattering in polycrystalline phosphor screen: typically > 100 ?m FWHM**

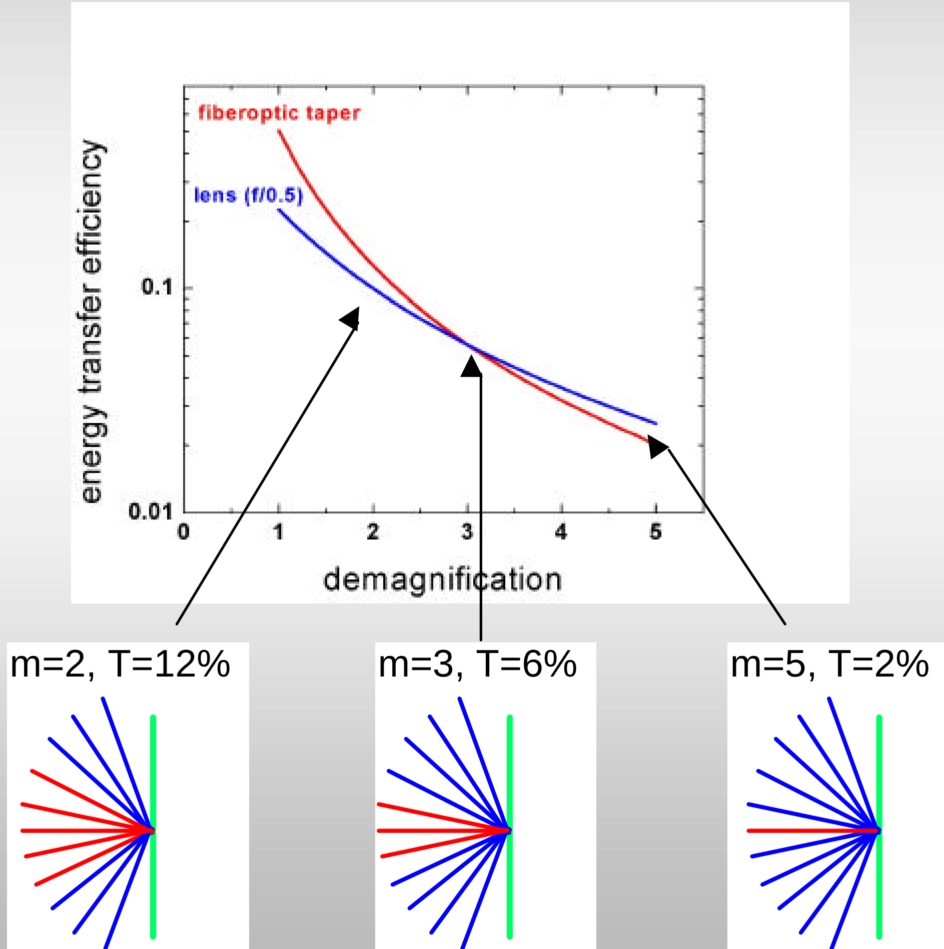


Limitations of conventional scintillators: Light loss in demagnifying optics



- Conventional screens are Lambertian
- However, light emitted at *large angles* is lost in the optics
- Only *low angle* light is transmitted to CCD

Transmission efficiency scales as $1/m^2$



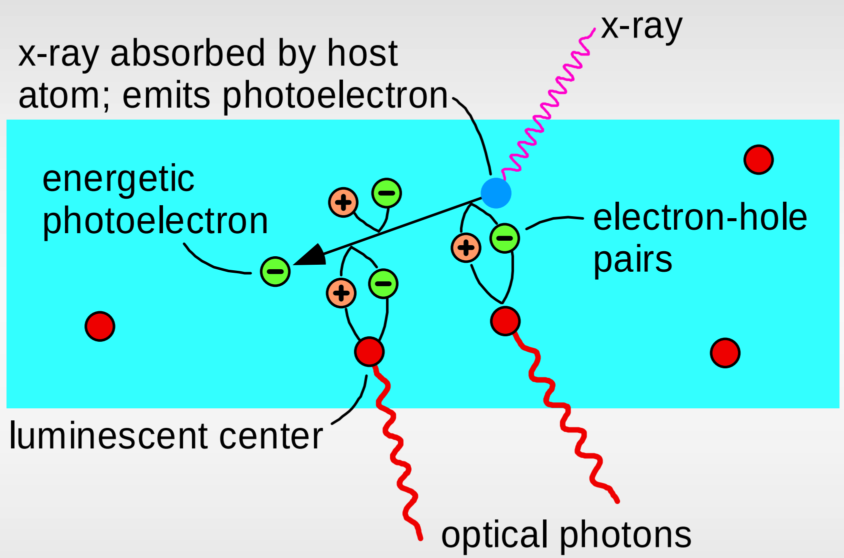
Present day integrating detectors do not achieve optimal sensitivity

- **Gruner (1996) noted that for optimal dynamic range and near-quantum limited performance an integrating detector (CCD, a-Se, …) should achieve a SNR of order 1.**
- **Because of transmission losses and point spread, no present *large area*, integrating detectors satisfy this criterion...**

	CCD (typical)	a-Se (typical)
Quantum gain	10 electrons	120 electrons
Noise	10 electrons	500 electrons
Integrated noise	40 electrons	500 electrons
True SNR	0.25	0.25

Design of high gain X-ray phosphors

- **Characteristics of efficient x-ray phosphors**
  - **High x-ray absorption (large ?$_{x\text{-}ray}$)**
  - ***Low cost per electron-hole pair (small ?E_g)***
  - **Efficient electron-hole transport (S?1)**
  - **High luminescent efficiency (QE_l?1)**
  - ***Low optical self absorption (small ?$_{ph}$)***



e-h pair production

luminescent QE

$$? _{phosphor} ? \left[1 ? e^{??_{x?ray}\langle t\rangle}\right]\left[\frac{E_{ph}}{?E_g}\right]\left[S\right]\left[QE_l\right]\left[e^{??_{ph}\langle t\rangle}\right]$$

x-ray absorption

e-h transport

optical self absorption

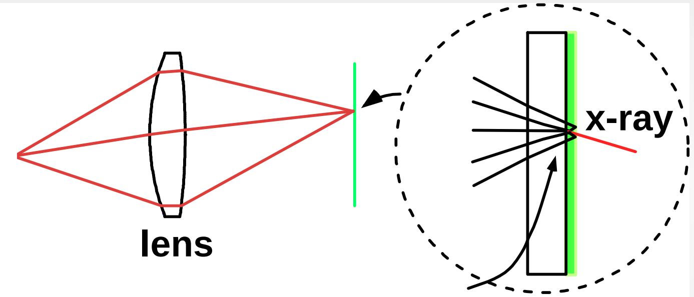
Development of high gain x-ray phosphors

	E_g (eV)	E_{eh} (eV)	Gain (photons/x-ray)
ZnTe	2.3	5.0	2,400
ZnSe	2.7	5.9	2,040
ZnS	3.8	11.0	1,040
CsI	6.4	16.0	755
Gd_2O_2S	4.4	17.2	700
$CaWO_4$	4.6	32.2	370

- **ZnSe:Cu,Ce has the highest known x-ray conversion efficiency**
  - ***-Three times higher than Gd_2O_2S:Tb***
  - ***-Status: commercially available***
  - ***-However, not suitable for MAD phasing because of Se edge***
- ***ZnTe under development for macromolecular applications****
  - ***-Collaboration with MBC, Georgia Tech, TTU.***
  - ***-Efficiency potentially comparable to ZnSe***
  - ***-No Se edge, suitable for MAD experiments***

Design of high resolution scintillators: Thin film phosphors

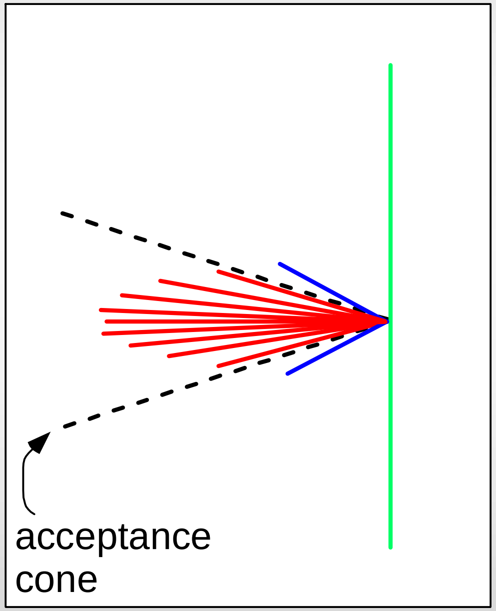
- Very high spatial resolution possible using ***thin film scintillators***
  - Thin (~15 ?m) solid film deposited on glass substrate
  - No scattering, thus better PSF (e.g., Koch 2000)
- However, solid scintillating films are inefficient
  - Typically >90% of light is trapped in screen by total internal reflection
  - *<10% of light is emitted*
- *Thin film scintillators give high resolution but poor sensitivity*



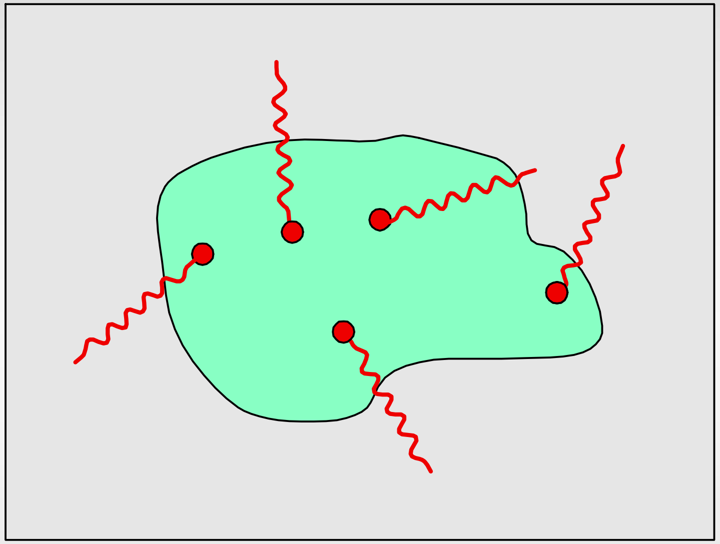
no light scattering
in thin film scintillator

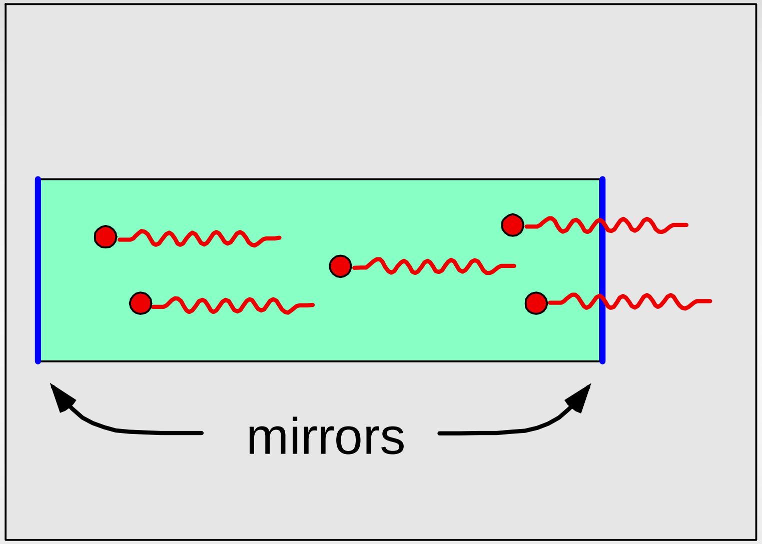
Ideally, scintillator emission should be *forward peaked*

- **Allows more efficient coupling to optics**
- **Prevents trapping by total internal reflection**
- ***How could such a screen be realized?***



Directional emission in a resonant cavity





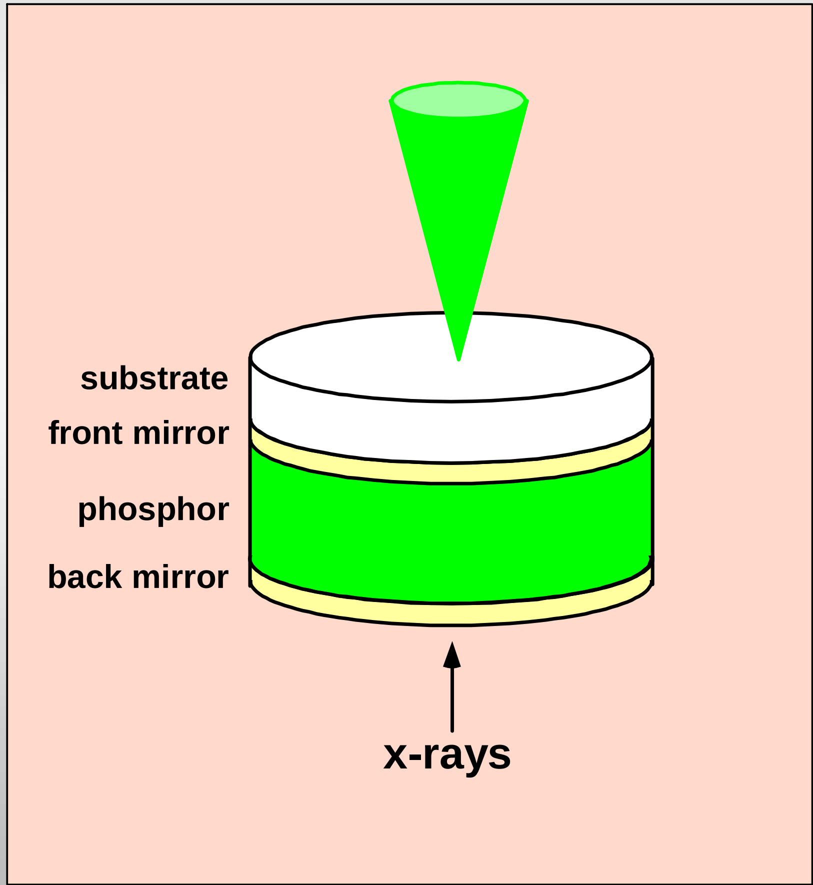
- In a conventional scintillator, emission is spontaneous
- Random, no preferred direction

- In a laser, emission occurs in a high-Q resonant cavity
- Emission is stimulated: highly directional
- *Can this principle be applied to a scintillator?*

Quantum Resonance Convertor (QRC)*

- Phosphor deposited between mirrors
- Mirror x-ray transparent
  - Low-Z dielectric stack
- Phosphor layer must be sufficiently thick so as to absorb incident x-rays
  - >12 ?m for Gd_2O_2S, 8 keV
- Vacuum deposited on substrate
  - glass
  - fiber optic faceplate

**Patents pending*



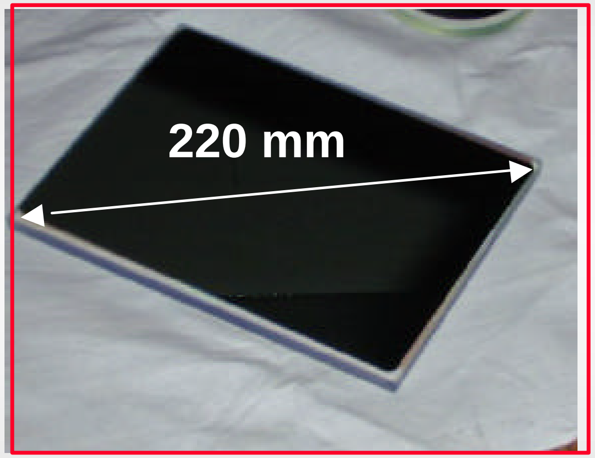
QRC vs laser

- **QRC and laser have similar structures, however QRC is *not* a laser**
  - **There is no gain medium (I.e., no population inversion)**
  - ***There is no amplification in a QRC, the same number of photons are emitted but the angular distribution of the emitted light is modified***

$$W_{i?\,?n?} ? \frac{2?}{\square^{2}} ?_{n} \left|\langle n|e\overset{\square}{r}\,?\hat{E}_{T}(R)|i\rangle\right|^{2} d(?_{n} ?\, ?_{i})$$

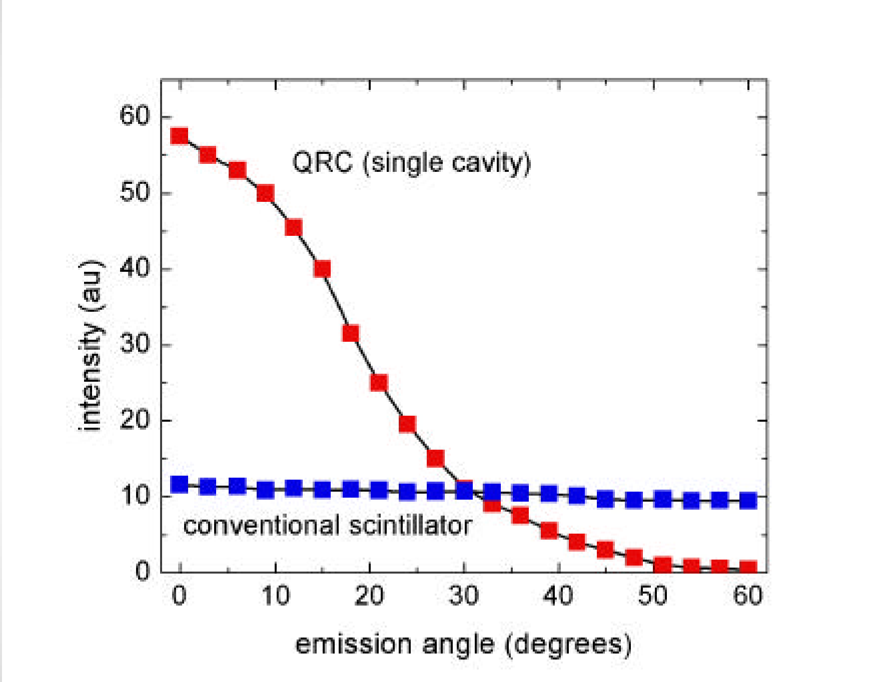
- **In a conventional scintillator, emission probability is isotropic**
- ***In QRC, emission* is strongly peaked due to interference**
  - **Resonant modes (forward peaked) enhanced**
  - **Non-resonant modes (high angle) suppressed**

QRC prototypes



- Prototype QRC screens up to 220 mm diagonal have been produced to date

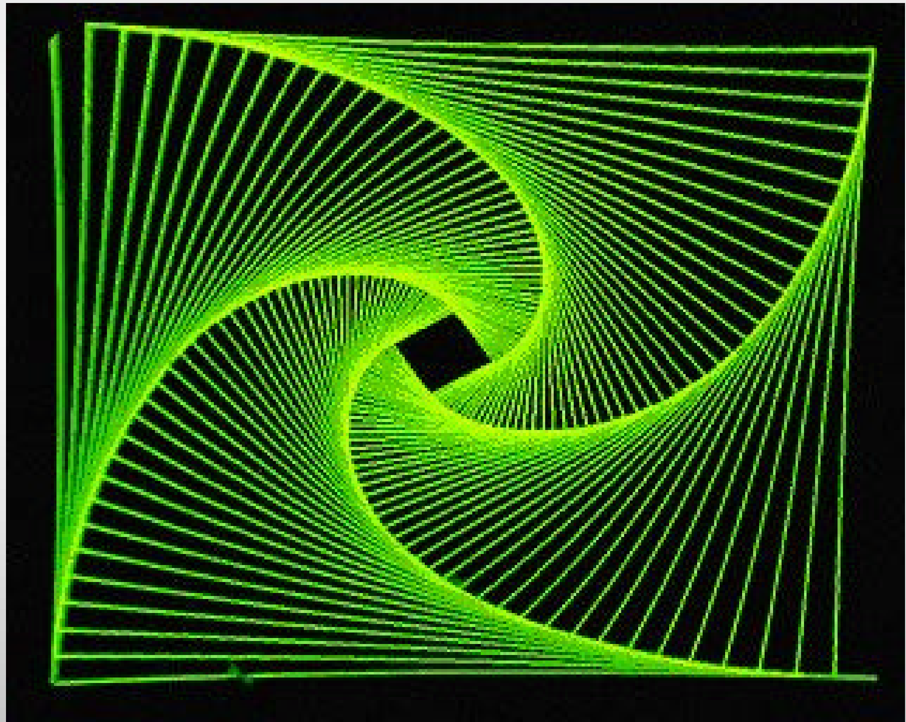
QRCs exhibit strongly forward peaked emission



- **>3-5 times brighter than conventional screen demonstrated**
- ***In theory, with improved cavity design gains >20 are possible***

QRC spatial resolution

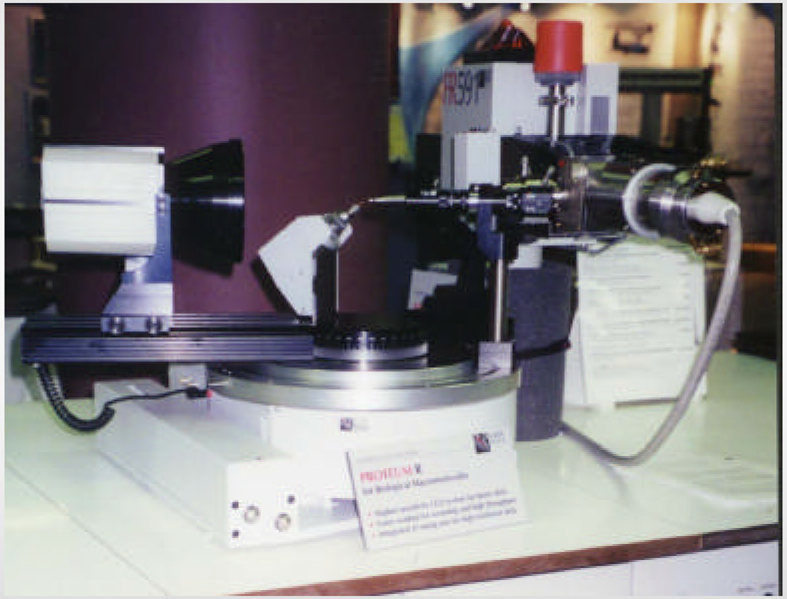
- **No scattering in screen allows high spatial resolution**
- ***PSF < 20 microns: 5 times better than conventional phosphor screen***



Pattern generated by 10 micron e-beam on QRC

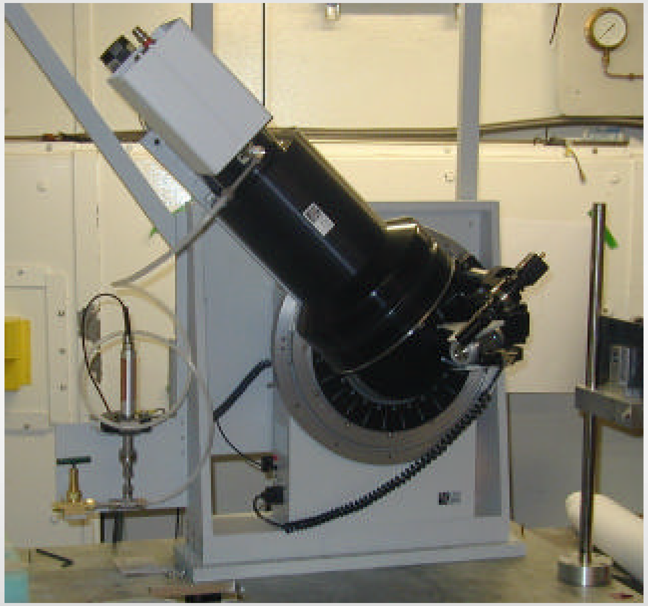
Application of QRCs: Fiber optic coupled CCDs

- **QRC screens will be back compatible with new and existing fiber optic cameras**
  - **Multilayer deposited on fiber optic faceplate**
- **Simple field upgrade**
  - **Improved sensitivity (est. >3X)**
  - **Improved point spread function (est. >4X)**



Application of QRCs:
Advanced lens-coupled cameras

- Forwarded-peaked emission from QRC couples more efficiently to lens optics as well
- Lens-coupled QRC
  - large active area
  - very high sensitivity
  - high resolution
  - relatively low cost
- Especially suitable for high speed CCDs
  - Eg., Frelon camera…



200 mm active area
lens-coupled detector

Summary

- Conventional scintillator screens are not optimal
  - Scattering degrades spatial resolution
  - Lambertian emission couples inefficiently to demagnifying optics
- Screens can be improved by
  - Increasing the screen quantum efficiency: ZnSe, ZnTe
  - Modifying the emission profile to be highly forward peaked: Quantum resonance scintillator
- New scintillator technologies are compatible with both fiber optic and lens-coupled CCD camera designs
  - Also TFT arrays or CMOS…