



# **Advances in X-Ray Scintillator Technology**

**Roger D. Durst  
Bruker AXS Inc.**

# Acknowledgements

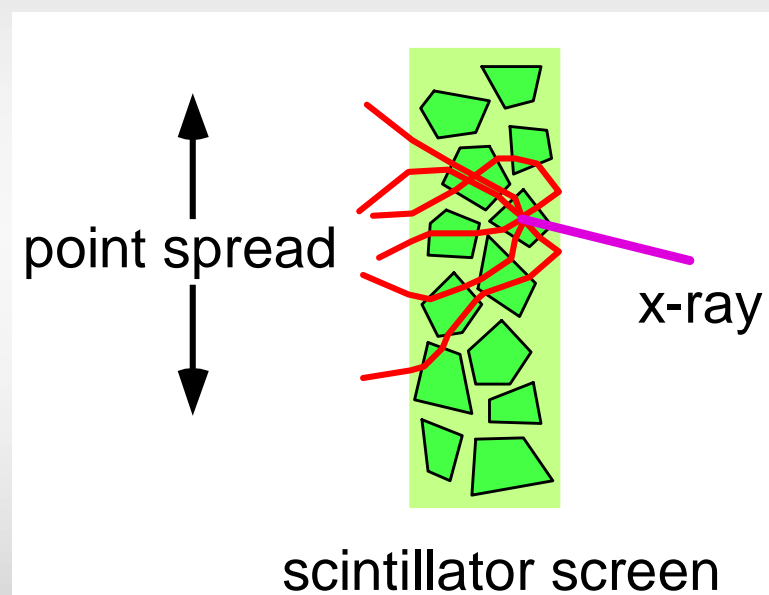
- ✍ **T. Thorson, Bruker AXS**
- ✍ **Y. Diawara, Bruker AXS**
- ✍ **E. Westbrook, MBC**
- ✍ **J. Morse, ESRF**
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- ✍ **B. Wagner, Georgia Tech/PTCE**
- ✍ **V. Valdna, TTU**
  
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# Scintillator-based imagers

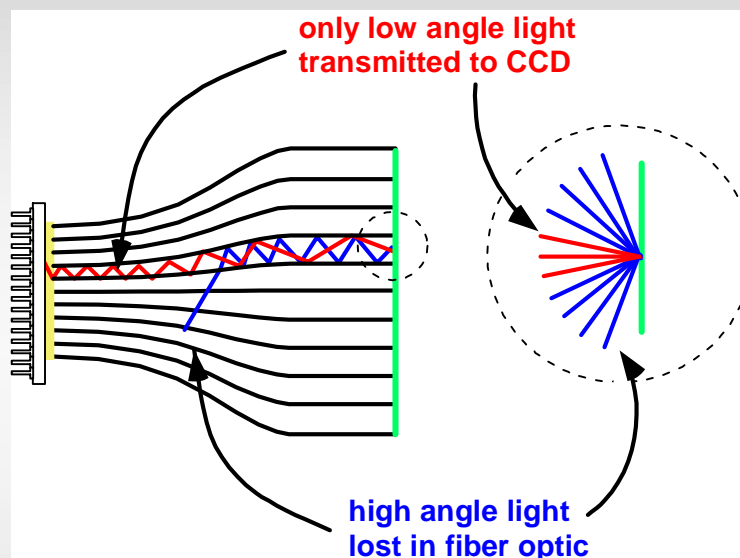
- ✍ **One of the earliest techniques employed for imaging ionizing radiation**
- ✍ **Scintillator-based imagers remain one of the most flexible and successful techniques for x-ray imaging**
  - ✍ **Crystallography**
  - ✍ **SAXS/WAXS**
  - ✍ **Microtomography...**
- ✍ **However, conventional scintillators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

# Limitations of conventional scintillators: point spread function

 **Point Spread Function (PSF)** is limited by scattering in polycrystalline phosphor screen: typically  $> 100 \mu\text{m}$  FWHM

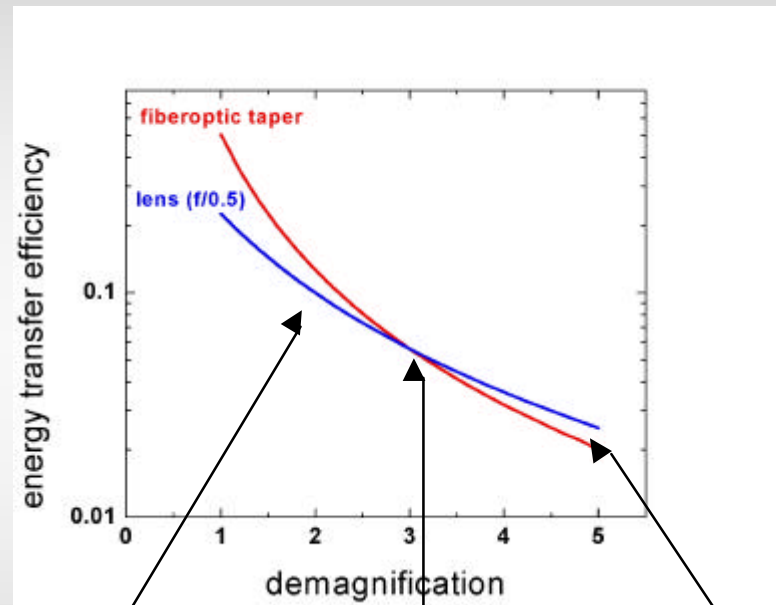


# Limitations of conventional scintillators: Light loss in demagnifying optics

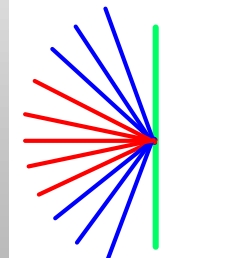


- ✘ Conventional screens are Lambertian
- ✘ However, light emitted at *large angles* is lost in the optics
- ✘ Only *low angle* light is transmitted to CCD

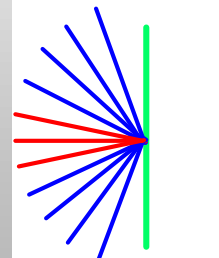
# Transmission efficiency scales as $1/m^2$



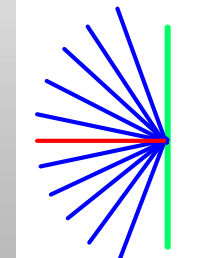
m=2, T=12%



m=3, T=6%



m=5, T=2%



# Present day integrating detectors do not achieve optimal sensitivity

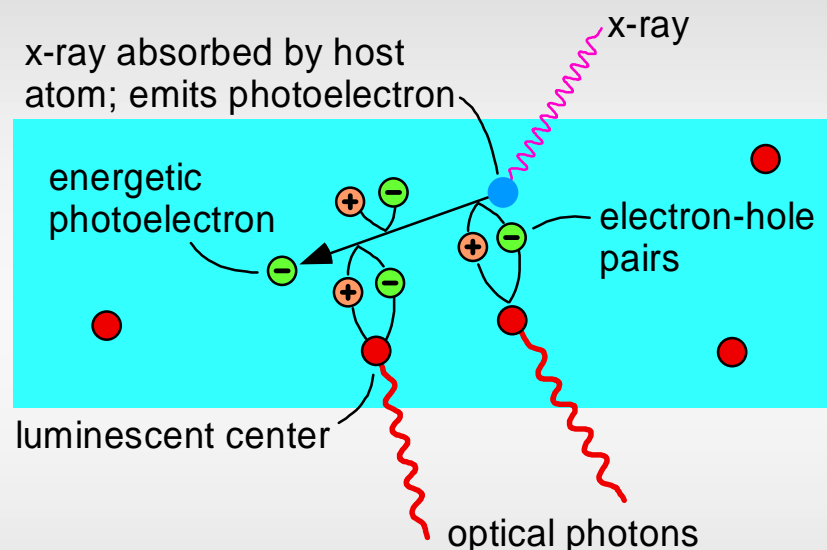
- ✍ Gruner (1996) noted that for optimal dynamic range and near-quantum limited performance an integrating detector (CCD, a-Se, ...) should achieve a SNR of order 1.
- ✍ Because of transmission losses and point spread, no present *large area*, integrating detectors satisfy this criterion...

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



$$\mu_{phosphor} \approx \left[ \mu_{x\text{-ray}} \right] \left[ \frac{E_{ph}}{E_g} \right] [S] [QE_l] \left[ e^{-\mu_{ph} \langle t \rangle} \right]$$

x-ray absorption
e-h transport
optical self absorption

e-h pair production
luminescent QE

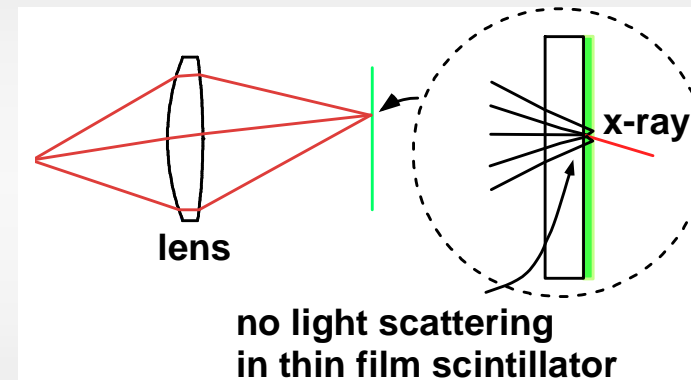
# Development of high gain x-ray phosphors

	$E_g$ (eV)	$E_{eh}$ (eV)	Gain (photons/x-ray)
<b>ZnTe</b>	<b>2.3</b>	<b>5.0</b>	<b>2,400</b>
<b>ZnSe</b>	<b>2.7</b>	<b>5.9</b>	<b>2,040</b>
ZnS	3.8	11.0	1,040
CsI	6.4	16.0	755
<b>Gd<sub>2</sub>O<sub>2</sub>S</b>	<b>4.4</b>	<b>17.2</b>	<b>700</b>
CaWO <sub>4</sub>	4.6	32.2	370

- **ZnSe:Cu,Ce** has the highest known x-ray conversion efficiency
  - *Three times higher than Gd<sub>2</sub>O<sub>2</sub>S: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*

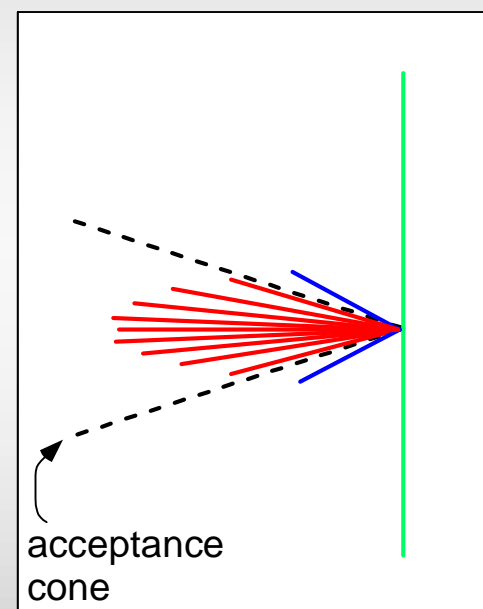
# Design of high resolution scintillators: Thin film phosphors

- ✍ **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***

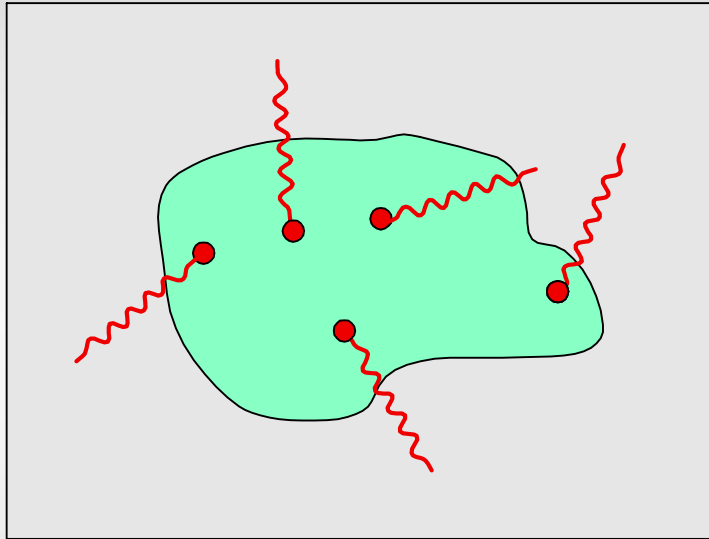


# Ideally, scintillator emission should be *forward peaked*

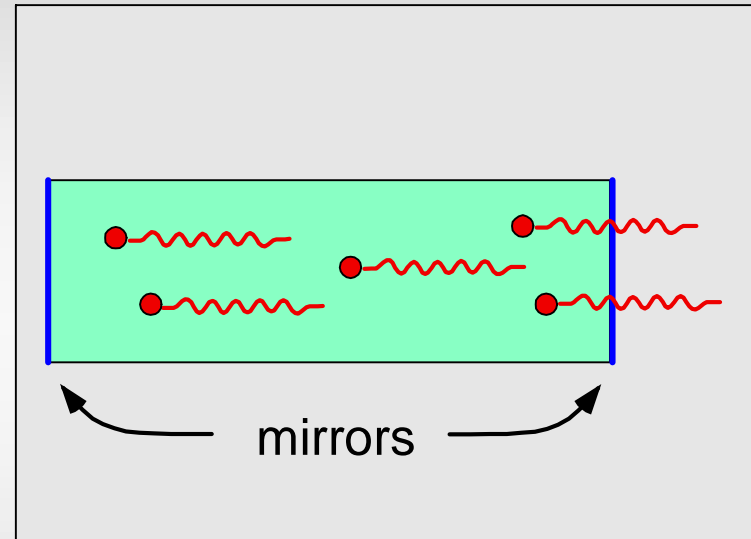
- ✍ Allows more efficient coupling to optics
- ✍ Prevents trapping by total internal reflection
- ✍ *How could such a screen be realized?*



# Directional emission in a resonant cavity



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

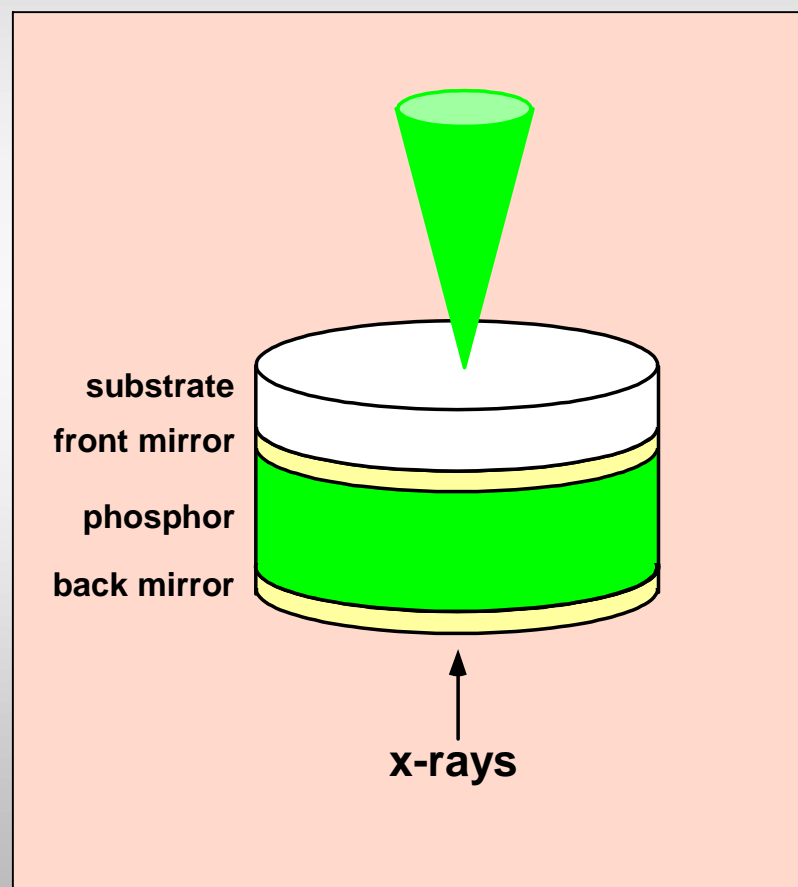


- ✍ In a laser, emission occurs in a high-Q resonant cavity
- ✍ Emission is stimulated: highly directional
- ✍ *Can this principle be applied to a scintillator?*

# Quantum Resonance Converter (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

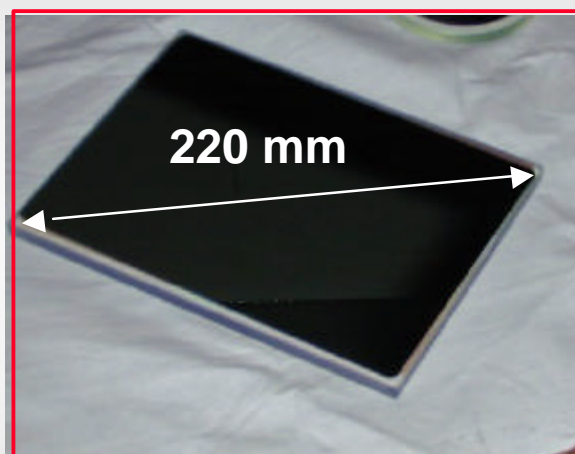
✍ QRC and laser have similar structures, however QRC is *not* a laser


- ✍ 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*

$$W_{i \rightarrow n} = \frac{2\pi}{\hbar^2} \int_n \left| \langle n | e^{i\mathbf{r} \cdot \mathbf{q}} \hat{E}_T(R) | i \rangle \right|^2 d\Omega_n$$

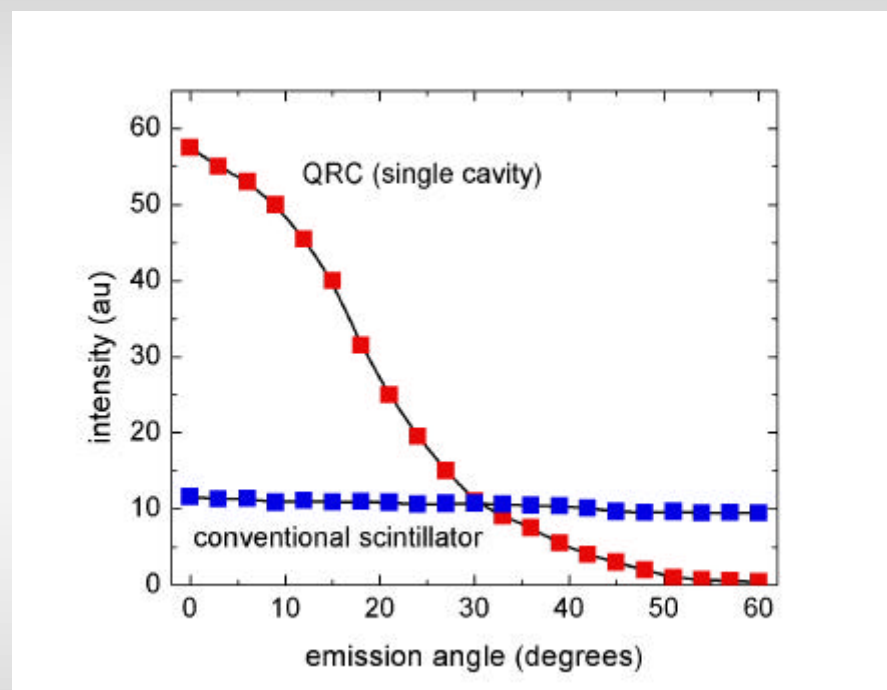
- ✍ In a conventional scintillator, emission probability is isotropic
- ✍ *In QRC, emission is strongly peaked due to interference*
  - ✍ Resonant modes (forward peaked) enhanced
  - ✍ Non-resonant modes (high angle) suppressed

# QRC prototypes



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

# QRCs exhibit strongly forward peaked emission

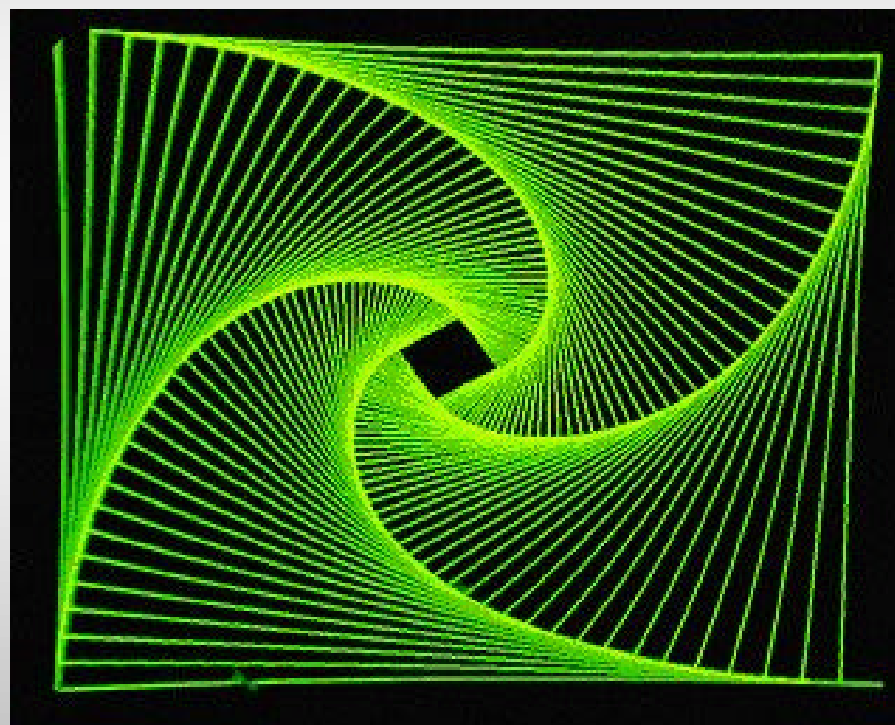


✍ **>3-5 times brighter than conventional screen demonstrated**

✍ ***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

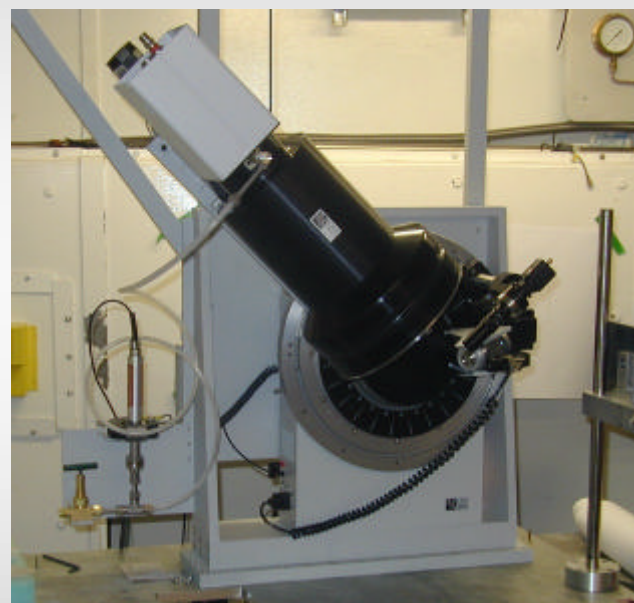
# Application of QRCs: Fiber optic coupled CCDs

- ✍ **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...**