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Radiochromic Film

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Acknowledgements

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Acknowledgements

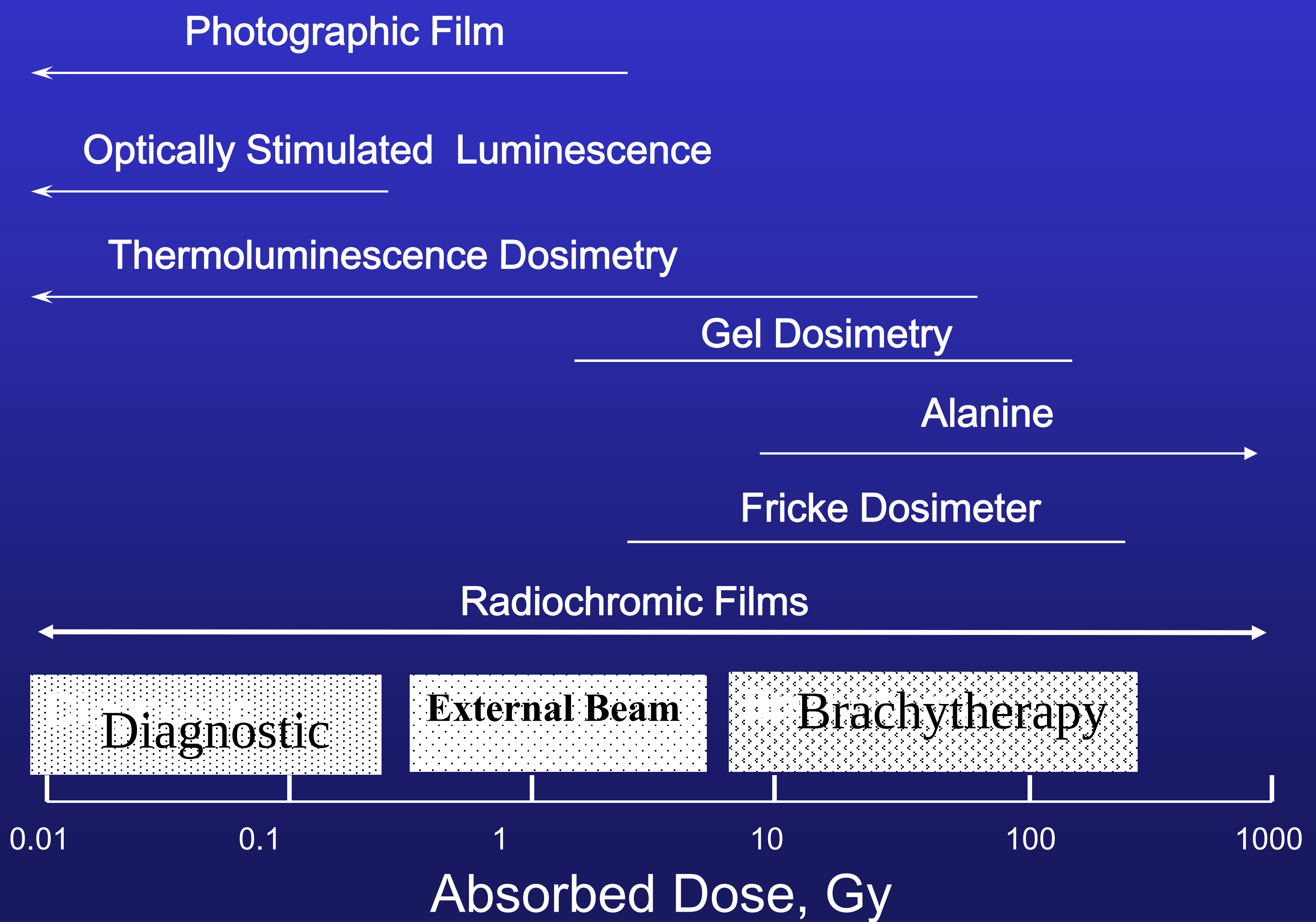
Dr. David Lewis
International Specialty Products (ISP), Wayne. NJ
supplying the dosimeter material used and the long years of friendship

Marcie Lombardi, Elizabeth Meek and Jason Walia
Georgetown University, Washington, DC
assistance with MD-55-2, EBT and EBT-1 film irradiations and readouts at NIST

Scott Robertson
University of Maryland, College Park, MD
assistance with filter, EBT2 and EBT2-1 film irradiations and readouts at NIST

Drs. Ronaldo Minniti and Guerda Massillon
NIST, Gaithersburg, MD
assistance with ^{60}Co irradiations of films at NIST

Absorbed Doses in Typical Medical Procedures and Ranges of Passive Detectors



Pioneers

- **William McLaughlin, NIST**
  - **From 1965 to 2005**
    Organic free-radical imaging medium can combine photopolymerization with leuco dyes that produce color upon irradiation.
- **David Lewis, International Specialty Products (ISP)**
  - **Since 1980s:**
    Radiochromic films based on polydiacetylene have been introduced for medical applications

Radiochromic Films

Radiochromic film consists of a single or double layer of radiation-sensitive organic microcrystal monomers, on a thin polyester base with a transparent coating

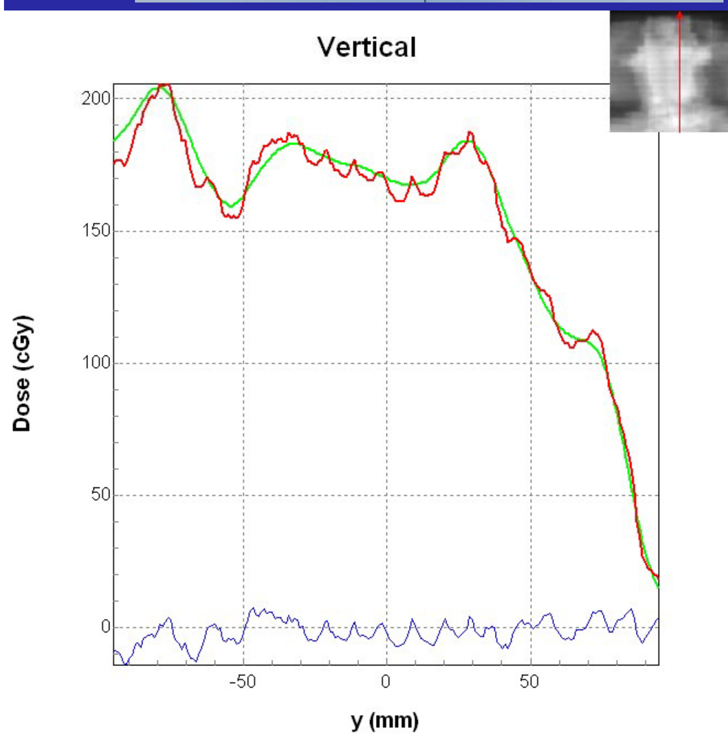
Radiochromic Films (Cont.)

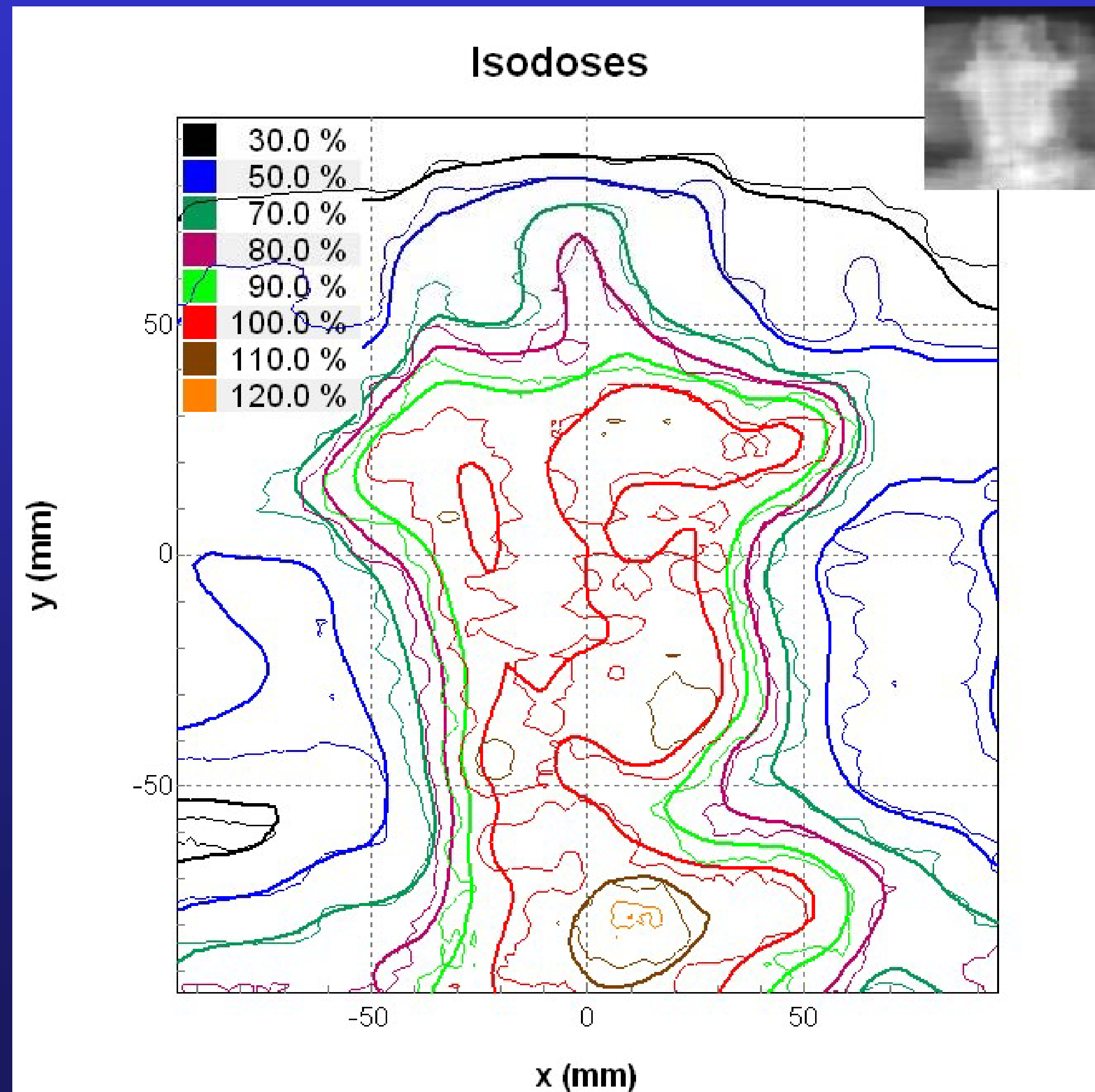
Color of the radiochromic films turns to a shade of blue upon irradiation.

Darkness of the film increases with increasing absorbed dose.

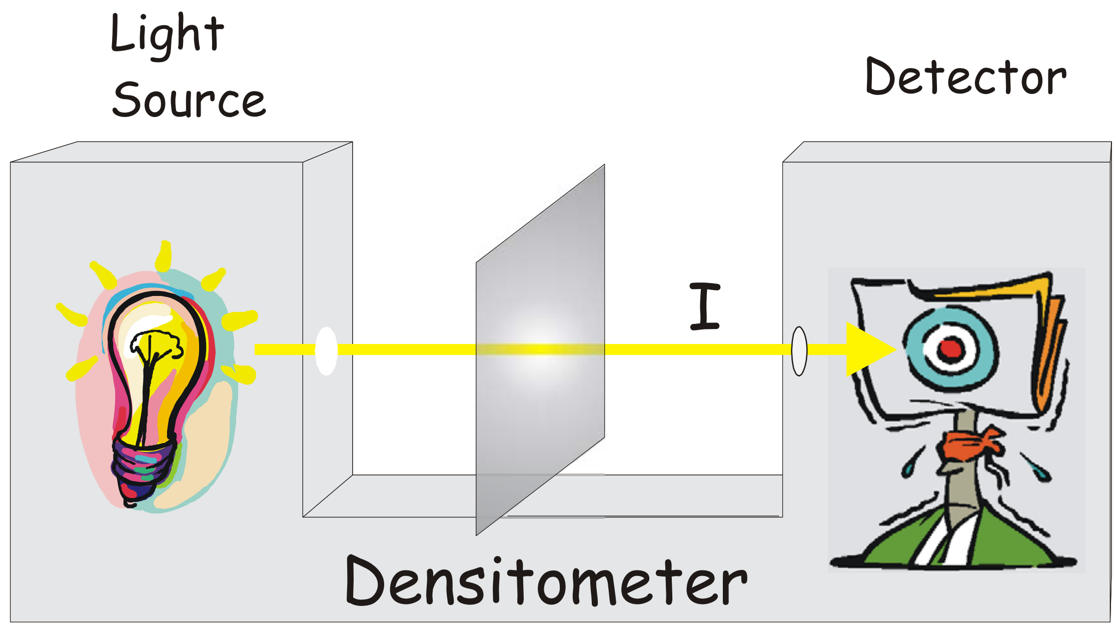
No processing is required to develop or fix the image.

Sample Application: IMRT QA





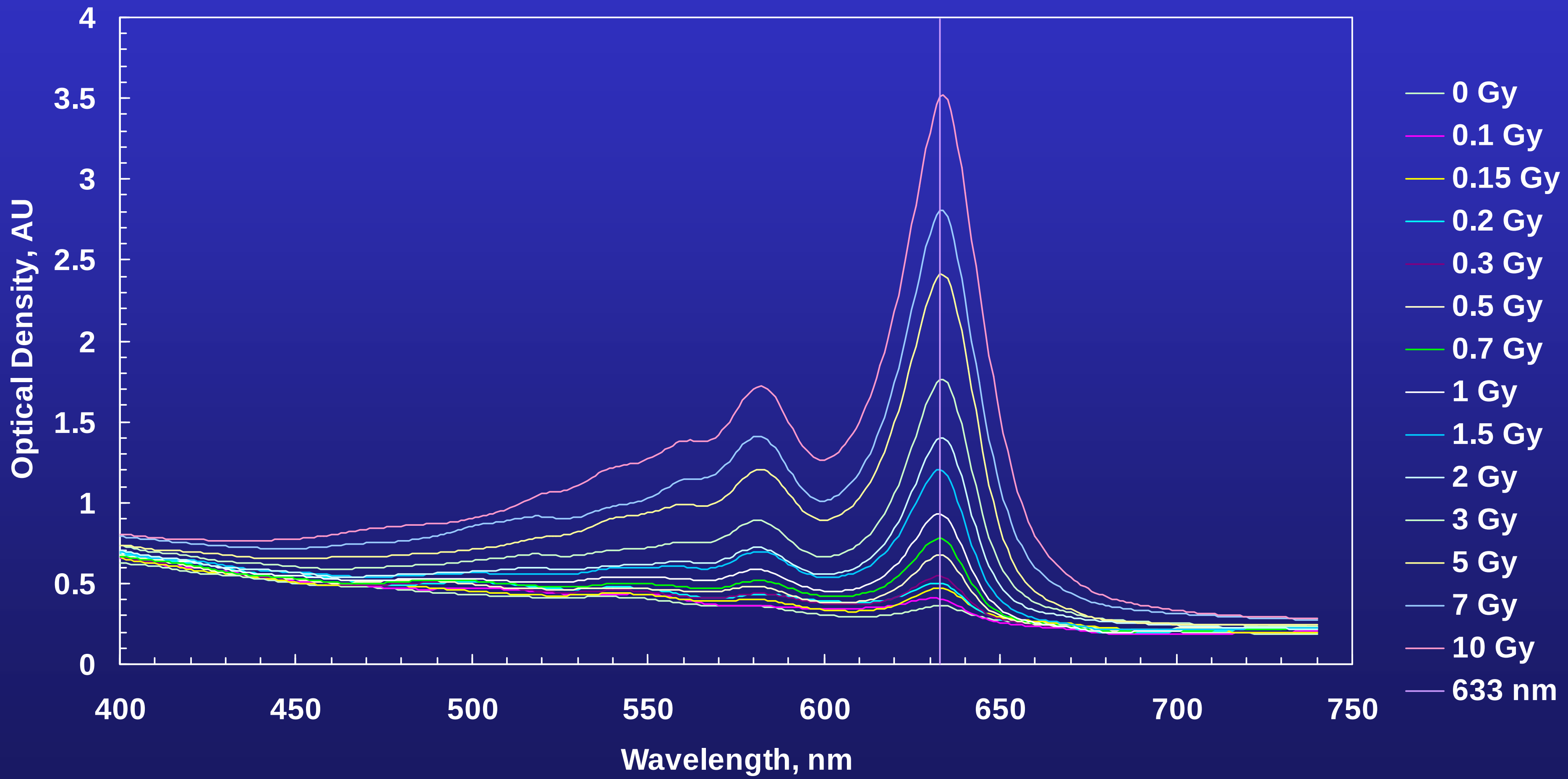
Measuring Transmission & Optical Density



$$Transmission = \frac{I}{I_0}$$

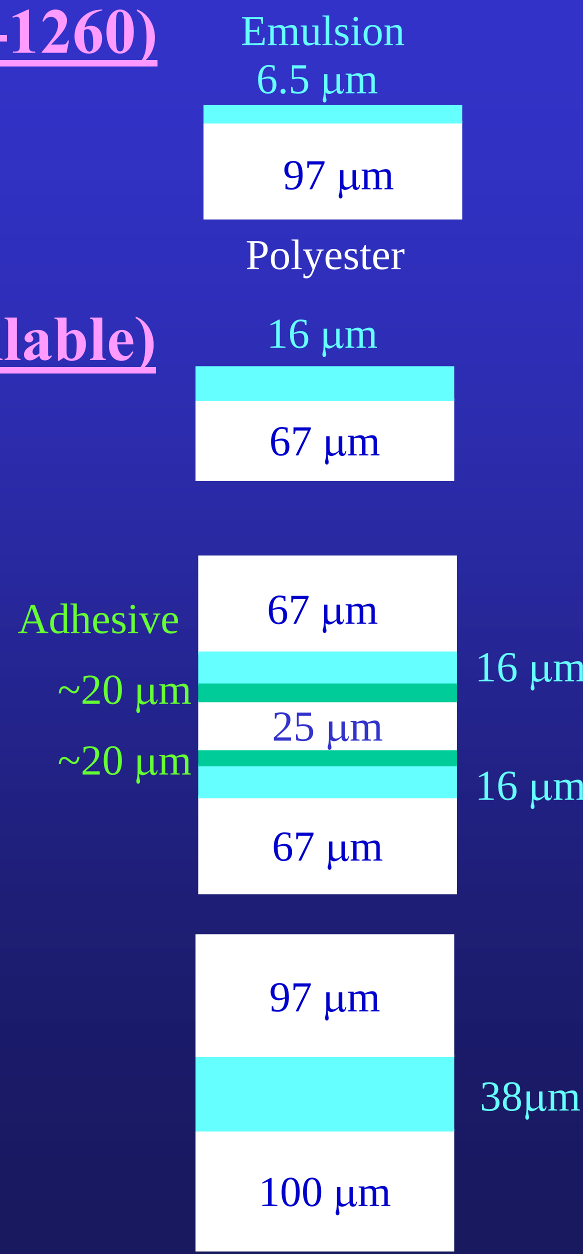
$$OD = \log\left(\frac{I_0}{I}\right)$$

Absorbance Scans of EBT Film Irradiated with ^{60}Co



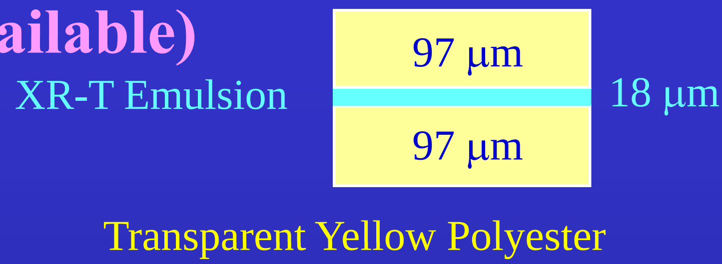
Older Radiochromic Film Types

- **GAFCHROMIC HD-810 (Formerly: DM-1260)**
  - 20 cm x 25 cm x 0. 1 mm
  - Nominal dose range: 10-1000 Gy
  - Approximate sensitivity: 3 mAU/Gy
- **GAFCHROMIC MD-55-1 (no longer available)**
  - 12.5 cm x 12.5 cm x 0.08 mm
  - Nominal dose range: 2-200 Gy
  - Approximate sensitivity: 10 mAU/Gy
- **GAFCHROMIC MD-55-2 (aka NMD-55)**
  - 12.5 cm x 12.5 cm x 0.23 mm
  - Nominal dose range: 1-100 Gy
  - Approximate sensitivity: 20 mAU/Gy
- **GAFCHROMIC HS (no longer available)**
  - 12.5 cm x 12.5 cm x 0.23 mm
  - Nominal dose range: 0.5-50 Gy
  - Approximate sensitivity: 35 mAU/Gy

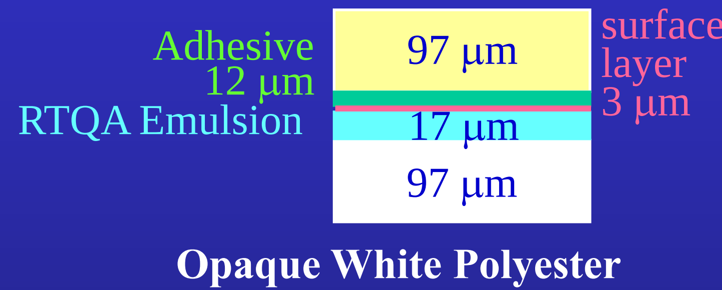


XR Radiochromic Film Types

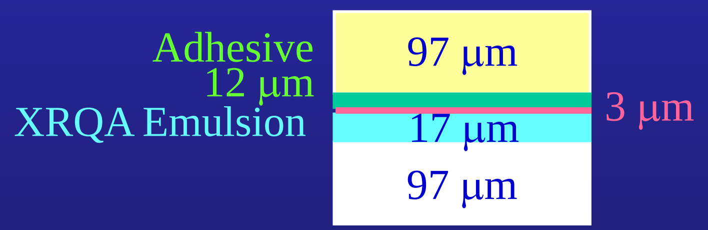
- **GAFCHROMIC XR-T (no longer available)**
  - **12.5. cm x 12.5 cm x 0.21 mm**
  - **Nominal dose range: 0.01-5 Gy**



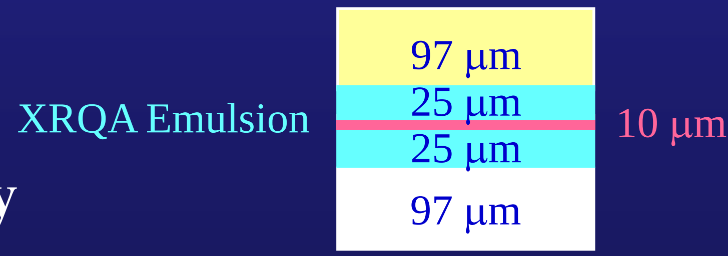
- **GAFCHROMIC RTQA**
  - **36 cm x 43 cm x 0.23 mm**
  - **Nominal dose range: 0.01-5 Gy**



- **GAFCHROMIC XR-RV2**
  - **36 cm x 43 cm x 0. 23 mm**
  - **Nominal dose range: 0.01-5 Gy**



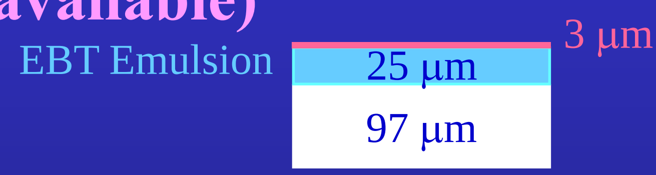
- **GAFCHROMIC XR-QA**
  - **36 cm x 43 cm x 0.26 mm**
  - **Nominal dose range: 0.001-0.2 Gy**



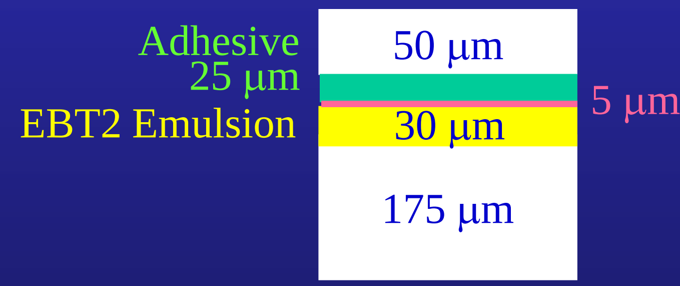
EBT Radiochromic Film Types

- GAFCHROMIC EBT (no longer available)
  - 20 cm x 25 cm* x 0.23 mm
  - Nominal dose range: 0.05-100 Gy
  - Approximate sensitivity: 400-800 mAU/Gy

- GAFCHROMIC "EBT-1" (no longer available)
  - 36 cm x 43 cm x 0.12 mm
  - Nominal dose range: 0.1-200 Gy
  - Approximate sensitivity: 200-400 mAU/Gy



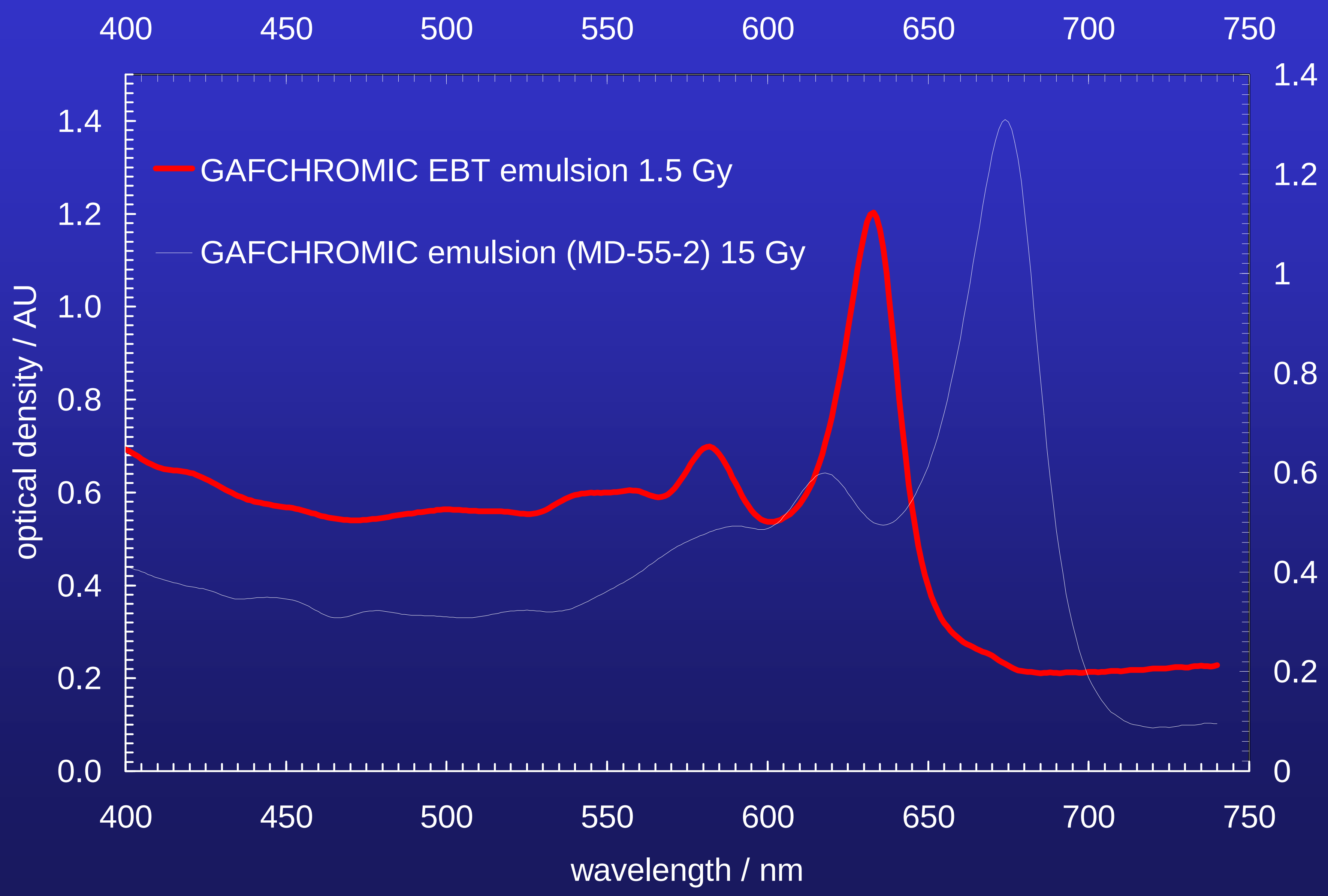
- GAFCHROMIC EBT2
  - 20 cm x 25 cm* x 0. 29 mm
  - Nominal dose range:
  - Approximate sensitivity:



- GAFCHROMIC "EBT2-1" (by request only)
  - 20 cm x 25 cm x 0.20 mm
  - Nominal dose range:
  - Approximate sensitivity:

*typical size; 36 cm x 43 cm available

EBT vs Older Emulsion



Some Film Handling Tips

- try to control temperatures during irradiation, storage & readout in a consistent fashion
- handle films with care, avoiding dust, fingerprints or over bending
- store film in dry, dark environment
- avoid prolonged exposure to UV light
- cut sandwich films with scissors, punches or paper cutters
- wait a few days after cutting before irradiating
- at temps above 70° C dye is deactivated

More Tips

- write ID numbers on films in reproducible manner to indicate emulsion-coated side and direction
- HD-810 emulsion side easily determined by wetting a corner – turns cloudy temporarily
- MD-55-2 compressible – take care measuring thickness if it matters in an application
- use histogram (frequency) analysis for uniform films
- consider rolling film for equatorial measurements
- irradiate at slant incidence for single shot DDs

Dose Response for Older Emulsion

- film is insensitive to light at $\lambda > 300$ nm
  - But sensitive to UV at lower λ
- films should be stored in the dark, at temp < 25ºC and relative humidity < 50% to optimize the useful life of the film
- dependence of the absorption spectrum with dose has been documented
- difference between fractionated and unfractionated response is ~ 1%

Summary of Recommended Procedures: Film Use

- note model and lot numbers
- note film orientation and allignment
- control time between irradiation & readout (at least 24 h) or use film annealing
- check film uniformity
- for non-sandwich films in non-penetrating radiation applications, note emulsion side (check by wetting corner)

Calibration & Sensitivity

- **Calibration:**
  - irradiation of samples to known absorbed dose levels
- **Calibration curve:**
  - Relation between dose and response
- **Sensitivity:**
  - Average change in response per unit dose
    - calculate over most linear portion of the calibration curve
  - Depends on: λ used for readout, scanner, film batch, beam quality, readout time, temperatures, humidity, ...

Radiochromic Film Calibration Fields

contact irradiations with calibrated ^{90}Sr/Y planar applicator, or

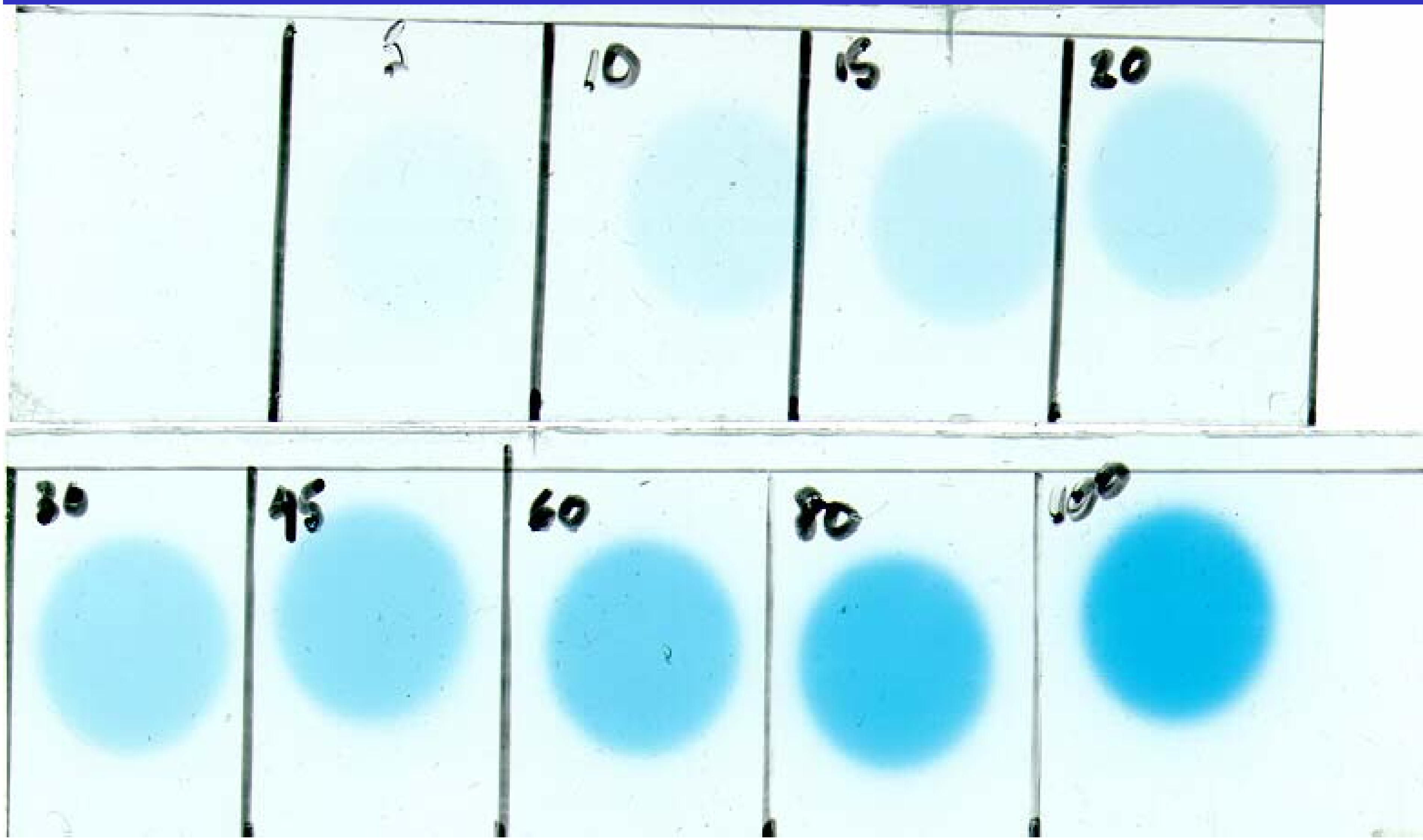
irradiations with ^{60}Co beams of known absorbed-dose rate, or

irradiations with photon or electron linac beams of known absorbed-dose rate

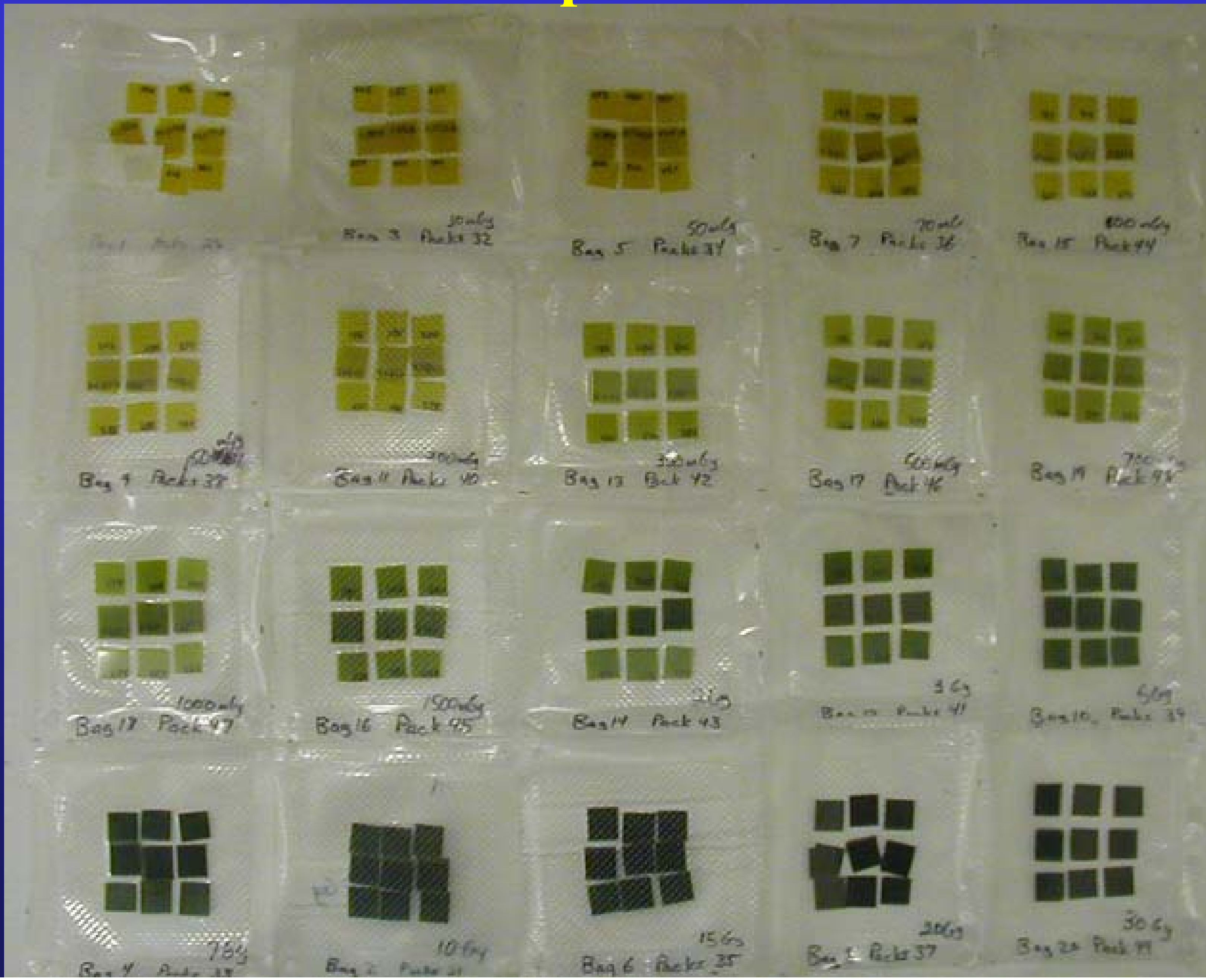
large well-characterized uniform radiation field

HD-810 Calibration Exposures w/ ^{90}Sr Eye Plaque

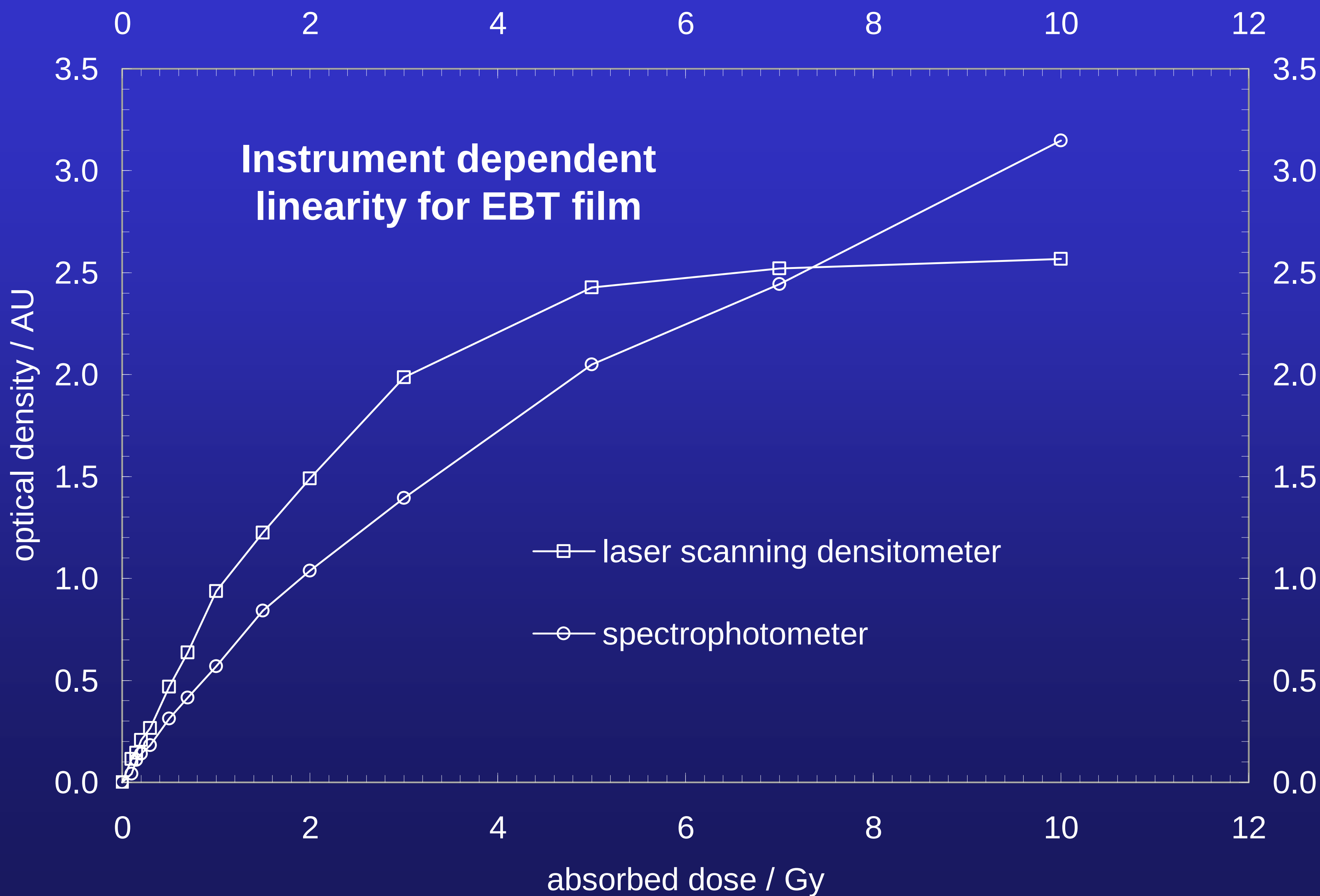
numbers are irradiation times in seconds at a dose rate of about 0.5 Gy/s



EBT2 Calibration Exposures w/ ^{60}Co in Water

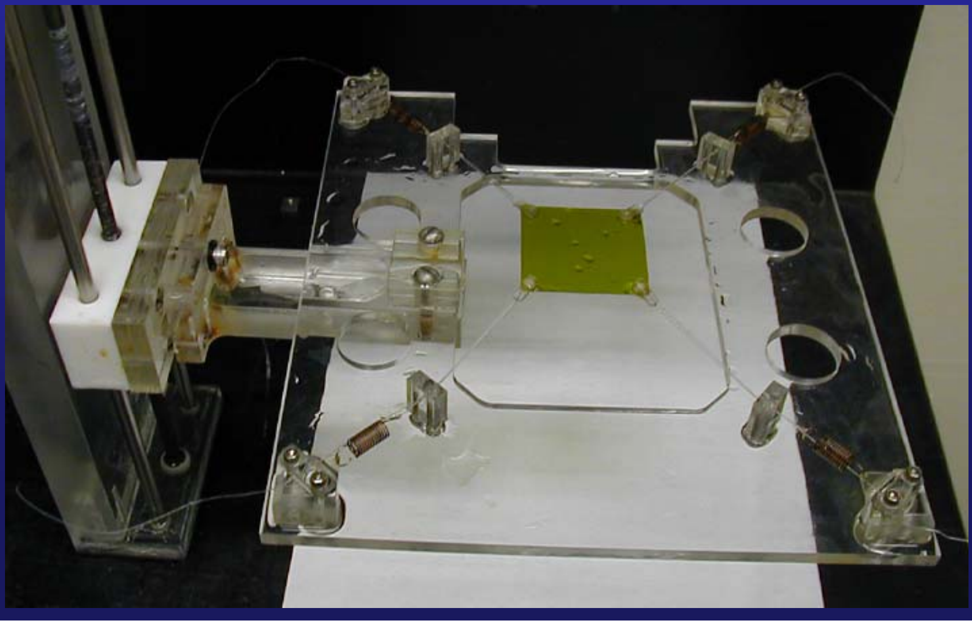


Linearity of Dose Response is Instrument Dependent



Calibration Phantoms and Mounting Jigs

- Sandwich films can be irradiated directly in water and held at depth in appropriately designed jigs
- Uncoated films can be sealed in waterproof pouches (e.g., Food Saver bags) and held in similar jigs



Plastic Calibration Phantoms

The usual cast of water-equivalent plastic characters can be used in lieu of in-water irradiations, such as

- polystyrene: best for beta particles, but also used for high-energy beams
- Solid Water^{TM} (WT1): standard for photon brachytherapy
- other water equivalent plastics (e.g. Plastic Water, Virtual Water, etc.)
- A150 plastic: for high rate charged particle irradiations (conducting)

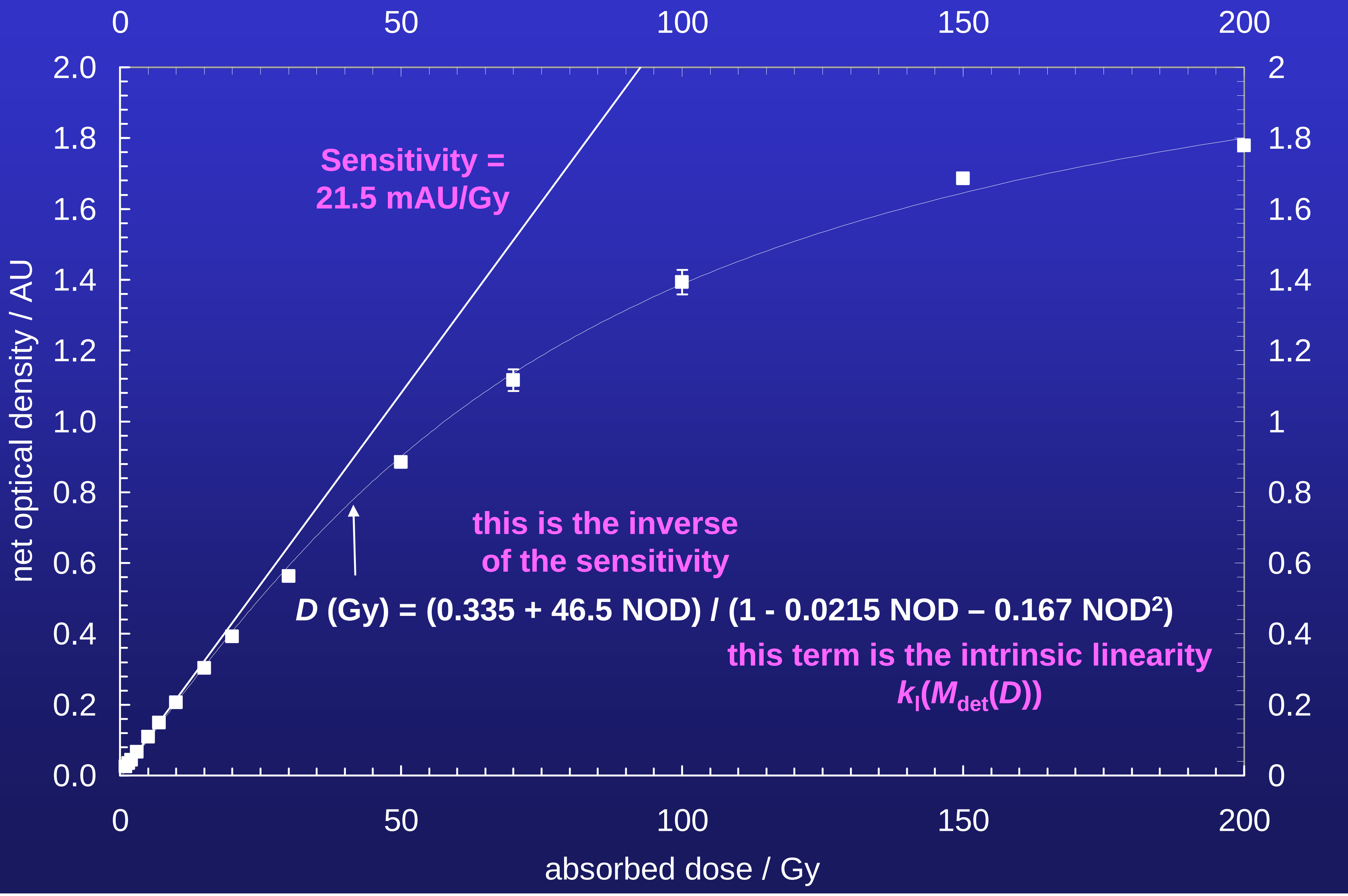
Note: in all phantom designs avoid air gaps to prevent electron streaming losses

Summary of Recommended Procedures: Calibration

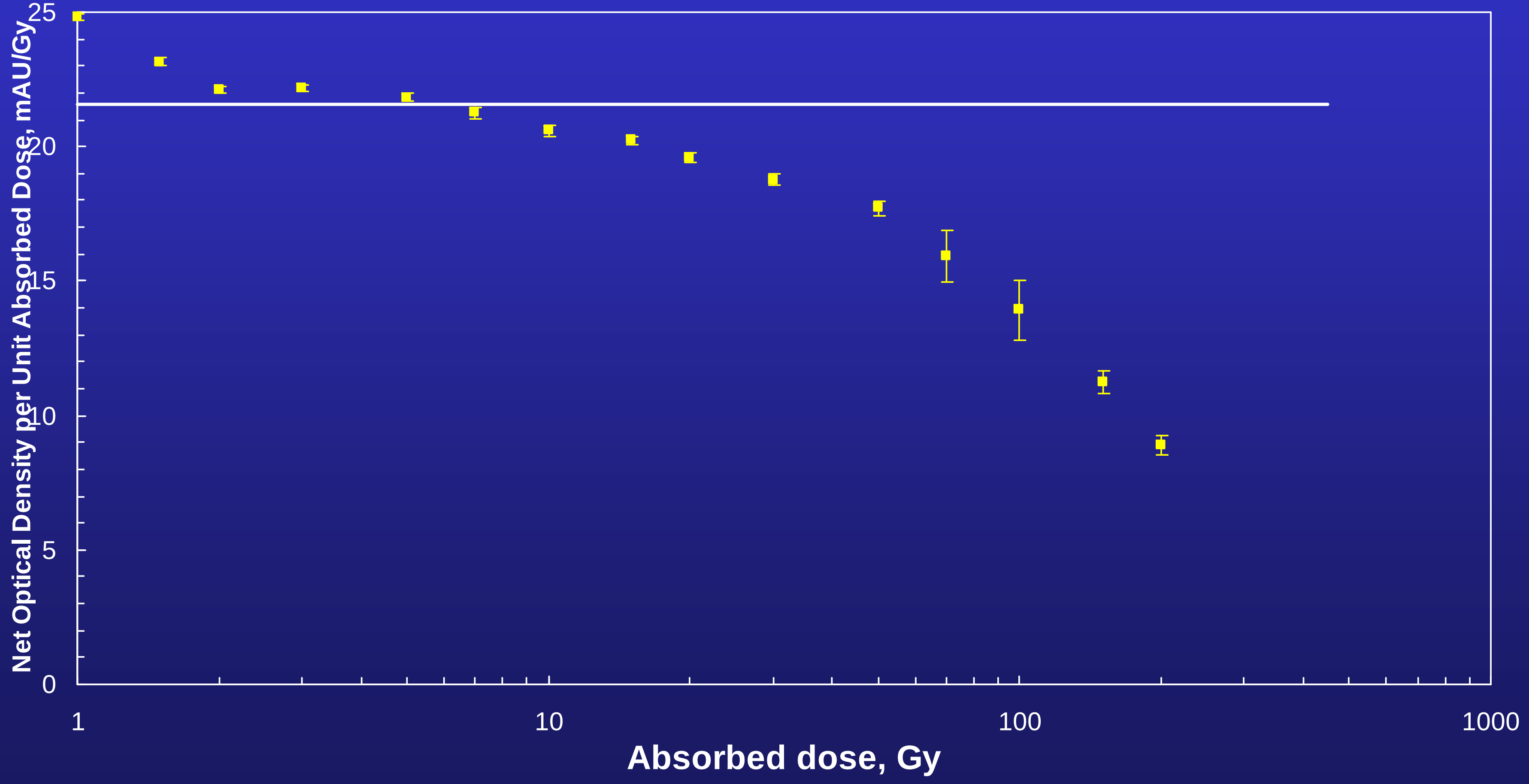
- use a large well-characterized field, ideally of the same quality as unknown field
- otherwise, any known dose rate field
- obtain response vs. dose over range of interest (extrapolation is dangerous)
- sandwich films can be irradiated unprotected in water but avoid prolonged immersions

Corrections: Intrinsic Linearity, $k_l(M_{det}(D))$

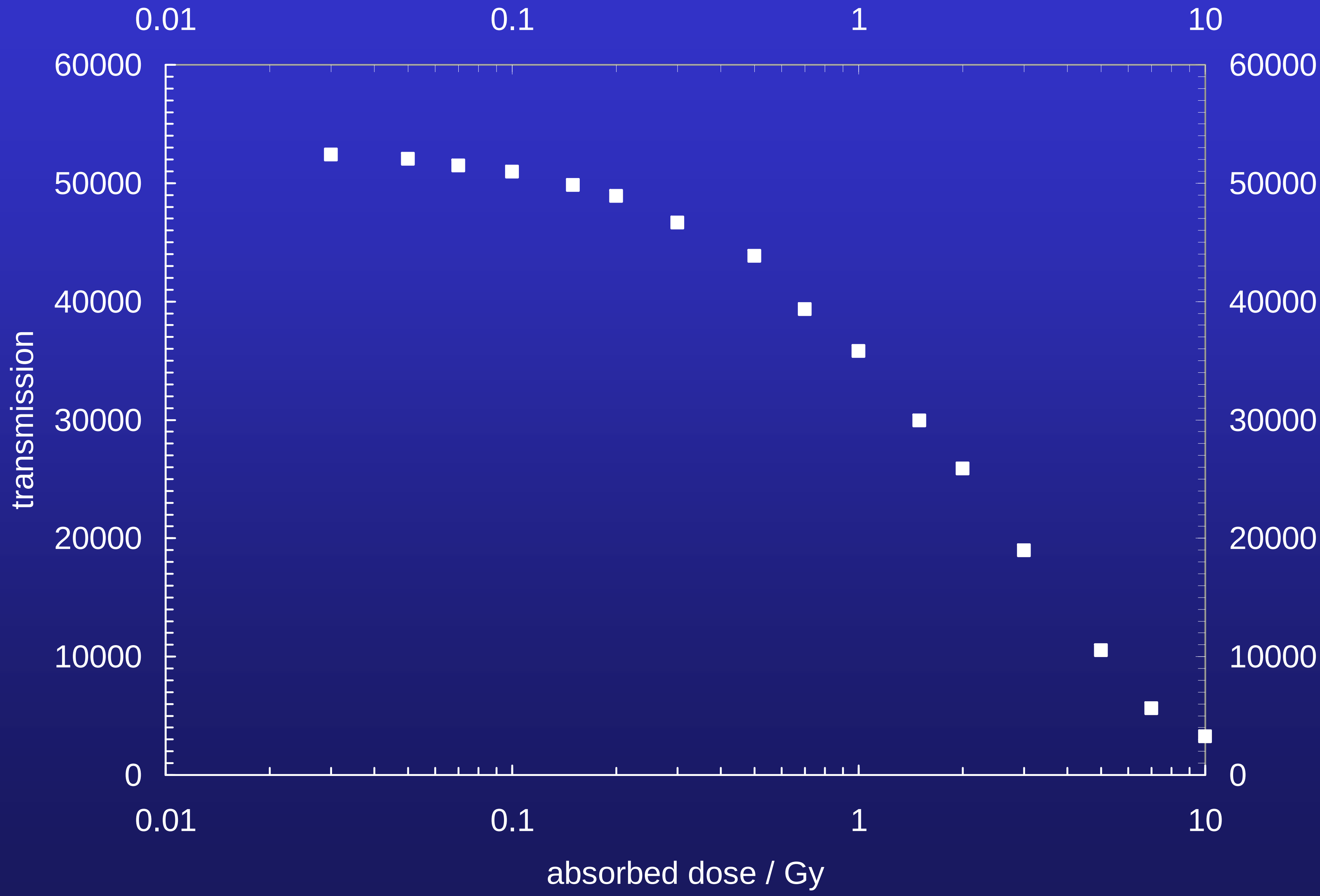
Calibration Curve for MD-55-2 film with ^{60}Co



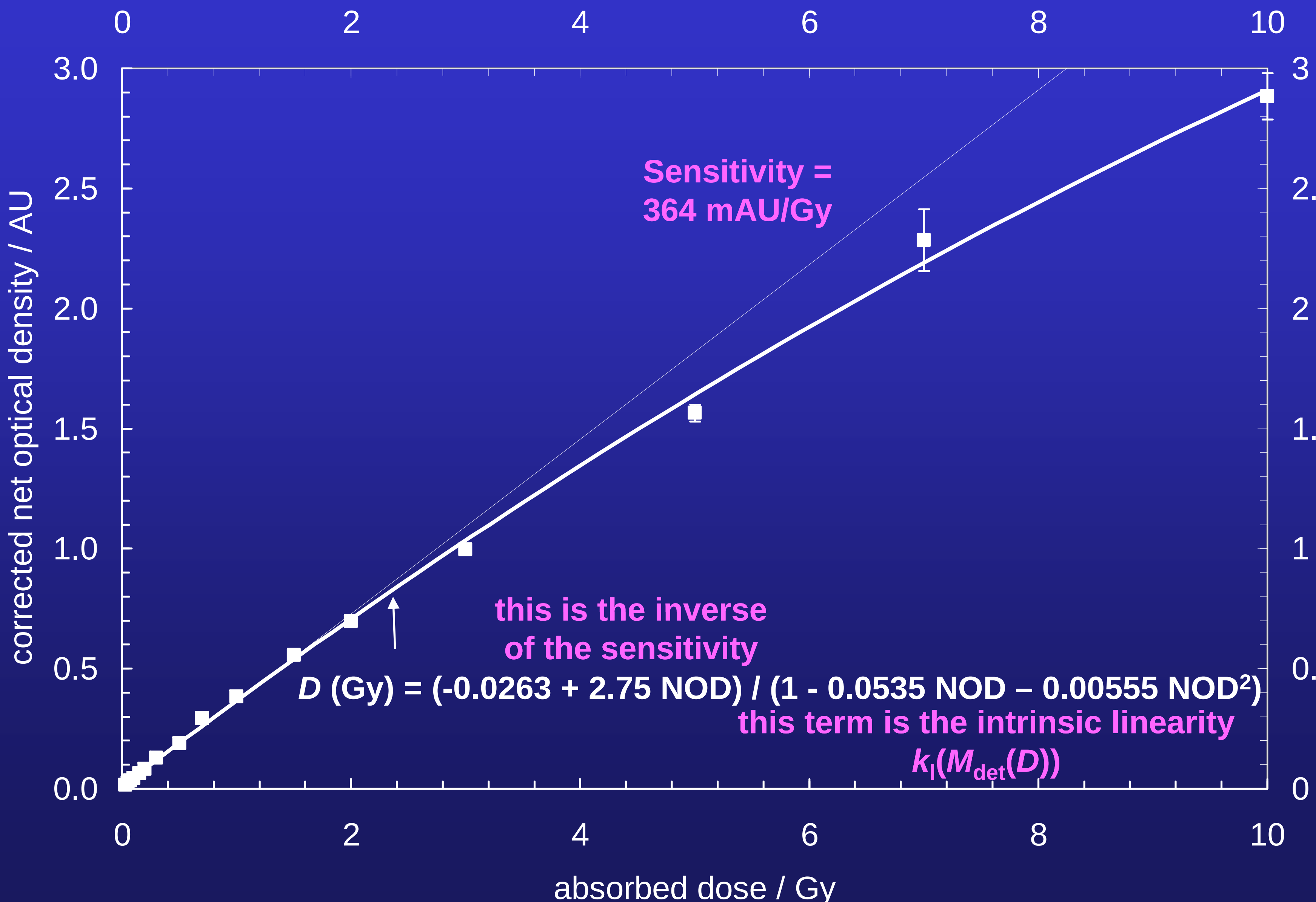
Calibration Curve for MD-55-2 film with ^{60}Co: Sensitivity Curve



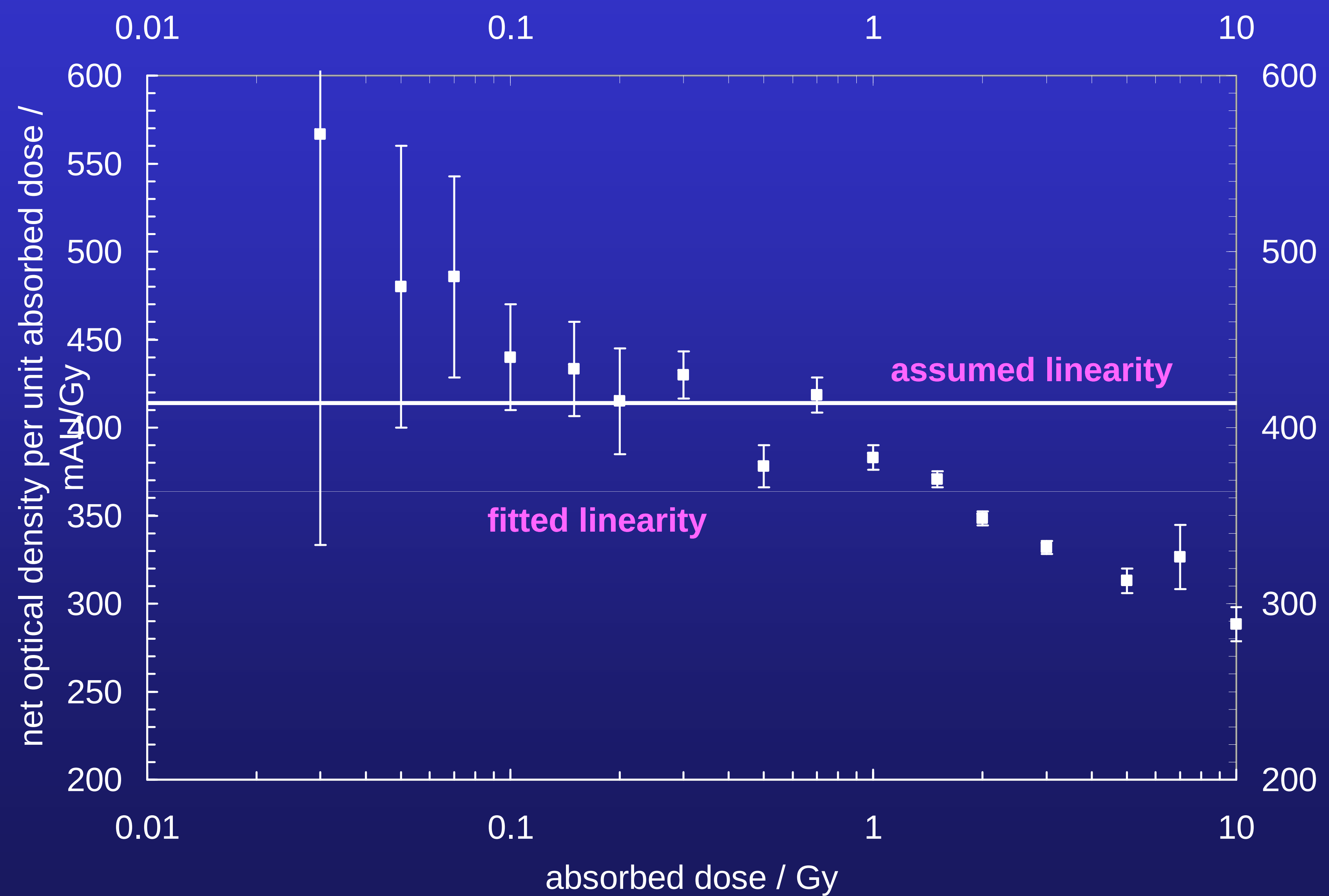
Calibration Curve for EBT film with ^{60}Co read in the red channel of a photo scanner



Calibration Curve for EBT film with ^{60}Co read in the corrected red channel of a photo scanner



Calibration Curve for EBT film with ^{60}Co
sensitivity curve for corrected red channel of photo scanner



Corrections: Dose-Rate Dependence, $k_{dr}(\dot{D})$

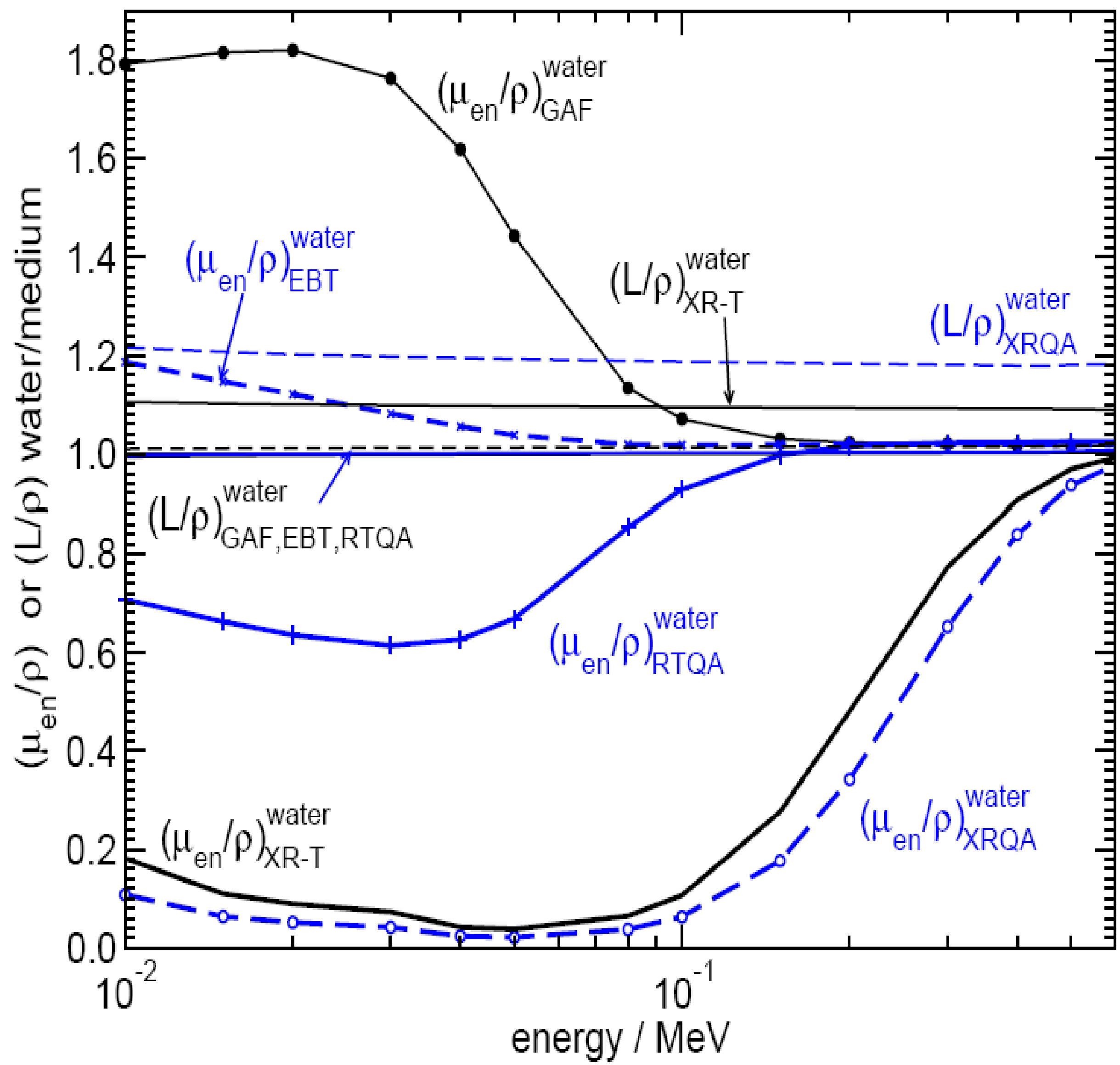
Usually taken as unity, although

- Saylor et al showed that for MD-55-1:
  - There is no dose rate response within an uncertainty of ~ 5% (± one SD)
- McLaughlin et al studied MD-55-2 for:
  - Dose = 20, 40, 60 Gy
  - Dose rate = 0.08 to 80 Gy/min
  - No dose rate response within an uncertainty of ~ 5% (± one SD)
  - But at 60 Gy there is ~ 10% higher response at lower dose rate

Corrections: Intrinsic Energy Dependence, $k_{bq}(Q)$

taken as a constant independent of energy since the energy necessary to polymerize the diacetylene molecule is small (< 1 eV)

Corrections: Absorbed-Dose Energy Dependence, *f*(*Q*) calculations for this textbook



GAFCHROMIC Emulsions Characteristics

- **Effective Z: 6.0 - 6.5**
- **Sensor material has similar electron stopping power as water & muscle**
- **Sensor material has similar mass-energy absorption coefficients as water and muscle for $h\nu > 100$ keV**
- **For secondary electron 0.1 to 1.0 MeV and $h\nu$ 0.1 to 1.33 MeV : ~2% of water and muscle**

Corrections: Non-Uniformity of Response, $k_{nu}(x,y)$

- Non-uniformity due to *local* fluctuations (spikes):
  - Small scale: film grain size, spatial and signal resolution of scanner, pixel size, electronic noise, …
  - Relative response is compared with the mean response in the ROI
- Non-uniformity due to *regional* variations:
  - Large scale: non-uniformity in film emulsion layer(s), systematic scanner problem(s)
  - Difference (or ratios) of max-min response in ROI

Non-Uniformity (Cont.)

- **Acceptable tolerances for film uniformity vary with the application**
- ***Regional*** **variations for MD-55-1 & MD-55-2 along two central orthogonal directions:**
  - **Longitudinal (| | to coating application): ~ 4%**
  - **Transverse (⊥ to coating application): ~ 15%**
- **L*ocal*** **fluctuations for MD-55-2:**
  - **Dose > 20 Gy: ~ ± 3%**
  - **Dose < 10 Gy: ~ ± 5%**

Double Exposure Technique

A technique has been suggested using a matrix of correction factors to be applied to an irradiated film (2) from the readings of a uniformly irradiated film (1):

$$OD_{net}(i,j) = [OD_2(i,j) - OD_1(i,j)] / f(i,j)$$

$$f(i,j) = OD_1(i,j) / \langle OD_1(i,j) \rangle$$

Problems with the Double Exposure Technique

- Requires second exposure, readout, doubling work

- Requires exact image registration for the two images (This often requires both translational and rotational transformations of one relative to the other)

- Only works if film uniformity is worse than statistical pixel-to-pixel fluctuations since these are compounded in taking of ratios

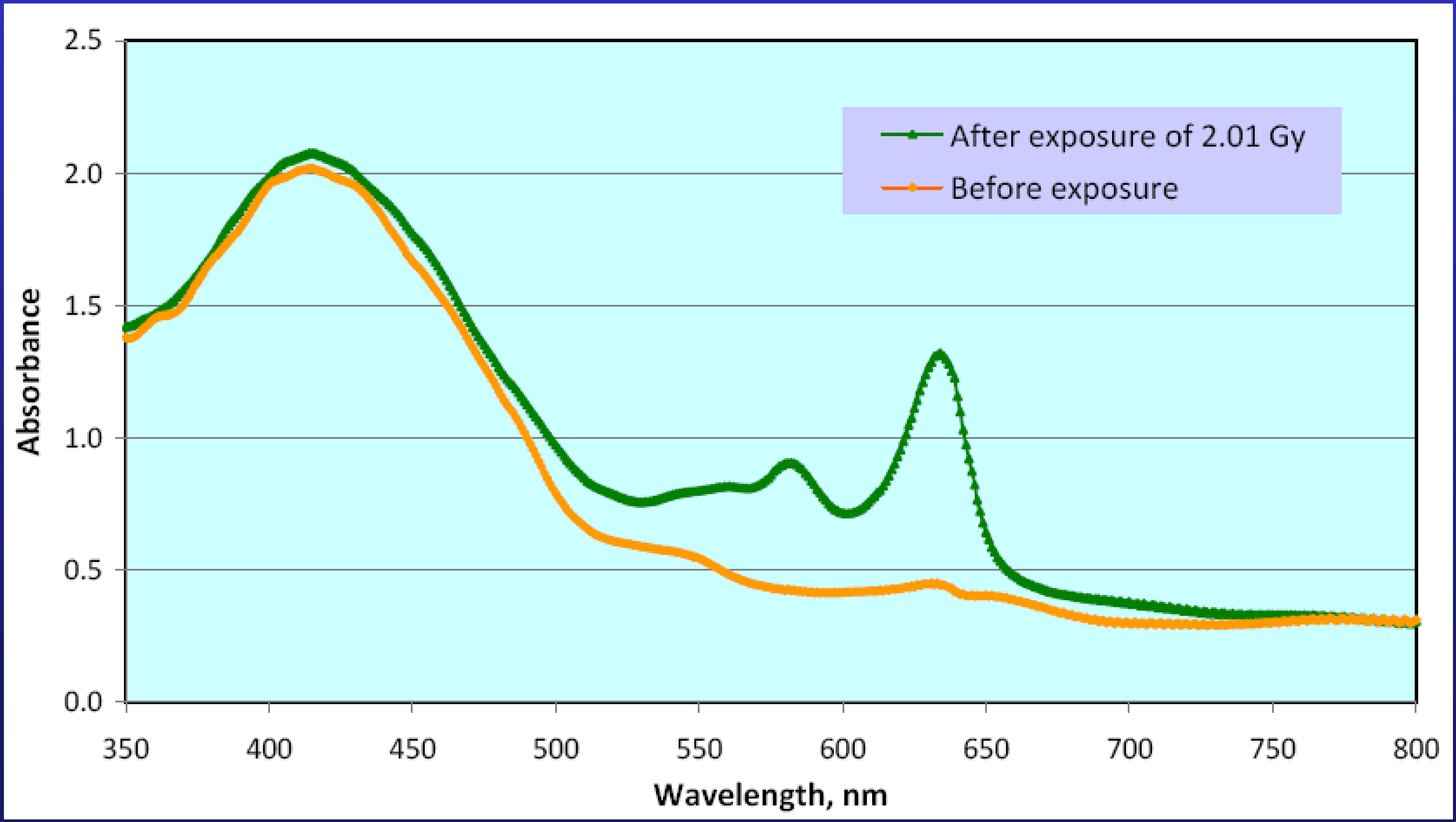
Simplified Double Exposure Technique

Rather than registering the images, just use the average density for the correction

Caveat: only works for small film samples ($1 cm^2$ or less) since uniformity variations are on this scale

Something Brand-New for Non-Uniformity Corrections

The newest versions of EBT2 contain a yellow marker dye in the emulsion which gives a strong absorbance in the blue portion of the spectrum. In principle this signal is proportional to emulsion thickness and can be used to calculate $\boldsymbol{k_{nu}(x,y)}$.



Corrections: Unirradiated Film Reading, $M_{\mathrm{det}}(0)$

- Necessary to obtain net optical density
- Important as check on film quality

Corrections: Readout Non-Uniformity, $k_{pos}(x,y)$

- if using small films, avoid this effect by always reading films in the same area of the densitometer or scanner
- for large films, can be quantified by using uniformly irradiated, large area reference films that have been checked for uniformity by independent methods

Corrections: Time and Temperature Effects, $k_{tT}(T,t,D)$

- Unlike TLDs, signal *grows* with time with RCF
- Growth is logarithmic with time
- During the 1st 24 hrs after irradiation, absorption increases by up to 16%.
  - 4% thereafter for up to 2 wks
- Greatest increase in absorption occurs at higher temp: ~ 40ºC
- Best approach is to control the times and temperatures and keep constant & uniform

Rapid Color Stabilization for Older GAFCHROMIC Film Models

Reinstein et al. suggest annealing at 45° C for 2 hours, which is the equivalent of storing at room temperature for months (for those too impatient to wait a few days)

Note: this has not been verified for EBT models

Environmental Factors

- Humidity (HD-810) effect for 6 to 94% < ± 2%
- Temperature effect (MD-55-1 & MD-55-2) for 10 to 50°C:
  - Response varies with dose as well as λ of analysis
  - At ~ 50°C there is an erratic variation in response
  - At > 60°C the blue dye changes to red and may cause significant change in sensitivity
- UV exposure with λ > 300 nm(sunlight or continuous white fluorescent lights) colors the film
  - Needs to be stored in opaque container
- Shipping and handling may cause damaged locations
  - Color of the film turns from clear to milky white
  - Need to be read no closet than ~ 1.5 mm away from cut edge

Overall Conversion of Reading to Dose to Medium, $D_{med}(Q)$

$$D_{med}(Q) = f(Q)k_{bq}(Q)k_{dr}(Q,\dot{D})k_{tT}(T,t,D)k_{pos}(x,y)k_{nu}(x,y)$$
$$\times k_l(M_{det}(D))\left[\frac{D_{med}(D_0,Q_0)}{\{M_{det}(D_0,Q_0)-M_{det}(0)\}}\right][M_{det}^{raw}(Q)-M_{det}(0)]$$

Net film response, $M_{det}^{raw}(Q)-M_{det}(0)$

Film calibration, $k_l(M_{det}(D))\left[\frac{D_{med}(D_0,Q_0)}{\{M_{det}(D_0,Q_0)-M_{det}(0)\}}\right]$

Absorbed-dose response, $f(Q)$

Intrinsic energy dependence, k_{bq}

Dose rate dependence, $k_{dr}(\dot{D})$

Time and temperature corrections, $k_{tT}(t,T,D)$

Film non-uniformity correction, $k_{nu}(x,y)$

Film reading position correction, $k_{pos}(x,y)$

Example of Uncertainty Budget for Measurement of a Low-Energy Photon Brachytherapy Source at 1 cm in Water with GAFCHROMIC Emulsion Calibrated with ^{60}Co Gamma Rays

	Uncertainty (%)	
Component of uncertainty	**Type A**	**Type B**
Net film response, $M_{\text{det}}^{raw}(Q) - M_{\text{det}}(0)$		2
Film calibration, $k_l(M_{\text{det}}(D))\left[\dfrac{D_{med}(D_0,Q_0)}{\{M_{\text{det}}(D_0,Q_0) - M_{\text{det}}(0)\}}\right]$		3
Absorbed-dose response, $f(Q)$	5	
Source detector positioning, $[D(r)/D(r_0)]$	0.2	
Intrinsic energy dependence, k_{bq}	0.5	
Dose rate dependence, $k_{dr}(\dot{D})$	0.5	
Time and temperature corrections, $k_{tT}(t,T,D)$	1	
Film non-uniformity correction, $k_{nu}(x,y)$	1	
Film reading position correction, $k_{pos}(\text{x,y})$	0.1	
Combined uncertainty	6.4	
Combined, expanded (k=2) uncertainty	13	

Film Measurement Methods

”Very Old School”: White Light Densitometers

apertures should be 1 mm or less
if manual, positional reproducibility may be difficult

67 µ

“Old School” High Resolution Scanning Densitometers

(laser densitometers)

point by point 2-D scanning
633 nm laser (HeNe)
100-µm diameter spot size
40- µm minimum step size

(camera based systems)

CCD imaging system
660 nm light bed (LEDs)
228 x 358 pixel array
<10µm minimum pixel size

“Wave of the Future”: Color Photo Scanners

inexpensive, buts use white light sources (UV concerns)
48-bit image depth recommended
have to learn to deal with transmission values & TIFF
up to 2400 dpi => 10 µm pixels possible
three color channels (RGB) available: new horizons!

Densitometer Parameters

- light source
- light detection
- response linearity
- response accuracy
- response reproducibility
- response stability
- spatial resolution
- positional accuracy
- bed geometry
- acquisition time
- control software
- environmental factors

Types of Densitometers

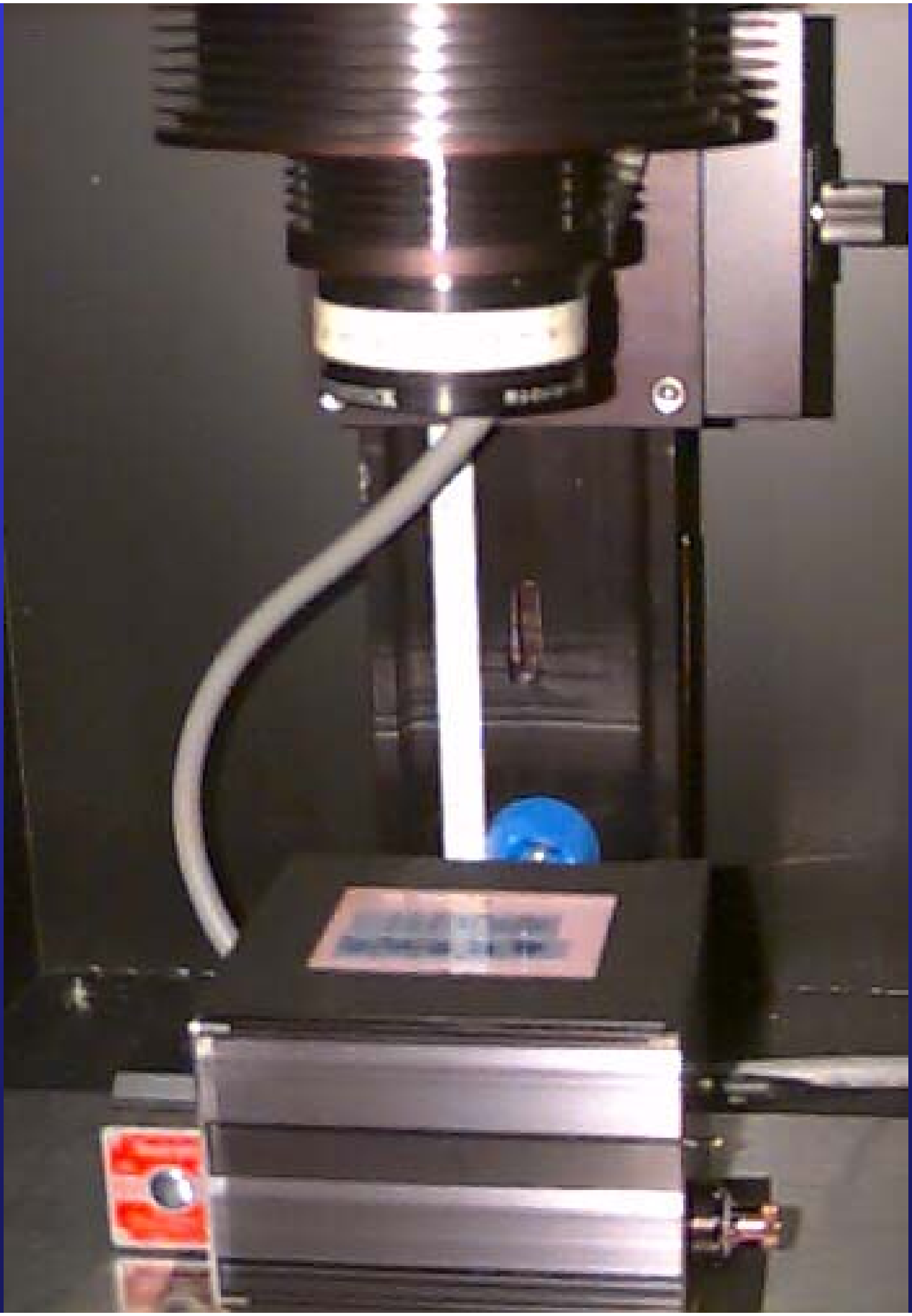
- Moving:
- *single light source*
- *single detector*
- *sample and/or light source-detector moved*

- Imaging:
- *uniform backlit bed*
- *imaging device*
- *no movement*

- Hybrids:
- *combination of the above*

Example of a Moving System

Example of an Imaging System

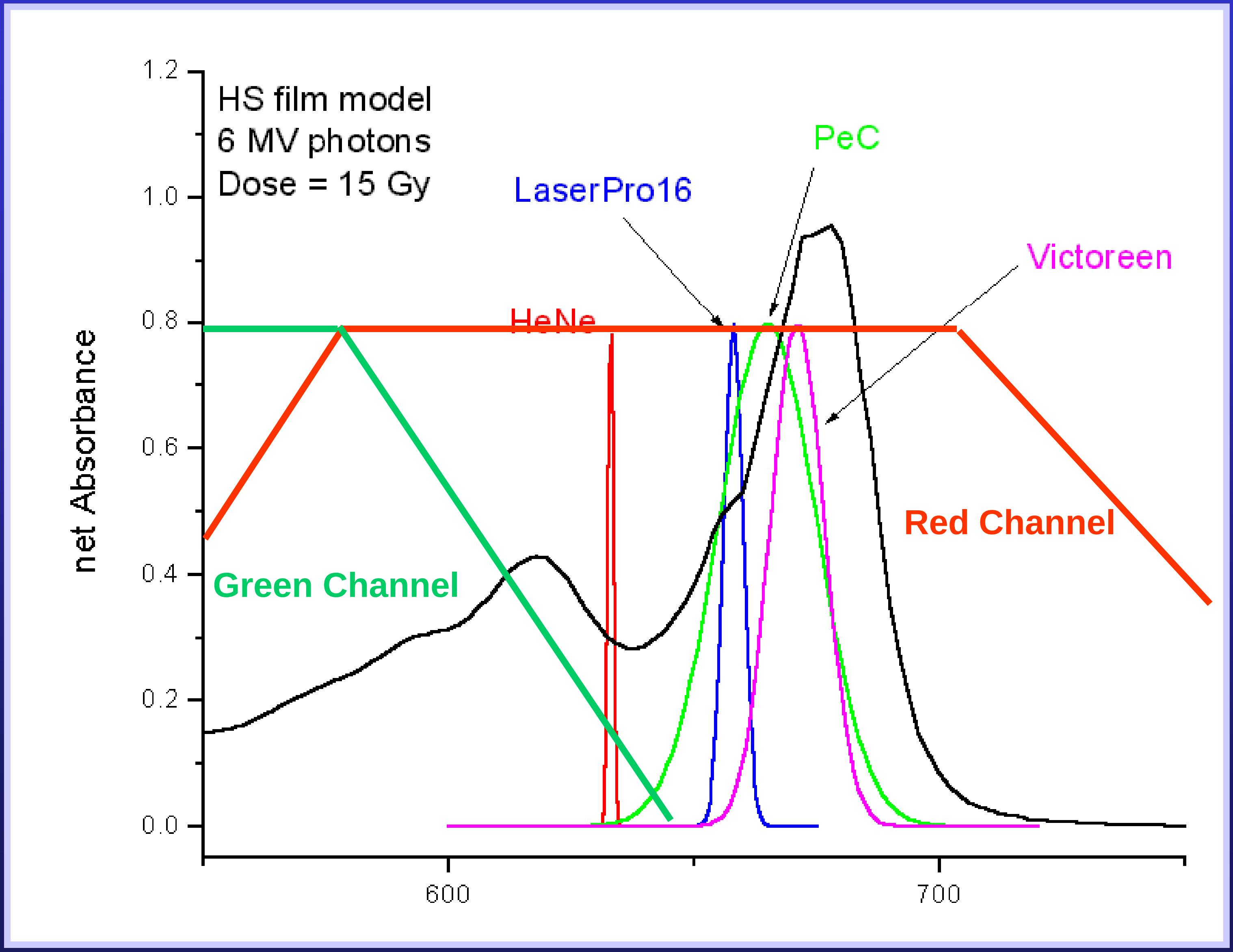


Light Sources

- wavelength
- FWHM
- intensity
- size
- uniformity
- match to light detector
- match to film being read

- *Examples:*
- HeNe laser, 633 nm, nearly 0 FWHM 1 mW, 50μm diameter spot
- Filtered white light
- LED light bed

Other Examples of Red Light Sources compared to GAFCHROMIC HS Absorbance Spectrum



Light Detectors

sensitivity

spectral efficiency

linearity

signal resolution

Types:

PMT

CCD: (linear array most common now)

Signal Resolution

The maximum number of "shades of grey" a pixel value may contain, expressed as a power of 2. Thus an "8-bit" scanner is capable of $2^8=256$ shades of coloration distinction, while a "16-bit" scanner is capable of $2^{16}=65536$.

Spatial Resolution

<u>Moving Systems:</u>

light source size

space between readings

<u>Imaging Systems:</u>

pixel size

dead area

<u>Both:</u>

light diffusion in sample

stray light

Positional Accuracy

Moving Systems:

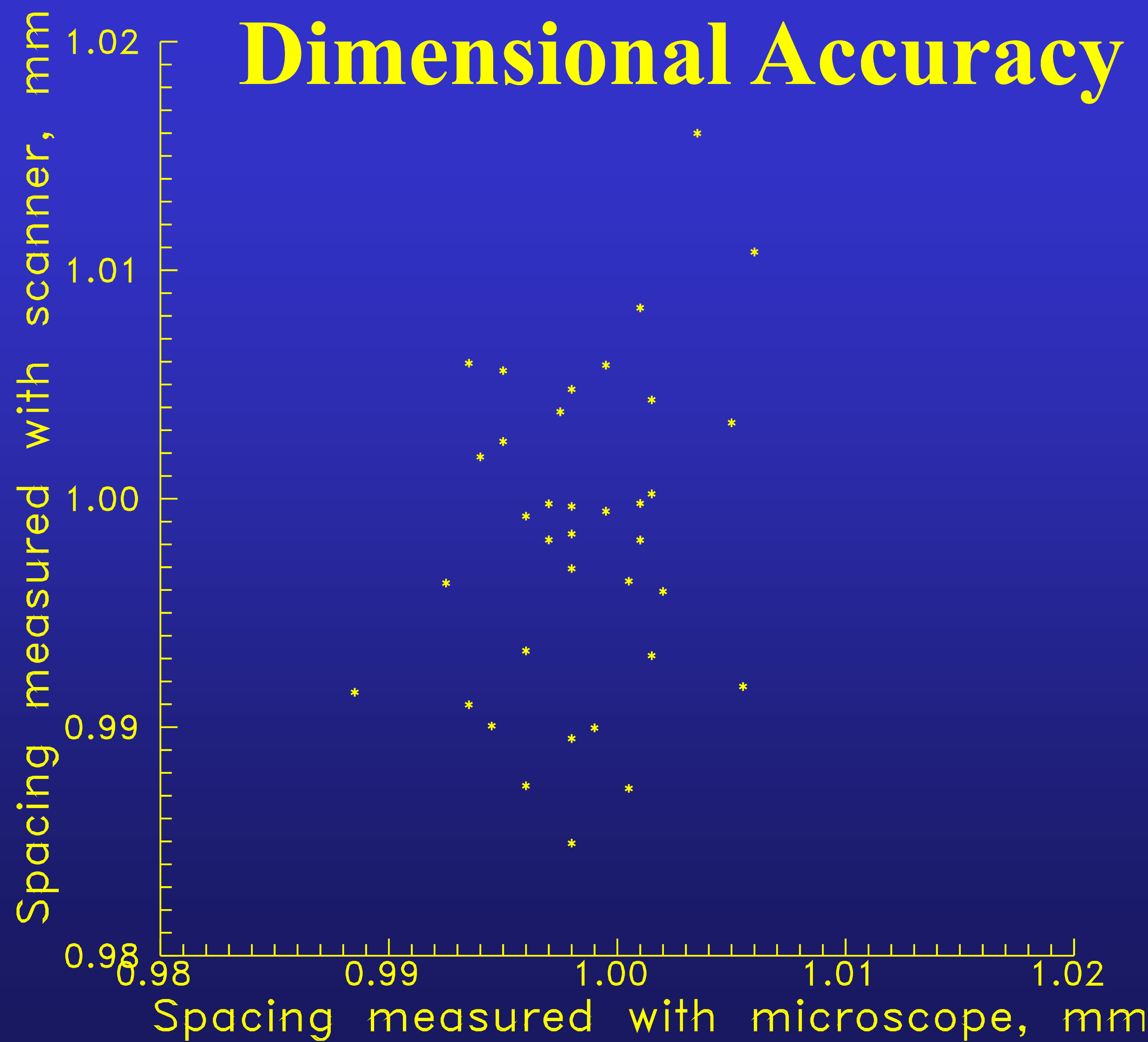
stepping accuracy

bi-directional motion

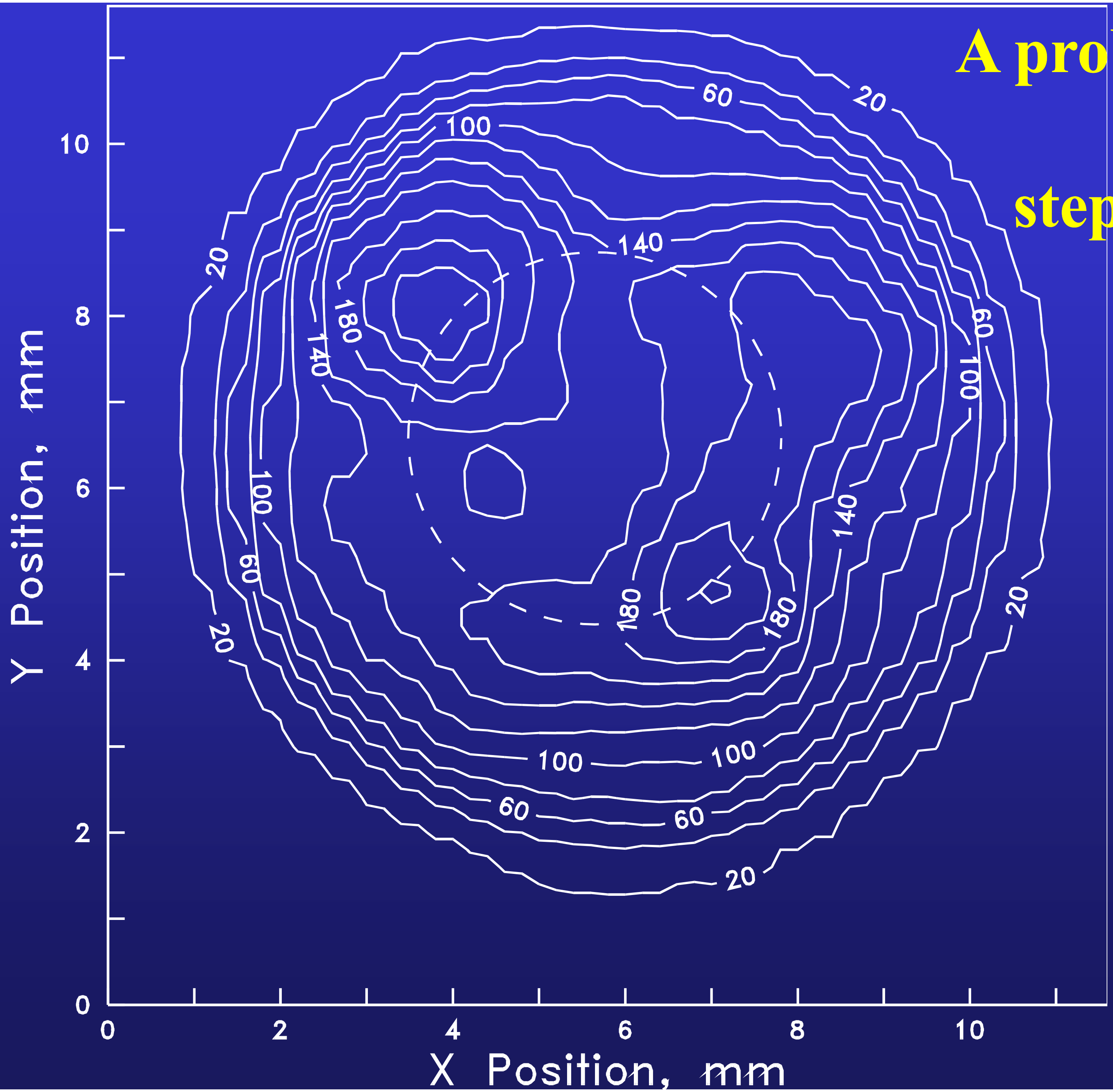
Imaging Systems:

regularity of imaging grid

Dimensional Accuracy



A problem with stepping



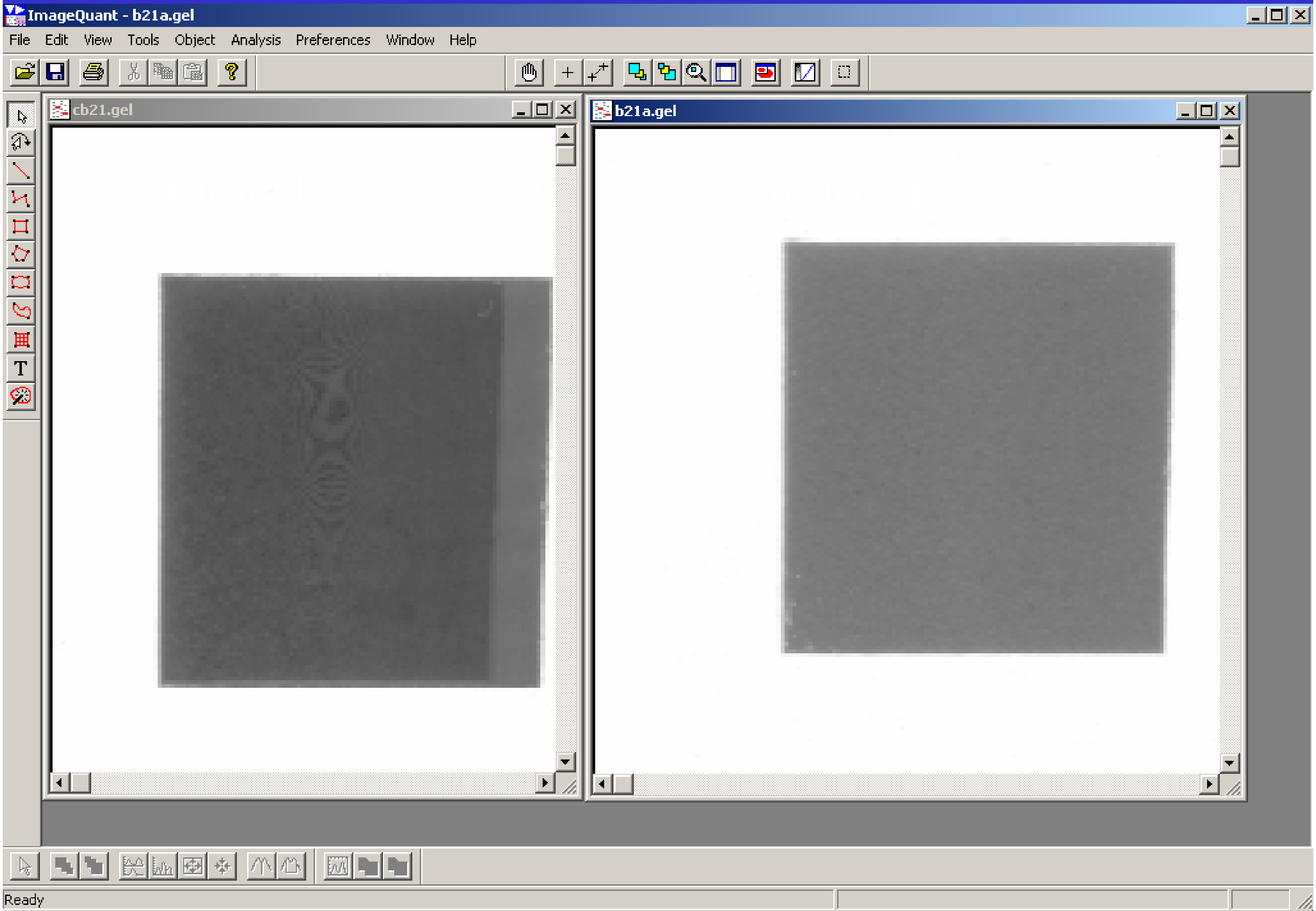
Reader Bed Parameters

Moving Systems:
maximum pixel size
transmission uniformity

Imaging Systems:
light source uniformity

Both:
film positioning
size

Moiré Patterns in Laser Densitometer with EBT Film (D=7 Gy)



Effect of Polarized Light

- **Klassen et al studied polarity effect for MD-55-2:**
  - **Microcrystals in sensitive layers have a preferred orientation (i.e. elongated)**
  - **Monomers in microcrystals have a preferred orientation in the same plane of the film**
  - **$\therefore$ OD would vary with the plane of polarization of the analyzing light and would change with film orientation**

Polarization Effects in EBT Films

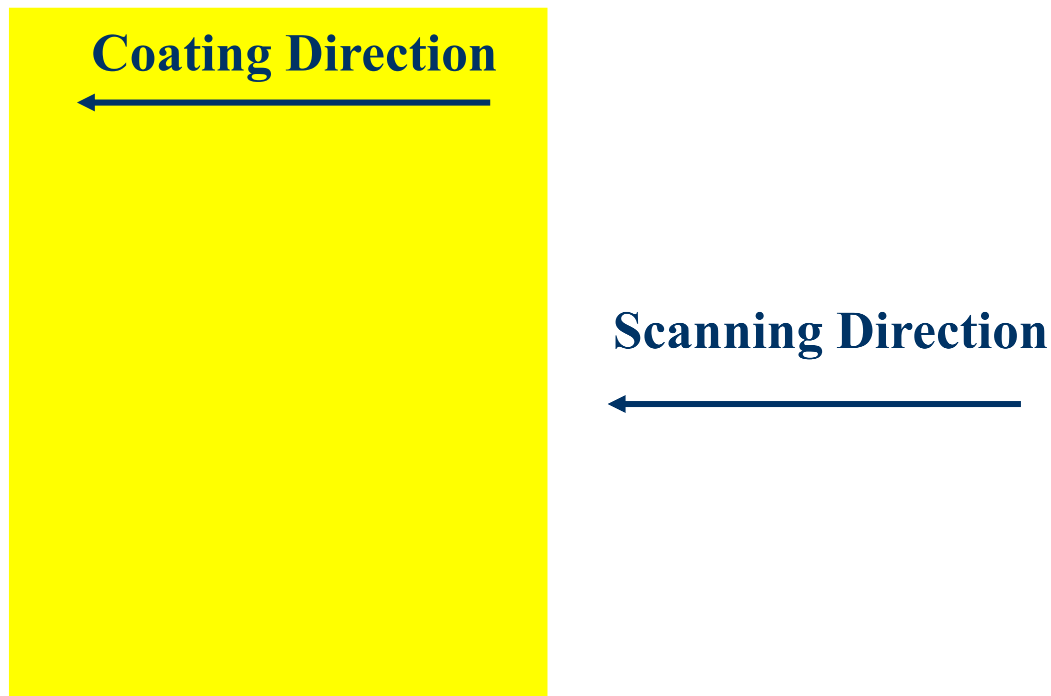
The new films exhibits film-orientation dependent polarization effects. These are severe when using <u>lasers</u> for readout:

- **Microcrystals in sensitive layers have a preferred orientation (i.e. elongated)**
- **Monomers in microcrystals have a preferred orientation in the same plane of the film**
- **∴OD varies as the plane of polarization of the analyzing light changes with film orientation**

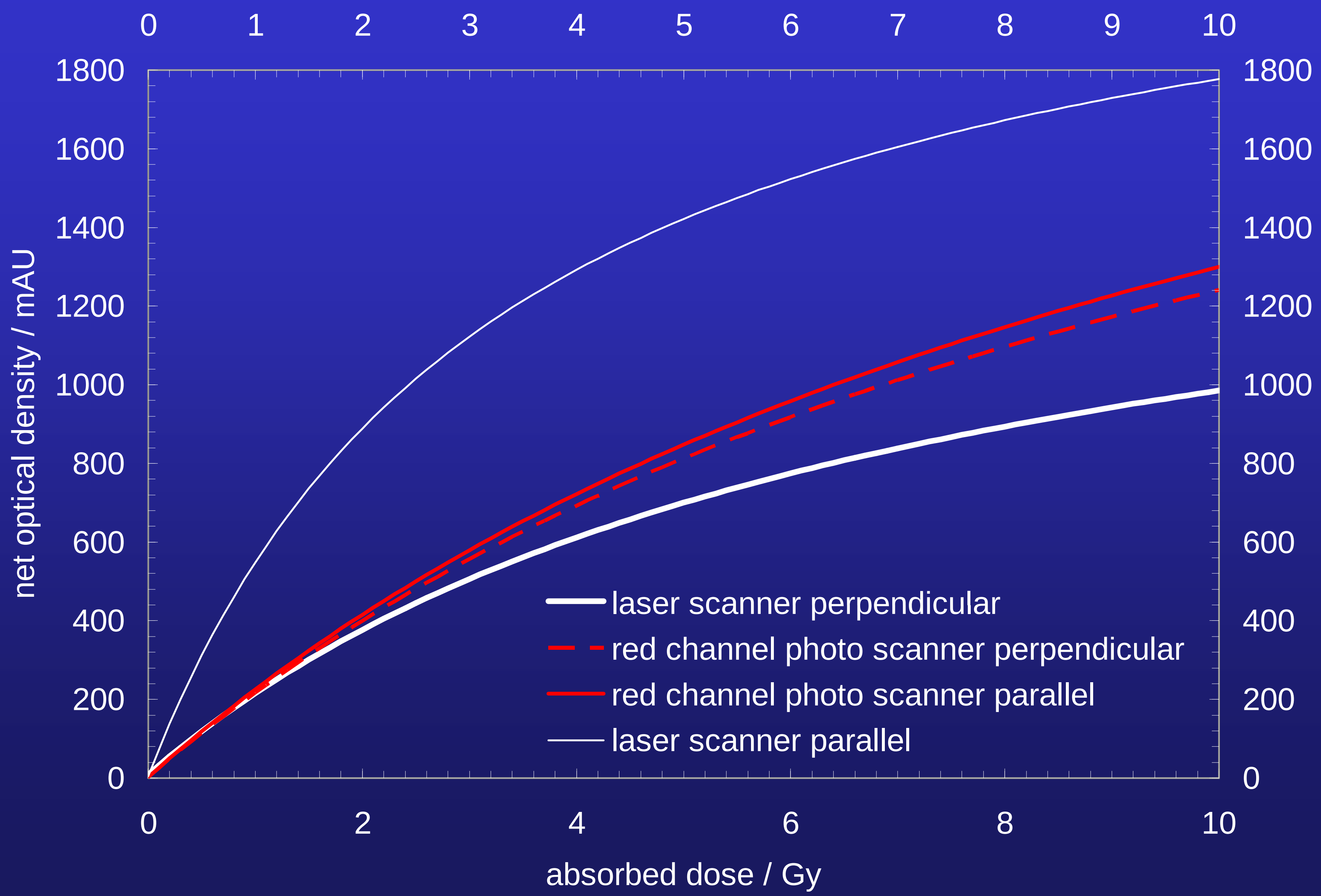
Solutions:

- **maintain rigorous film mounting convention <u>and keep consistent with calibration</u>**
- **use a diffusing layer during readout**

Manufacturer Recommendations for EBT Film Scanning Orientation



Effect of EBT-1 Film Orientation During Readout



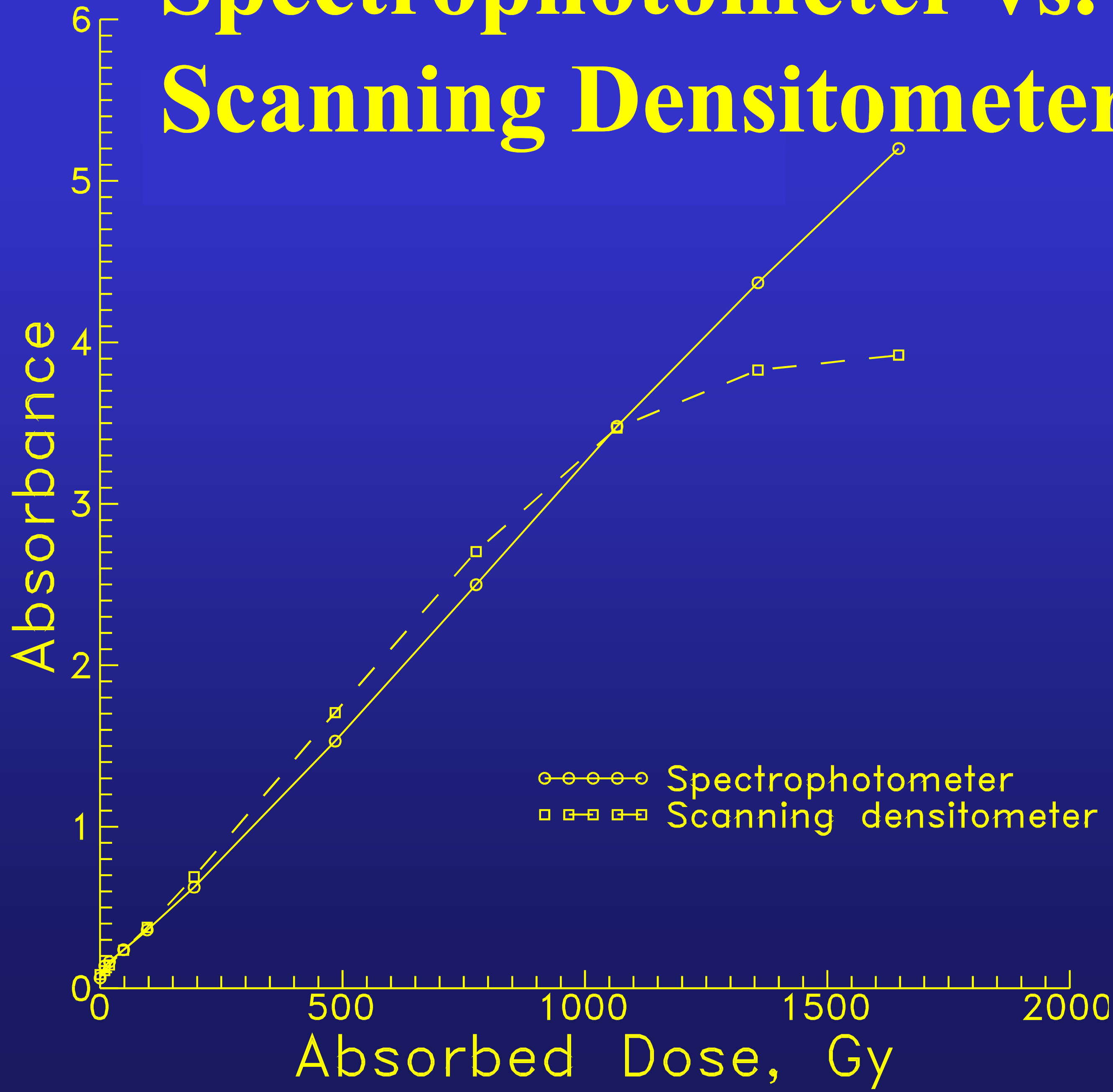
Response Linearity

calibration curve using film

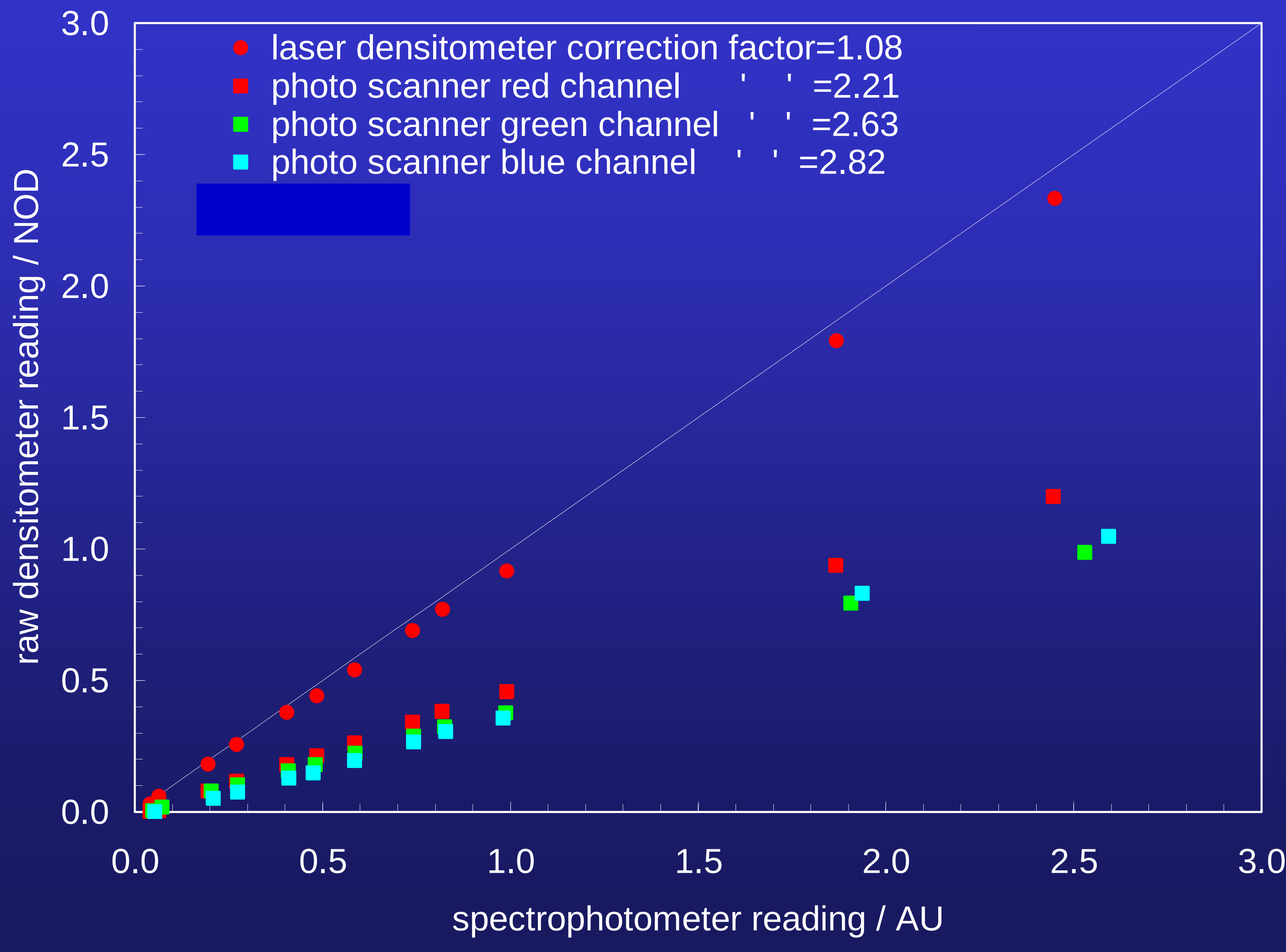
calibrated neutral density filters

comparison with spectrophotometer

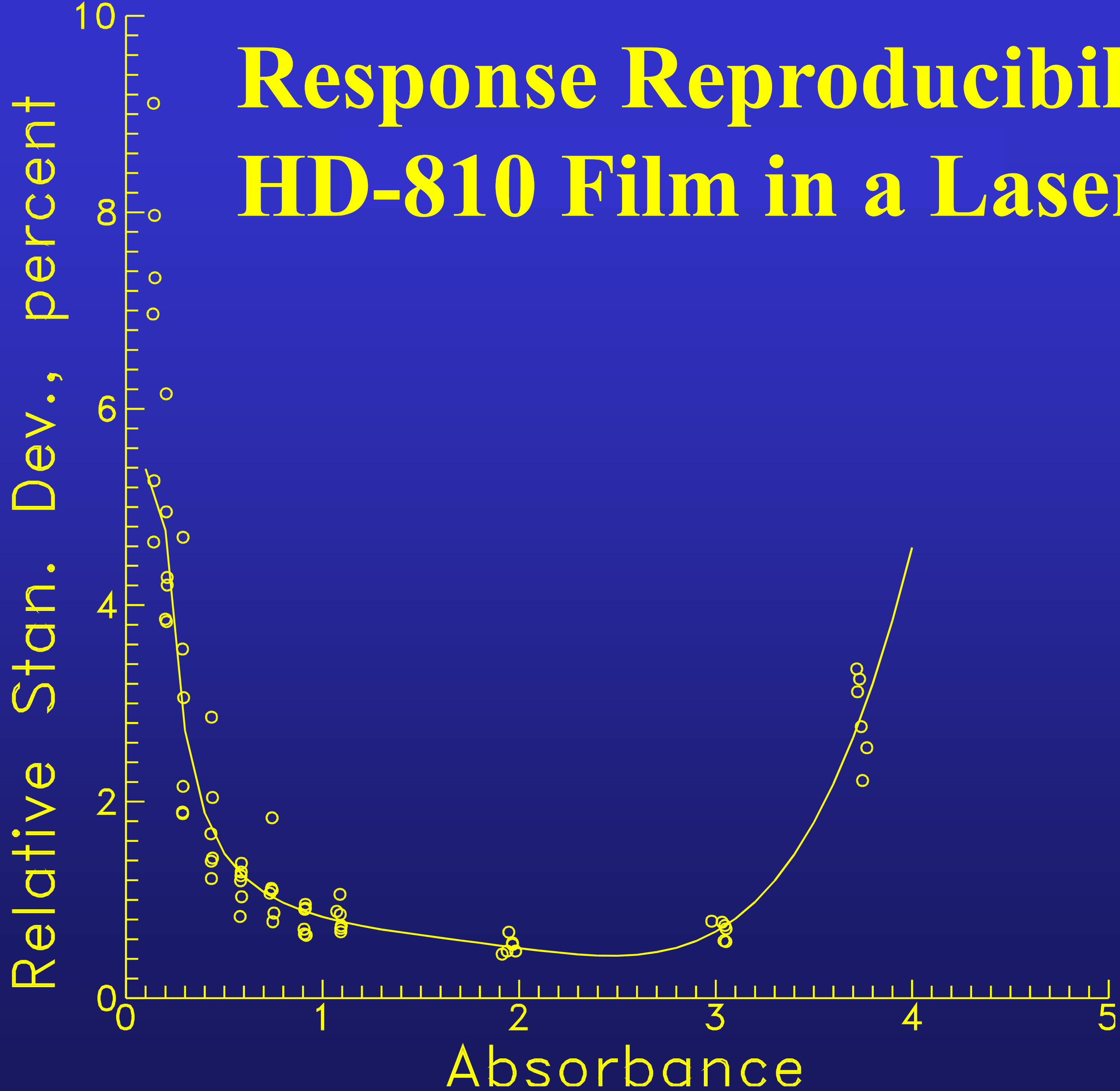
Spectrophotometer vs. Scanning Densitometer



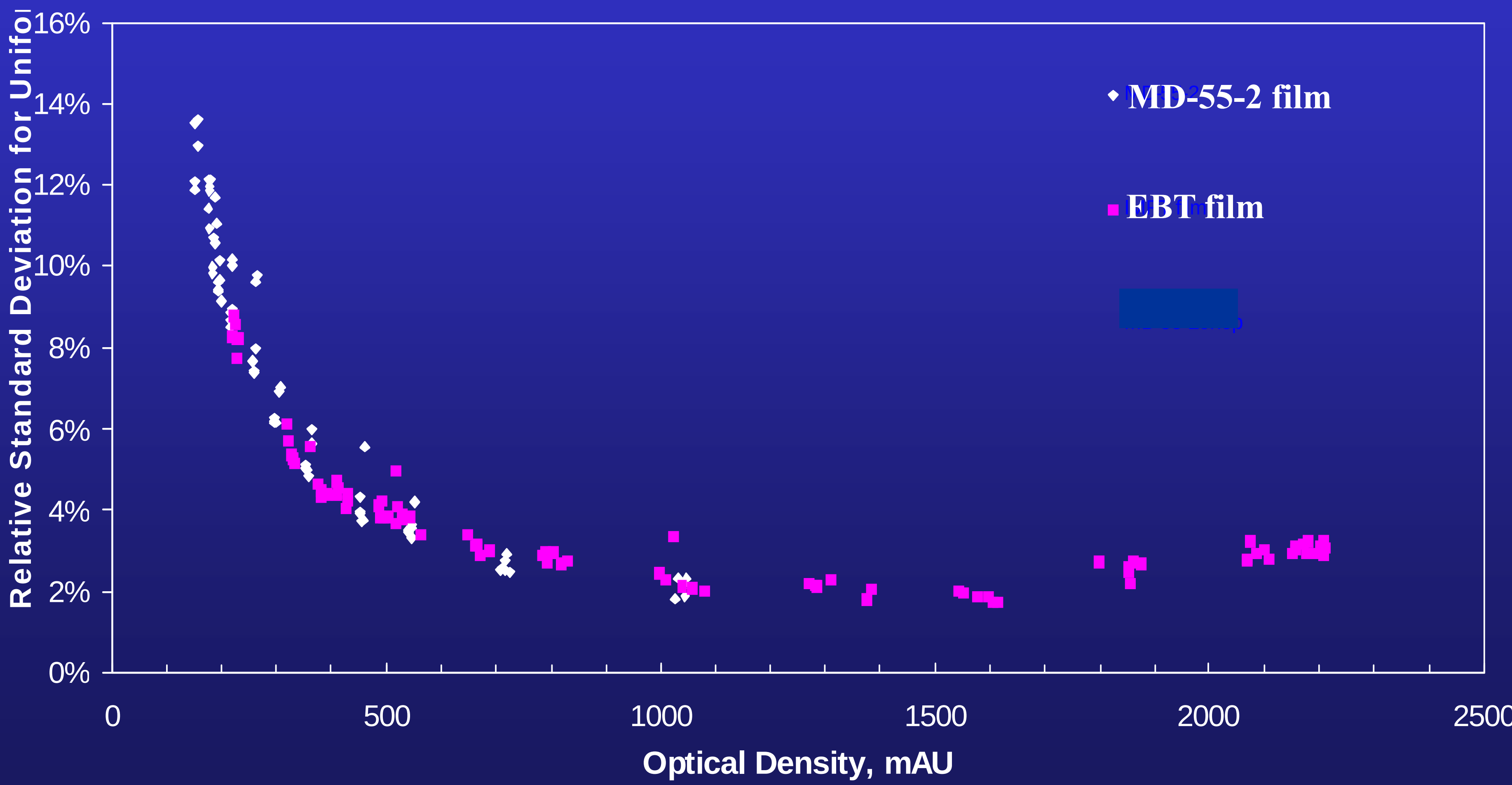
Calibration using Neutral Density Filters



Response Reproducibility: HD-810 Film in a Laser Scanner



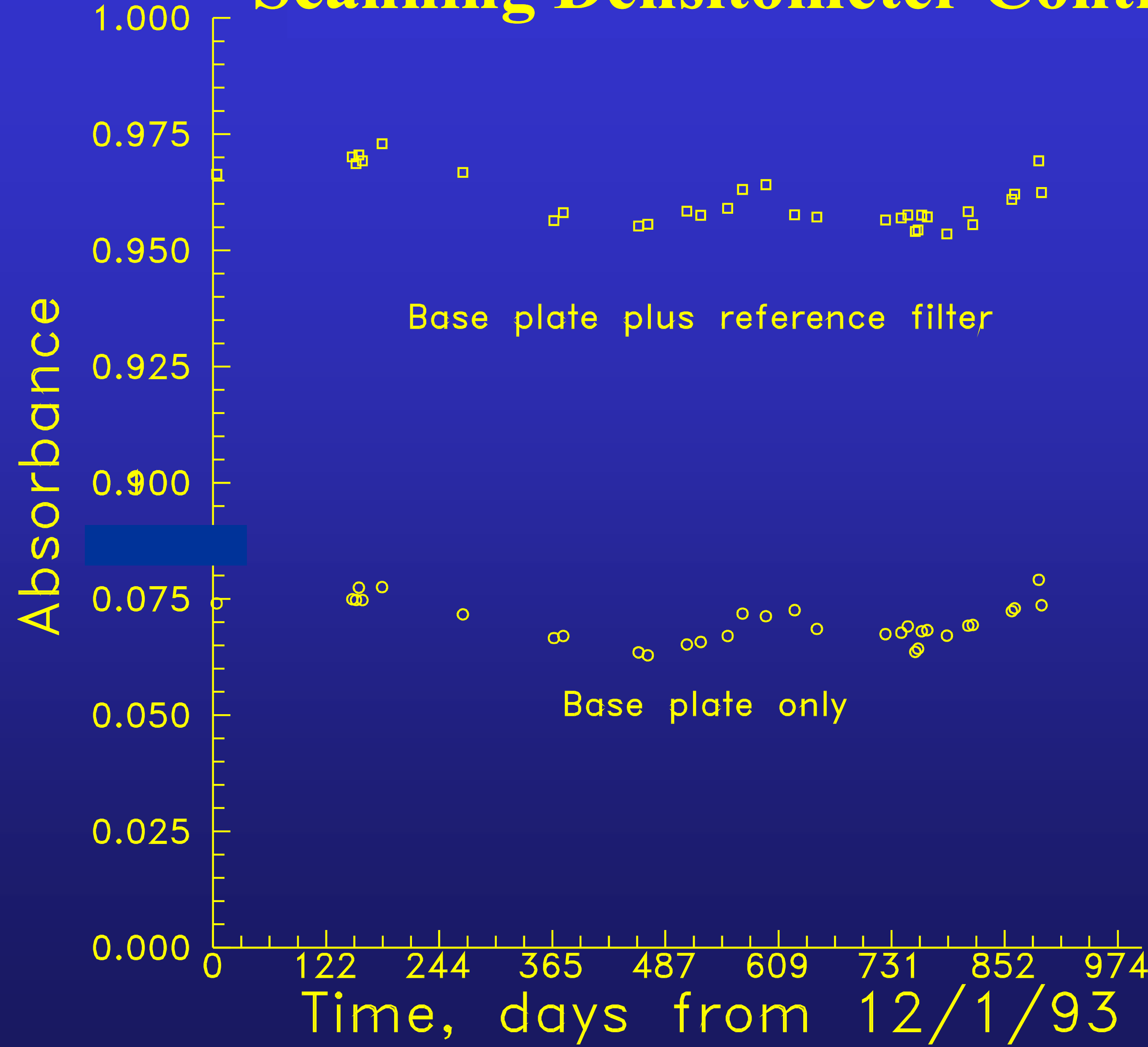
Another Laser Densitometer Characteristic Curve Determined with Old and New Emulsion Films

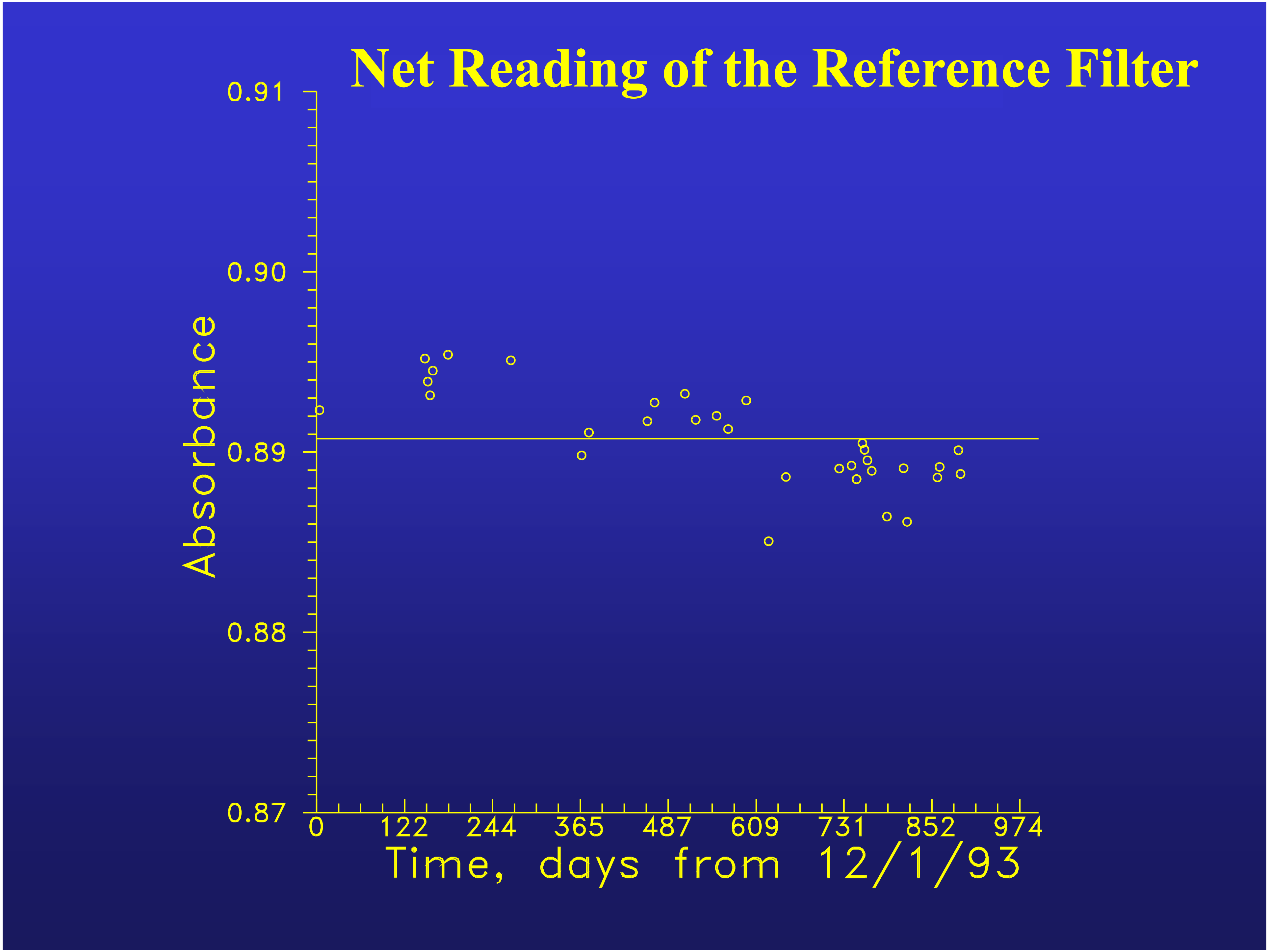


Daily Reader Quality Control

- Scan of bare reader bed
- Scans of stable reference artifacts (neutral density filters are best for this)

Scanning Densitometer Control Graph





Net Reading of the Reference Filter
0.91
0.90
0.89
0.88
0.87
Absorbance
0
122
244
365
487
609
731
852
974
Time, days from 12/1/93

Environmental Factors

temperature during readout

setup/interior lighting

Data Acquisition Time

Moving Systems:

time to step between positions

Both:

time to make measurement

data transfer time to host computer

Software

flexibility

access to data

color images

iso-density contour plots

conversion to dose via stored calibration

Special Considerations for Document Scanners

Pixel depth – should be at least 12 bits/color (make sure **all** color compensation & image adjustments are **turned off**)

Spatial resolution – should capable of at least 300 dpi (maximum that should be needed)

Data format – learn to deal with TIFFs

System linearity – check with neutral density filters; I am surprised at how good ours is

Dealing with Tagged Image File Format (TIFF)

Freeware is available, e.g., ImageJ
see http://rsb.info.nih.gov/ij/

If you prefer to "roll your own", get hold of a TIFF tag viewer to see how the header is constructed and where things are; see, e.g.,
http://www.awaresystems.be/imaging/tiff/astifftagviewer.html

Remember to use "uncompressed" format

Summary of Recommended Procedures: Readers

- select densitometer with sufficient signal resolution
- determine maximum measurable OD
- measure OD at red wavelengths for maximum sensitivity
- use green & blue channels to extend dose measurement range
- monitor absorbance scale stability with neutral density filter readings

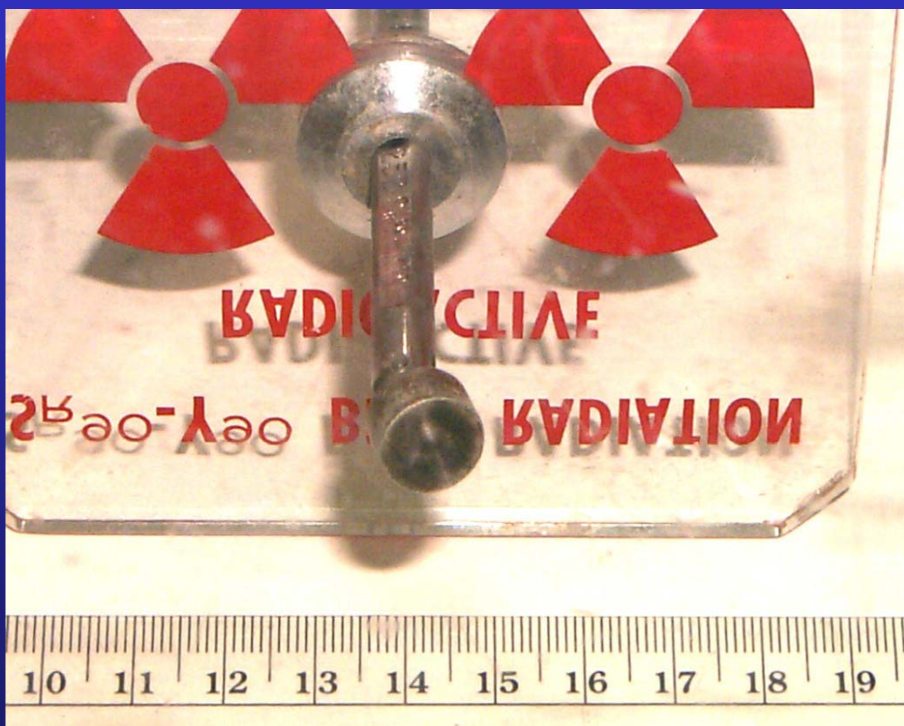
Some Medical Applications of Radiochromic Film Dosimetry

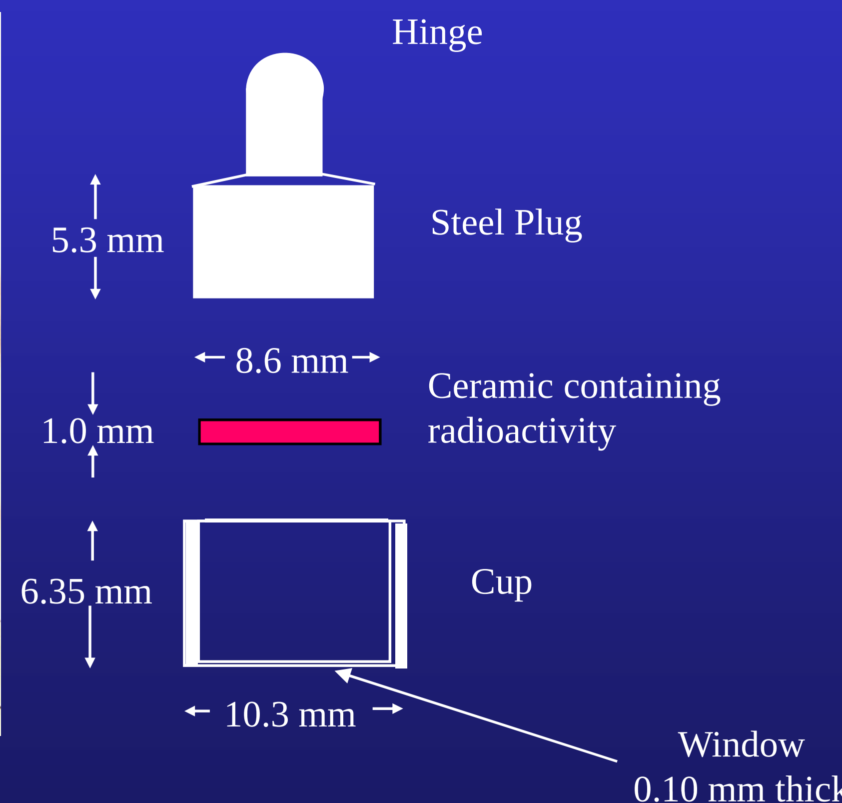
- Hot particle dose averaging
- Beta-ray ophthalmic applicator calibration
- Interface effects
- Stereotactic radiosurgery
- Intravascular brachytherapy
- Beam penumbra measurements
- Proton beam depth dose
- Radium applicator retrospective studies
- QA of IMRT beams
- Linac and HDR commissioning and QA
- and many more …

Conclusions

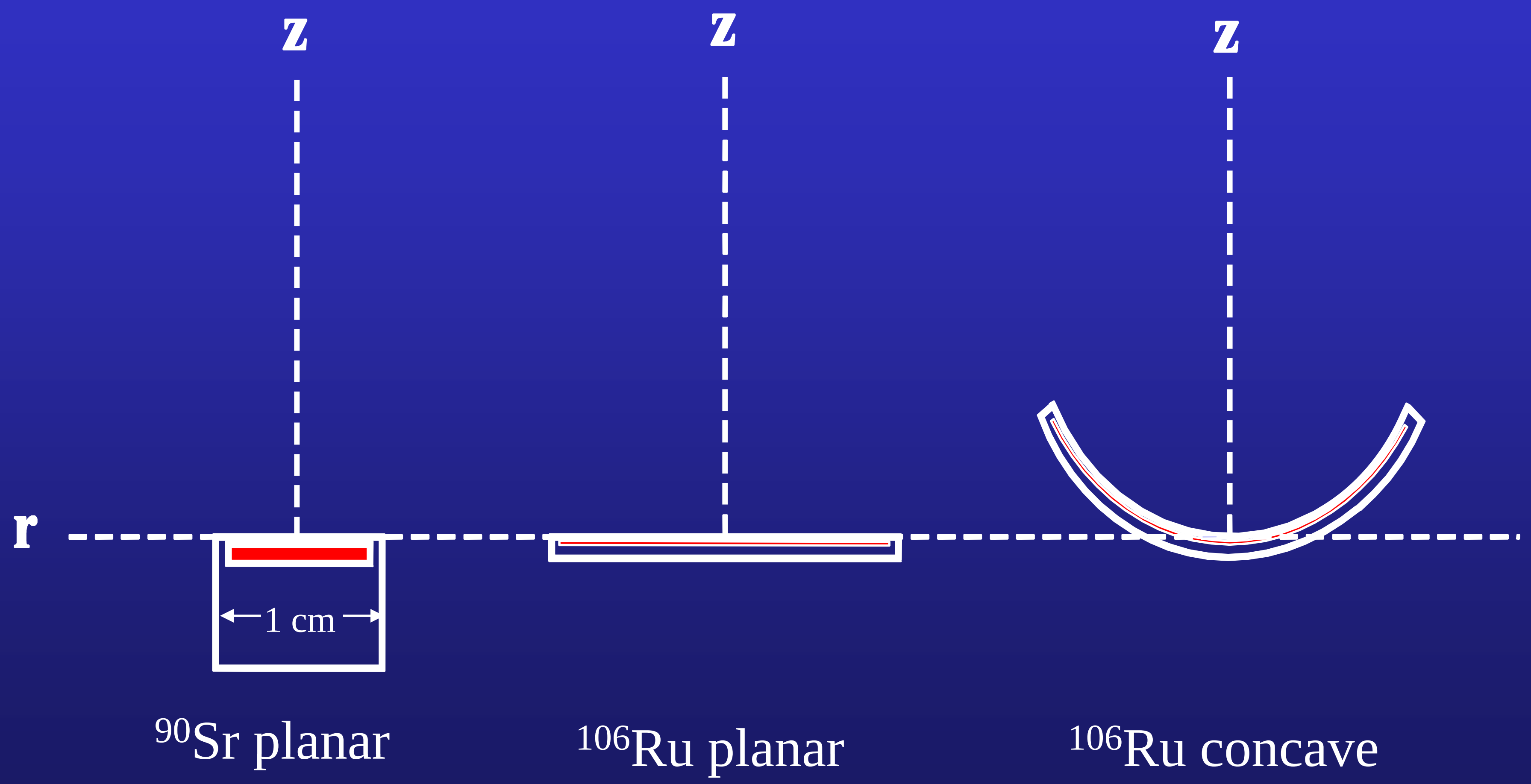
- There has never been a more exciting time to be working with radiochromic film dosimetry (I can say this having done so for more than 20 years now)
- It is the most inexpensive dosimetry and dose imaging technology available
- New film models and readout techniques promise improved accuracy and precision over anything previously available

^{90}Sr/Y Planar Ophthalmic Applicator





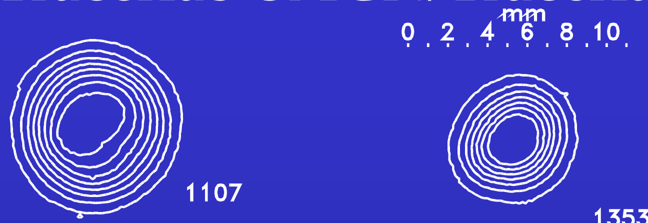
Source Geometries



Typical Source Profiles

0 2 4 6 8 10 mm

Tracerlab & ICN/Tracerlab



New England Nuclear

3M

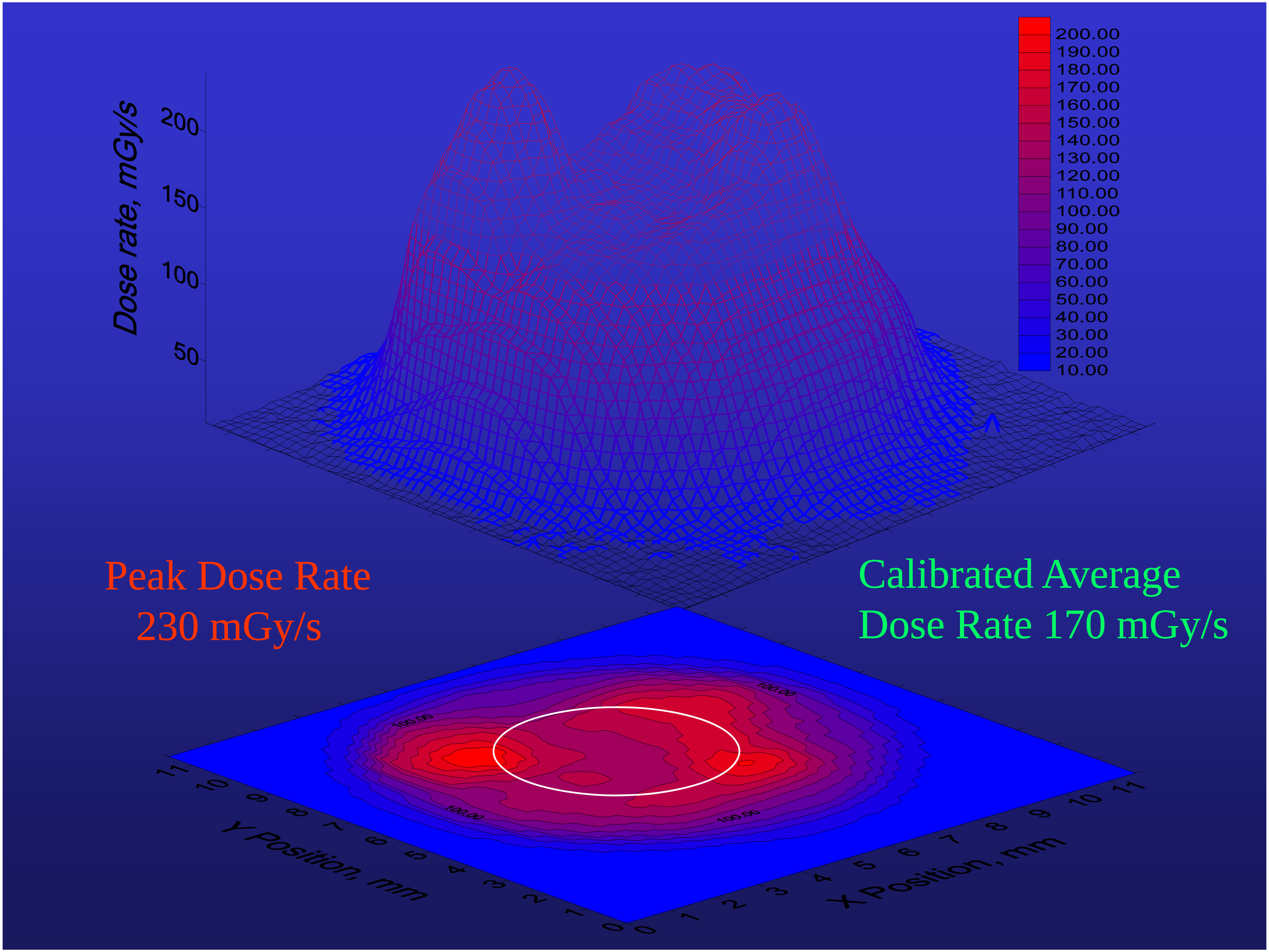
Atlantic Research Corp/Atomchem

Technical Operations

Isotope Products Lab/Nucl. Assocs.

Manning Research

Amersham International

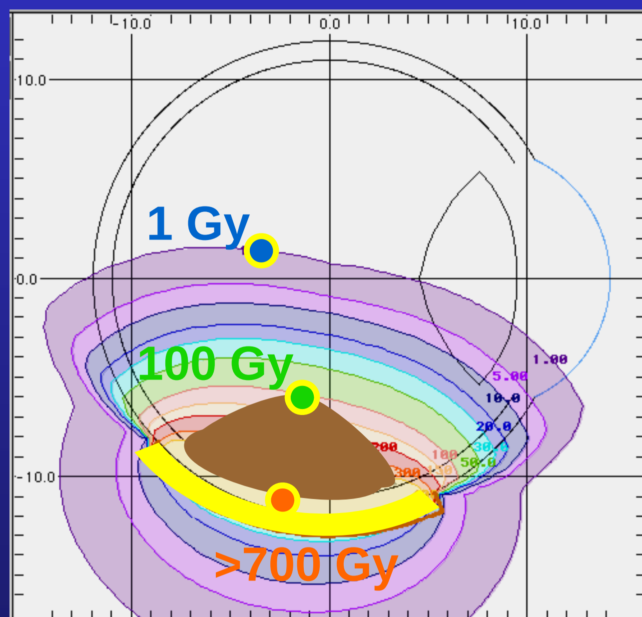


Dose rate, mGy/s
200
150
100
50
200.00
190.00
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
Peak Dose Rate
230 mGy/s
Calibrated Average
Dose Rate 170 mGy/s
100.00
Y Position, mm
X Position, mm
0 1 2 3 4 5 6 7 8 9 10 11

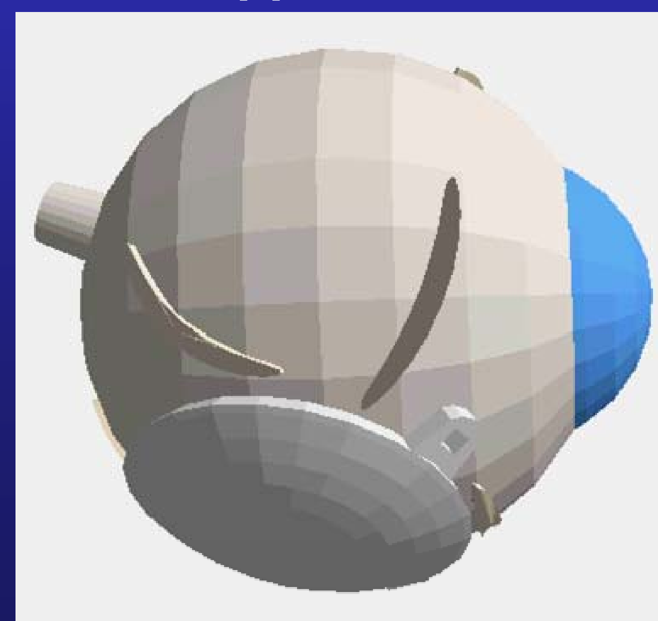
Ophthalmic Brachytherapy

Intraocular Tumor

$^{106}Ru/^{106}Rh$

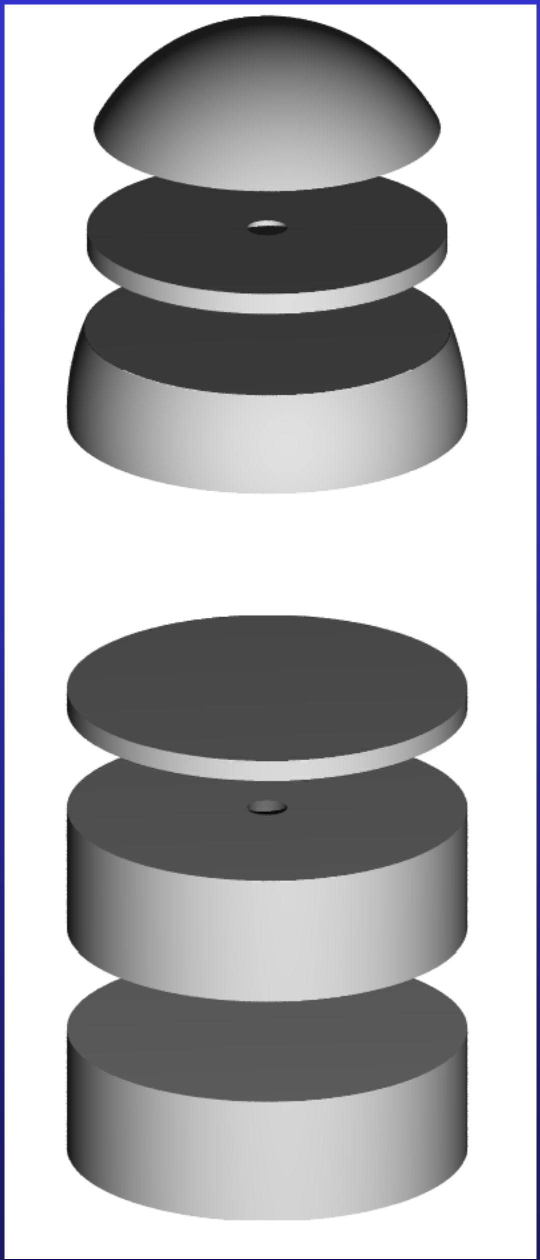


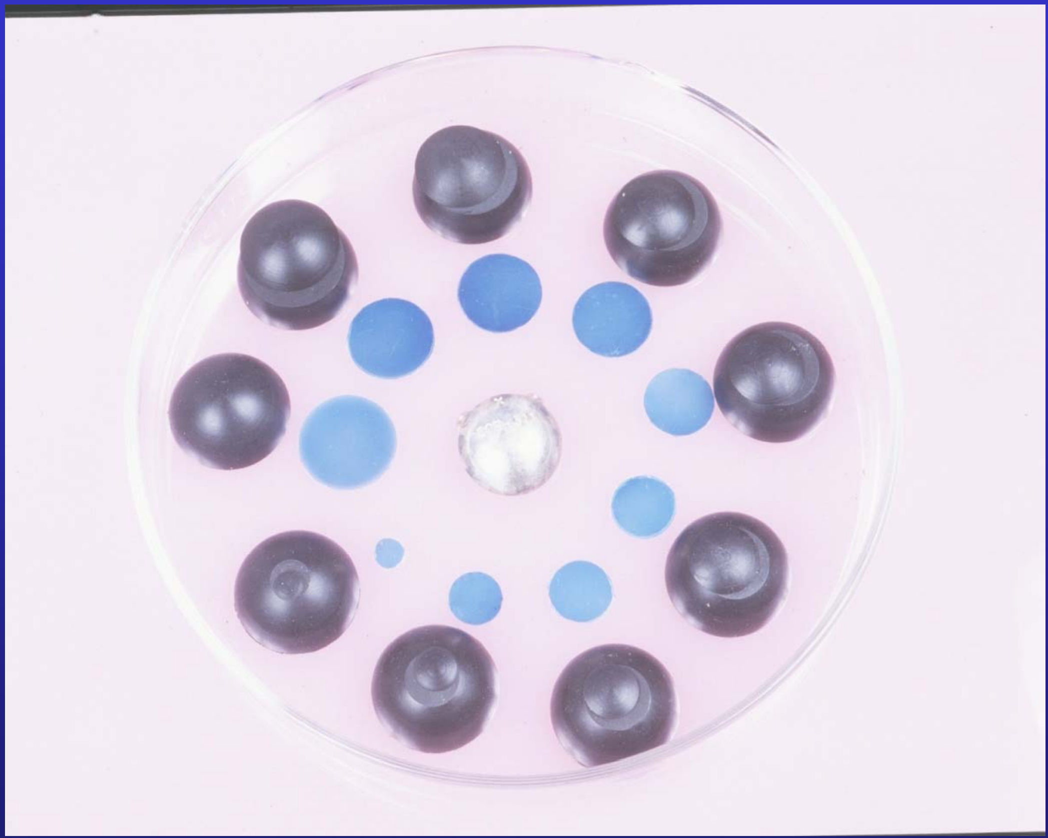
Ophthalmic Applicator



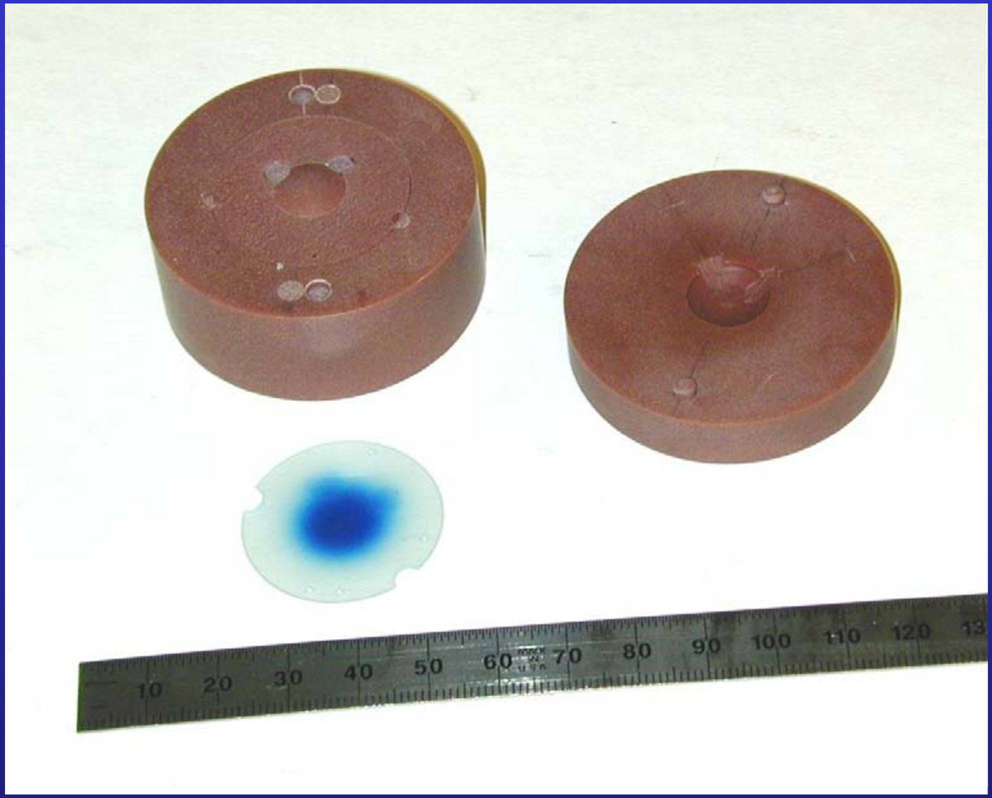
^{106}Ru/Rh Concave Applicators

Eye Phantoms

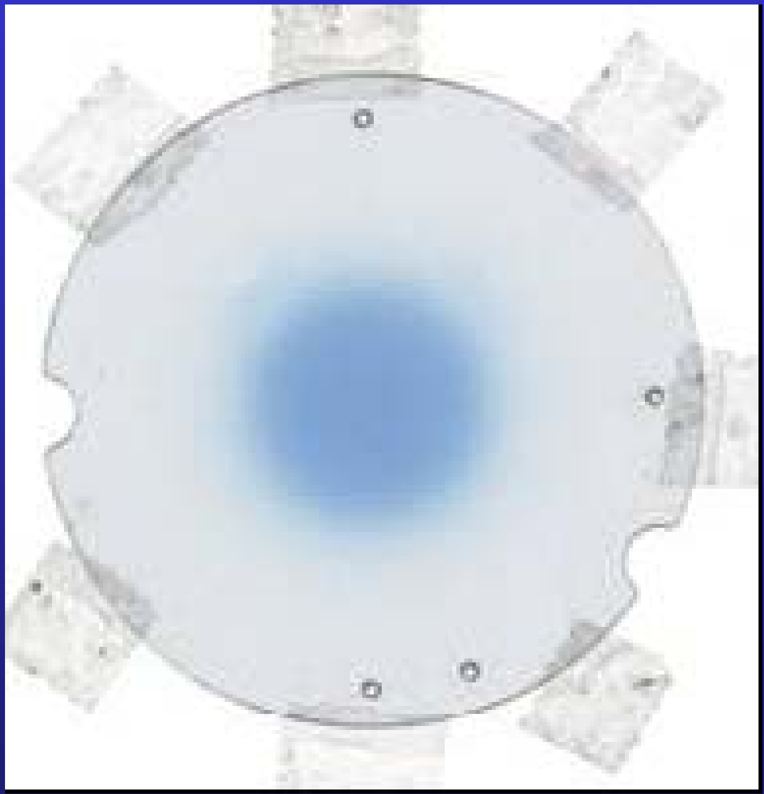


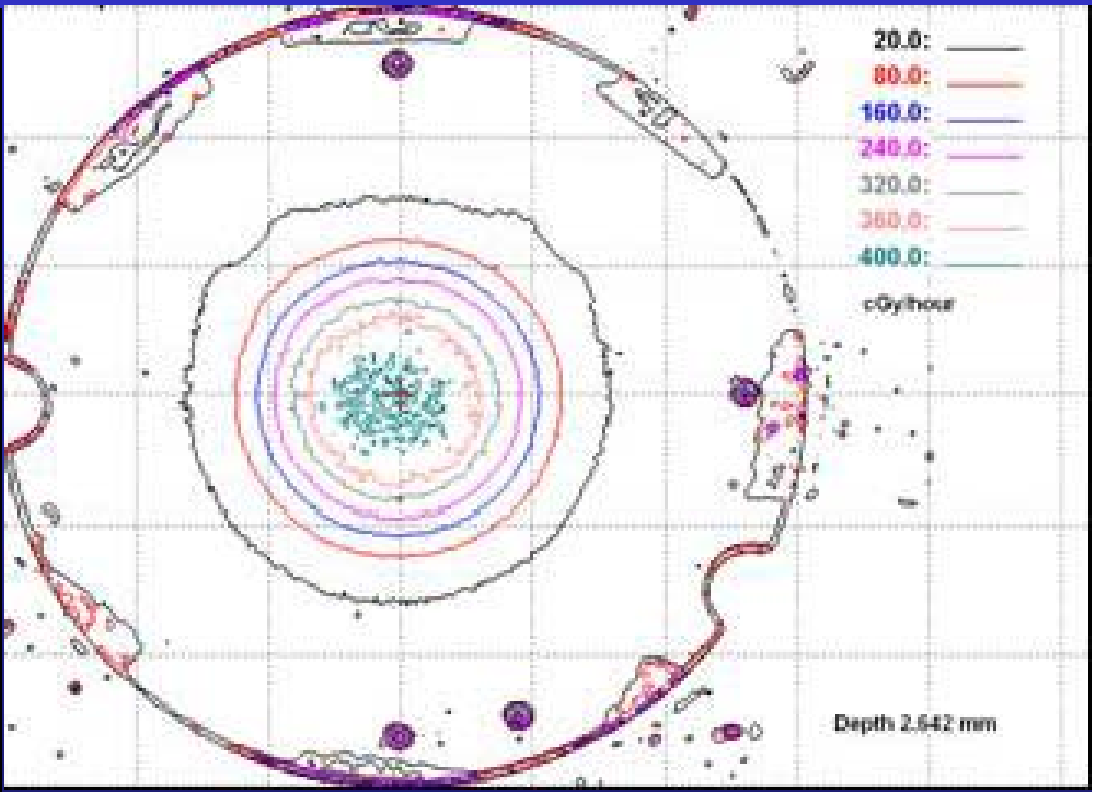


Better Eye Phantoms



EBT-1 Film Exposed at a Distance of 2.62 mm from the Inner Surface of a CCX Plaque





Measurement Comparison of Ophthalmic Applicators

National Institute of Standards & Technology
USA **Chris Soares**

National Physical Laboratory
UK **Tudor Williams**

Radiation and Nuclear Safety Authority
Finland **Hannu Järvinen**

Catholic University of Louvain, St.-Luc Hospital
Belgium **Stefaan Vynckier**

Algemeen Ziekenhuis Middelheim
Belgium **Bob Schaeken**

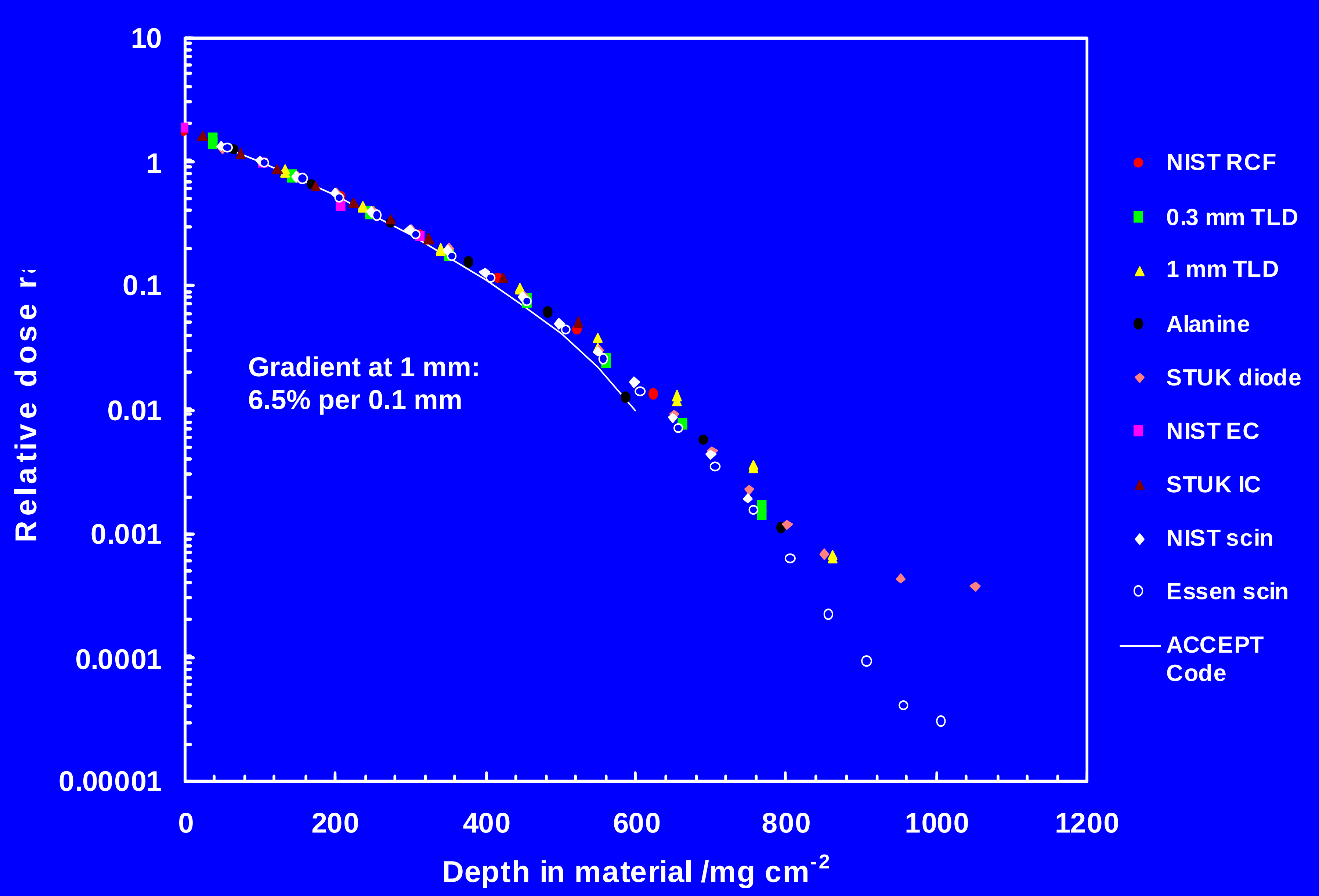
University Hospital of Essen
Germany **Dirk Flühs**

Results of Reference Dose Rate Determinations

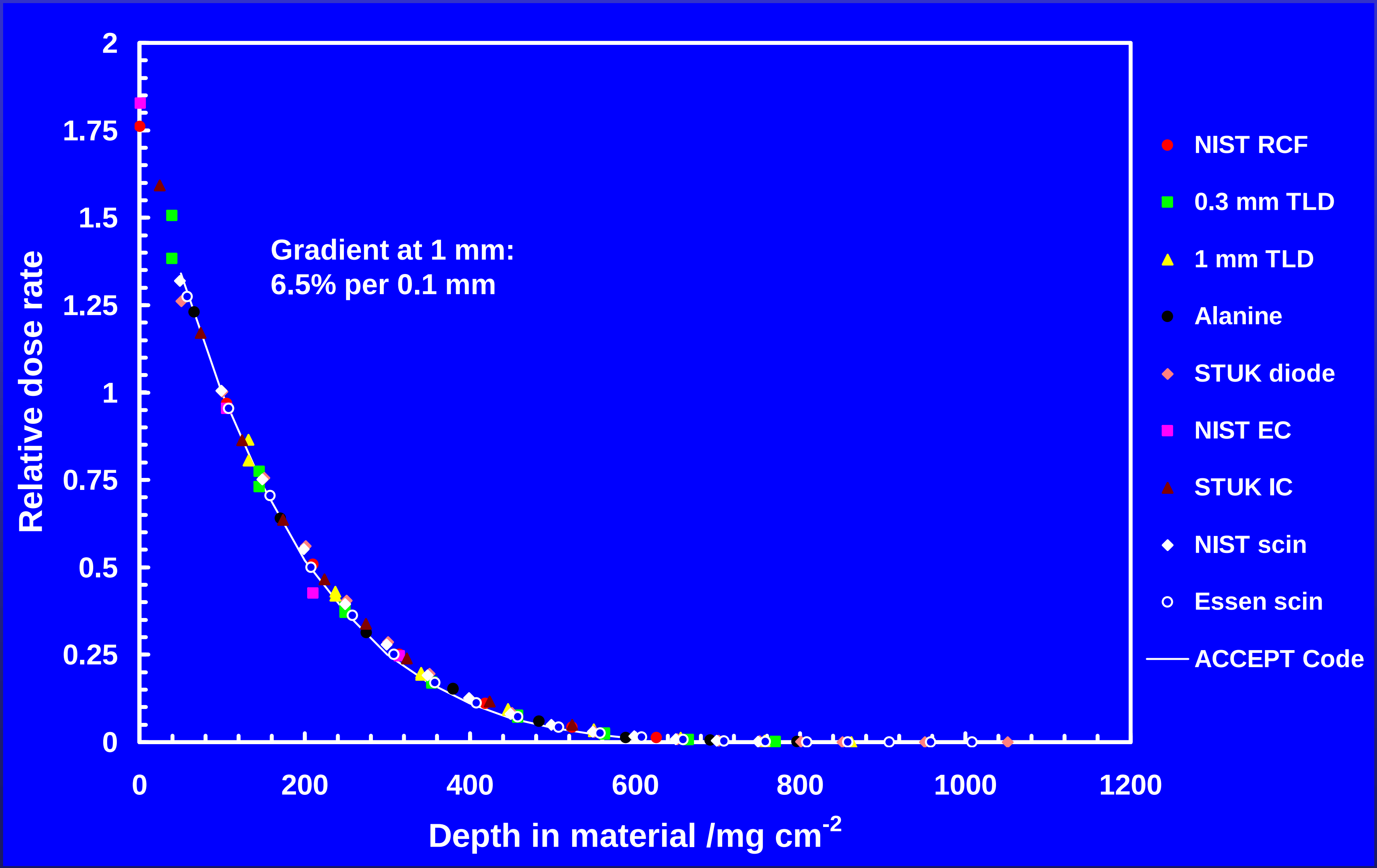
Source	Extrap. Chamb. (NIST)	Extrap. Chamb. (NPL)	GAF Film (NIST)	GAF Film (STUK)	0.3mm TLD (UCL)	0.3mm diamond (STUK)	0.4mm scin (NIST)	1mm TLD (UCL)	1.2mm alanine (AZM)
^{90}Sr NEN 0258	0.237 Gy/s	0.260* Gy/s	0.229 Gy/s	0.258 Gy/s	0.248 Gy/s	---	0.278 Gy/s	0.308 Gy/s	0.272 Gy/s
^{106}Ru BEBIG planar	1.61** mGy/s	1.82** mGy/s	1.62 mGy/s	1.63** mGy/s	1.40 mGy/s	1.99 mGy/s	1.69 mGy/s	1.75 mGy/s	1.49 mGy/s
^{106}Ru BEBIG concave	--- mGy/s	--- mGy/s	2.48 mGy/s	2.10*** mGy/s	2.55 mGy/s	3.17 mGy/s	--- mGy/s	2.79 mGy/s	2.89 mGy/s

*from a contact measurement with a factor of 0.573 applied to correct to 1 mm
** from a contact measurement with a factor of 0.742 applied to correct to 1mm
***from a measurement at 1.2 mm with a factor of 1.082 applied to correct to “

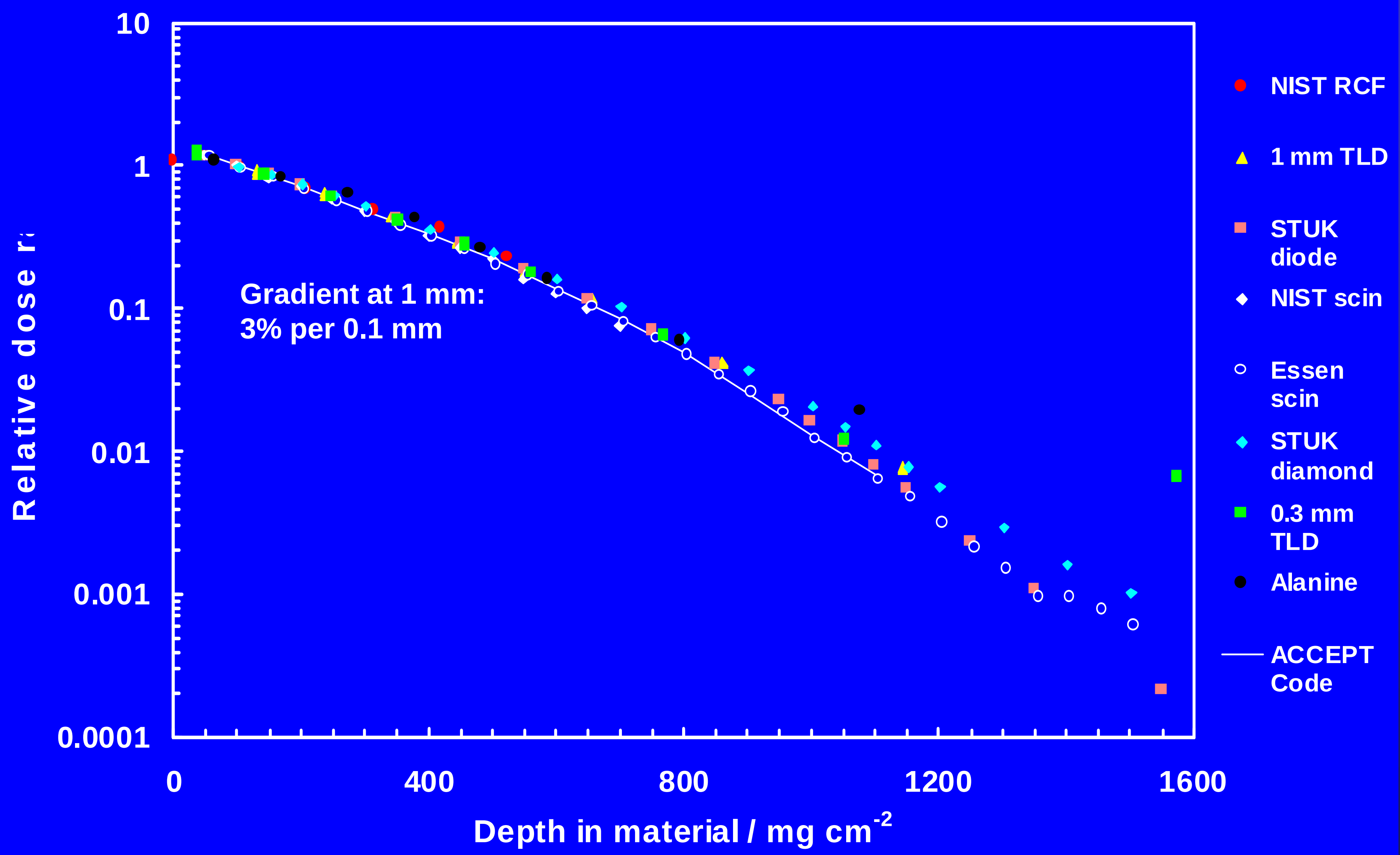
Depth Dose Measurements of a ^{90}Sr Ophthalmic Applicator



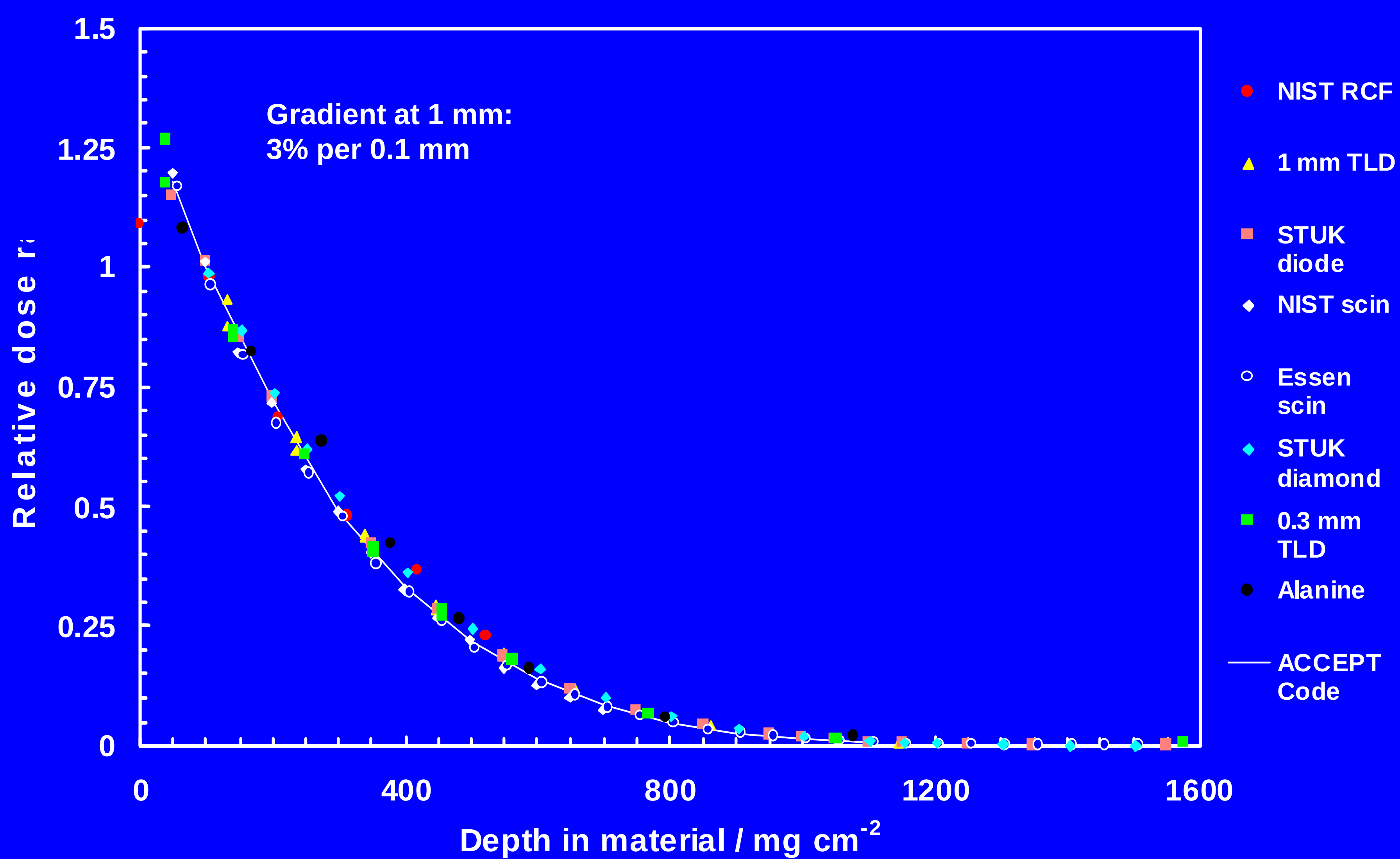
Depth Dose Measurements of a ^{90}Sr Ophthalmic Applicator



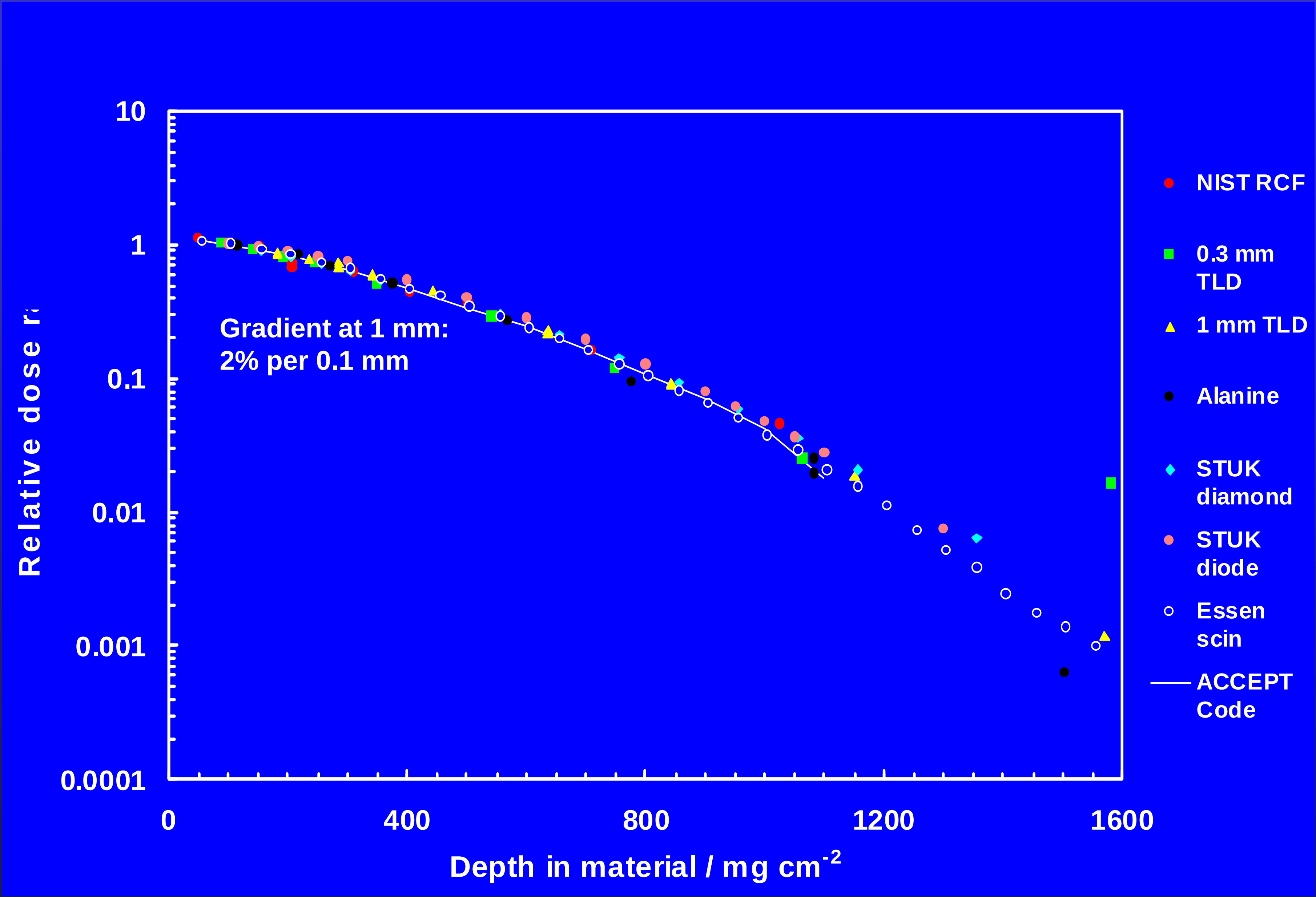
Depth Dose Measurements of a Planar ^{106}Ru Ophthalmic Applicator



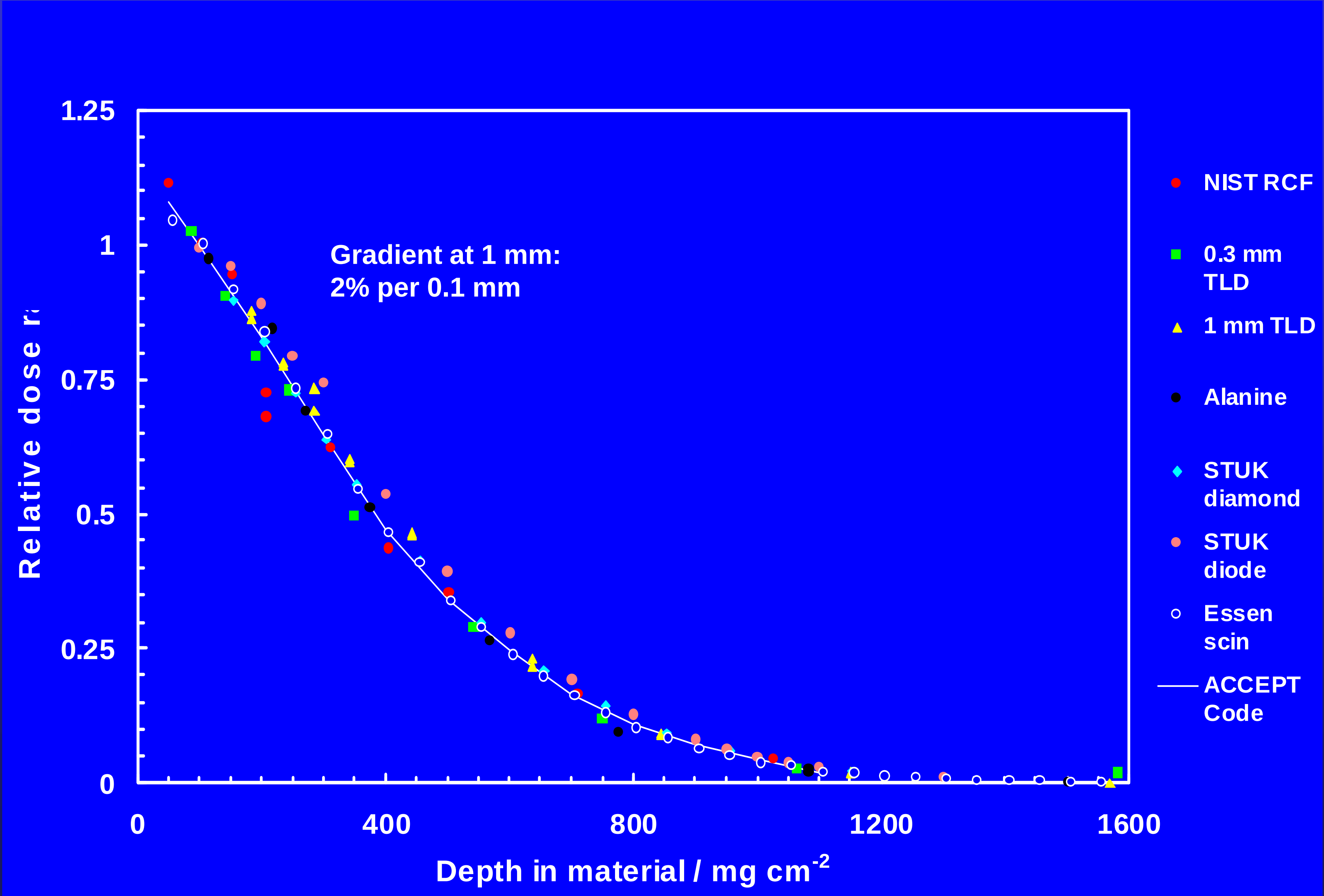
Depth Dose Measurements of a Planar ^{106}Ru Ophthalmic Applicator



Depth Dose Measurements of a Curved ^{106}Ru Ophthalmic Applicator



Depth Dose Measurements of a Curved ^{106}Ru Ophthalmic Applicator



Spread in Measurement Results

Source	Contact	**1 mm**	2 mm	3 mm	4 mm	5 mm	7 mm	10 mm
^{90}Sr NEN 0258	6.2% (10)	**9.6%** (8)	5.3% (10)	3.4% (10)	4.8% (9)	8.8% (9)	---	---
^{106}Ru BEBIG planar	5.5% (8)	**10.5%** (9)	4.0% (8)	6.1% (8)	6.4% (8)	6.8% (8)	10% (7)	19% (7)
^{106}Ru BEBIG concave	8.2% (8)	**14%** (6)	4.8% (8)	6.9% (8)	7.3% (8)	7.0% (8)	9.4% (8)	18% (8)

All percentages are single standard deviations. **Yellow** values are for reference absorbed dose rate; white values are for relative central-axis dose.