X-Ray Framing Camera Sensitivity Notes

Presented to NIF user Forum

Joe Holder
Framing Camera RS
& X-ray Diagnostic Campaign co-lead

October 2017

LLNL-PRES-739764
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

2 strip HGXD with ERASER

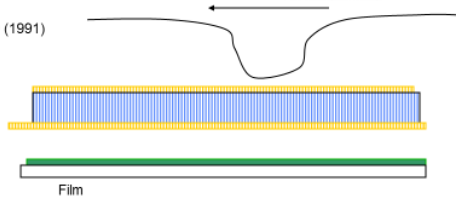
Gain Shutter transit speed ~c/2

Microstripline

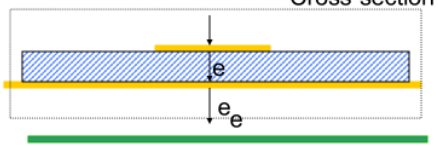
See history in review by
J.D. Kilkenny in *Lasers and Particle Beams* **9**, 49 (1991)

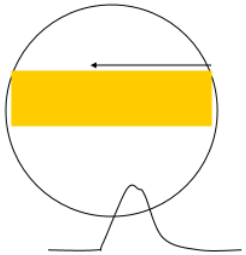
Flying shutter is electrical pulse-

propagate a high-voltage gate pulse across a microwave transmission line deposited on the front surface of a Microchannel Plate.
MCP/microstripline is: Photocathode
Pb glass blocks X-rays (mostly) w/o pulse
with pulse MCP Amplifier /
transit shutter ($v_{shutter}$ ~c/2)



Microstripline
Cross section

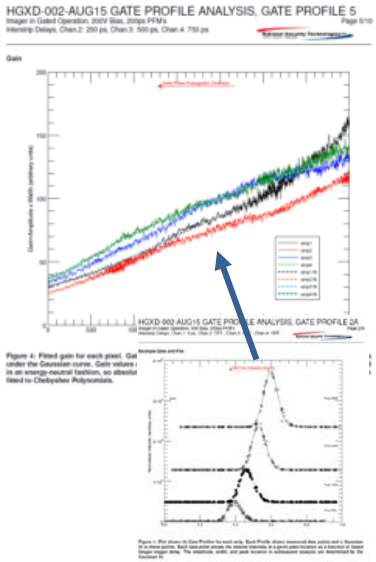




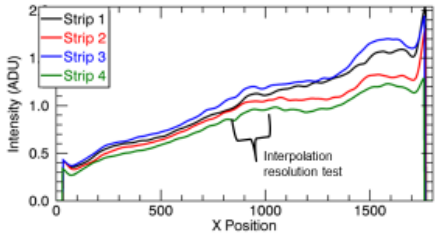
Z~ 12.5 Ohms for L/D 40 ~6mm

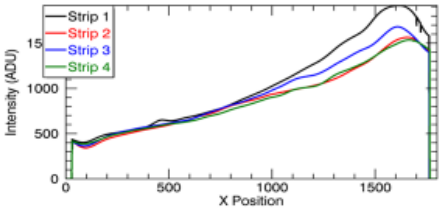
~1000V 10^5 Watts launched on microstrip – less than 5 ns

Synthetic UV and NIF X-ray FF

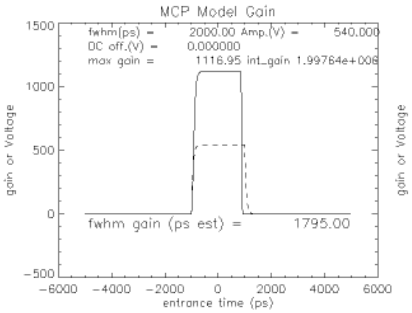


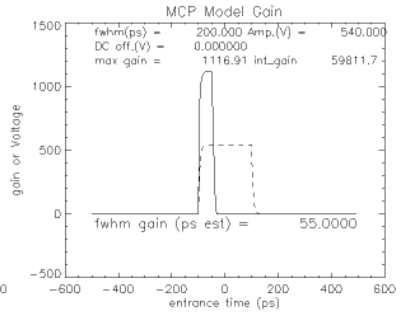
150V: 0/250/500/750 ps
(0/250/514/743ps from uv data)





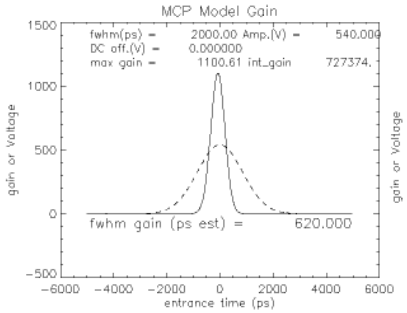
Square Pulses (with time constant)
Long time: gain power law
Short time: transit time

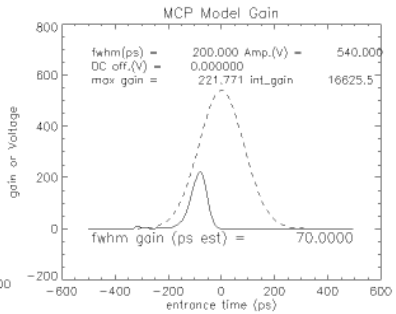




electron transit time

Gaussian Pulses
Long time: gain power law
Short time: transit time





gain narrowing electron transit time

Use simple simplified scaling to get framing camera signal levels into estimated linear range

Expected signal- aim for mid strip maximum of GXD 4000-5000 or 2500-3500 for HGXD

Also have per photon numbers later in presentation

$$signal_{shot2} = gain_{ratio} * camera_{ratio} * spectral_{ratio} * imaging_{ratio} * signal_{shot1}$$

Signal from shot

Compare x-ray paths
Same area units

Bracket with calibrations, models and literature
Angles and other details –pores, MCP "cooking"

CCD Counts per 9um pixel or Exposure units per 20um pixel
Mostly from flat field shots, scaled: distances, bias voltage
Errors: configuration details, source normalization,…
Usually compared center of strip2

Use approximation that 50V more back-bias voltage decreases gain by 3X
(nearer 2 at low back-bias voltage and nearer 4 at high voltage)

See Wiki to compare cameras

https://nifit.llnl.gov/wiki/display/vc/X-ray+Framing+Cameras+:+GXD+and+HGXD

NIF 5

Framing Camera with CCD Status Update

Available GXD Framing Cameras at NIF

	Camera	# strips	DIM	Add'l INFO	Gain Rel[1]	Pulse Vel (mm/ns)	Gate width (ps)@(bias V)	Some Actual Interstrip Timings (UV)
CCD	RGXD1F	4	00-00 & 90-315		31	150	104 (150V)	ISD0:0/-3/1/2 average ISD200:0/176/383/604 ISD300:0/293/590/911
CCD	GXD3F &RGXD3F	4	90-78		5	142	115 (50V) 90 (300V)	ISD200:0/187/391/611
CCD	RGXD4F-200	4	*0-0* & 90-78	200 ps electrical	11	137	100 (100V)	ISD200:0/197/376/595
CCD	RGXD4F -600 extended integration	4	*0-0* & 90-78	600 ps electrical	176 (16x of -200 config)	139	228 (100V)	

RGXD4 - Door Added to allow Pulse Forming modules to be changed in field in R configuration, on equatorial DIMs can be fielded on two position rotation mount – the WGXD –note need to select snout rotation

- GXD2T removed from service, current GXDs do not have Early Radiation Artifact Suppression Electrode Rig,

1 Relative gains are extrapolated to 100V and compared to HGXD1 strip2 with average CCD counts/ CCD pixel compared to PDS film exposure counts / scan pixels

J.P. Holder, L. R. Benedetti & the framing camera team

Early view for GXDs format?

So set 0/200/400/600ps
Get 0/187/391/611
With <3ps jitter
1-2 crosstalk

Slower plates
Have smaller
Open Area
Ratio
cvac=299.792mm/ns
GXD4F
Frequency
Content or
Error bar

Sample calculation

- IF 4000 counts in center of GXD1F using 200V …
- Same imaging to GXD3F

- $4000*S_{gxd3}/ S_{gxd1} = 4000*5/31 = 645$
- want to be 4000-6000 counts
- Change bias to 100 V 9 *645 ~ 5800

Also HGXDs

Current HGXDs

NIF 7

	Camera[3]	# Strips	DIM	Add'l INFO	Gain Rel[2]	Pulse Vel (mm/ns)	Gate width (ps)@(bias V)	Actual Interstrip Timing
FILM	HGXD1T	2	0-0& 90-78	ERASER[1] reduced phosphor[4] 1800V	0.8*	154	106 (50V) 95 (150V)	0/-2 0/194 0/247
	HGXD2F[c]	4	0-0 & 90-78	ERASER; phosphor at 1800V setting	*2*	132	~92(50V)/ ~82(200V)	0/250/514/743@ 200V
	HGXD3T[a]	2	*90-78*	ERASER Run w/ phosphor at 1800V setting	*~0.8*	135	*~105(50V) 94(150V)*	0/1 0/194 0/266
	HGXD6F[b]	4	90-78	ERASER; phosphor at 1800V setting	2	135	~80(50V)/ ~72(250V)	

a) HGXD3T pulser replaced (March2015), Head(MCP/Phosphor) and PFMs nominally the same. Similar sensitivity to previous build expected.

b) HGXD6F is four strip framing camera first used in April2015 using new taper transformer drive head design

c) HGXD2F was rebuilt Aug 2015 to be like HGXD6, new MCP, new timings and sensitivity

1 Early Radiation Artifact Suppression Electrode Rig, see slide 4

2 Relative gains/sensitivity are extrapolated to 100V and compared to HGXD1T strip2 with 2300V phosphor setting

3 All HGXDs are "R" or "vertical" orientation for film recovery

- *Strip 1 on HGXD1T 20-30% less sensitive than Strip2(check flat field for specific delays/bias)

4. Engineering decision, Aug2015, to reduce phosphor pulser charge voltage to 1800V *on all HGXDs* (~7kV to imager)

HGXD4 and HGXD5 for pulsers currently being rebuilt

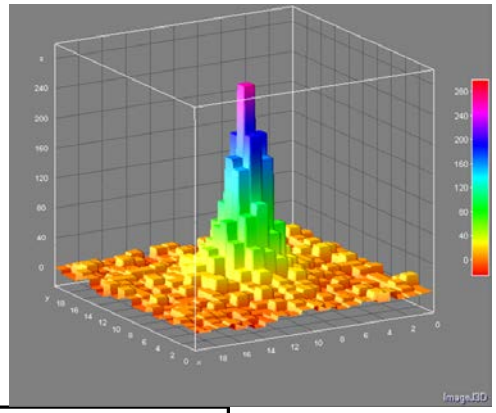
Starting from scratch:
X-ray response measurements of gated GXD1

LR Benedetti estimate from Supersnout2 data N130319:

Center **of strip 1 with 100V back-bias**

<7.5 keV > photons

Average response **400 ± 100 CCD ADU counts/ photon**



JPH estimate from **single hits** on N120608,
exponential gain distribution, Gate-width and droop estimate and DC x-ray data:

Center **of strip 1 with 100V back-bias**
<8.2 keV > photons
quantum detection efficiency of 4 ± 0.4% (DC MCP -750 may not be same)
Average of gain (exponential distribution) at Peak gain at strip center
(assuming 100ps FWHM and a droop of 3 across detector)
6655±674 CCD counts/(det photon)
Integrate.. "equivalent FWHM square gain"… 1.07*P
Average response **285 ± 60 ± model CCD ADU counts/ photon**

Framing Camera Operational Issues

- **GXDs : strip 1 must be first (no delay unit)**
  - **Bias voltage minimum = 60V (no alarms) –**
    - **do allow 50V setting but please annotate , hardware gets close**
  - **Bias voltages can be set in increments of 10 V –**
    - **prefer users use 60,100,150,200 , 250V etc to "lump" calibration and FF efforts**
    - **(other values will not be calibrated)**
  - **Maximum interstrip delay = 50 ns, in units of 25 ps**
    - **(pulser has lookup table for relays and traces/cables to best match to 25ps)**

- **HGXDs**
  - **Strip 1 is not required to be first**
    - **Some NIF software does not report strip1 delay**
  - **Bias voltage minimum = 50V (actually 0V seems to work)**
  - **Bias voltages can be set in increments of 50V**
  - **Maximum interstrip delay = 10.4 ns, in units of 25 ps (10400 ps)**
- **HGXD1 has higher gain on strip 2 due to cross talk (gain variation reduced after 1/2015 reclamp)**
- **HGXD2F rebuilt head after October2015 has relatively slow strips fed by tapered transformers**
  - **Do not operate with interstrip timing < 250 ps**
  - Observed delays with 0/250/500/750 settings 0/250/514/743@ 200V
  - Strip length on film ~35mm/(0.132 mm /ps) = ~265 ps

- **HGXD6F has relatively slow strips fed by tapered transformers**
  - **showed strong cross talk effects in calibration at 0/200/400/600 set**
    - **observed (1/3.8/3.2/2.4 x) with measured delays 0/189/402/590**
  - **Do not operate with interstrip timing < 250 ps**

Cross talk: delay to strip gain ratios (UV)

HGXD1T NSTECH AUG14

delay2	measured	bias	strip1 center	strip2 center
0	-2	50	1.065	1
200	194	50	1	1.366
250	245	50	1	1.263
250	250	150	1	1.167

Flat Field/ Droop Corrections – SAVI automated and standalone tools

GXD1F droop corrections available

GXD1_100V_0ps_NSTECgate_droop_corr.h5
GXD1_100V_0ps_NSTECgate_droop_corrRenamed.h5

Shot TC0000-0000_RGXD1_150V_0ps_Fa_Diag_AuSphere_Xray_S29_ABB

TC000-000_GXD1_150V_200ps_N110730_droop_corr.h5

TC090-315_GXD1_150V_200ps_N110115_droop_corr.h5

TC000-000_GXD1_200V_250ps_N160920_droop_corr.h5

TC000-000_GXD1_250V_200ps_N111010_droop_corr.h5

TC000-000_GXD1_250V_200ps_N121221_droop_corr.h5

TC000-000_GXD1_250V_300ps_N120819_droop_corr.h5

GXD3F droop corrections available

NIF 19

GXD3_N130319_60V_350ps_droop_corr.h5

GXD3_N150616_100V_200ps_droop_corr.h5
TC090-078_N120908_GXD3_100V_350ps_droop_corr.h5

TC090-315_GXD3_150V_300ps_N111010_droop_corr.h5

GXD3_N130401_200V_200ps_droop_corr_55.h5
GXD3_N130401_200V_200ps_droop_corr.h5

GXD4F-200 droop corrections available

NIF 20

N140515_GXD4_100V_200ps_droop_corr.h5	-	TOO BRIGHT
N140626_GXD4_250V_0-200-600-950_reemit_droop_corr.h5		Zr BL dev
N140626_GXD4_250V_200ps_droop_corr.h5		Zr BL dev
N140627_GXD4_250V_250ps_droop_corr.h5		Zr BL dev
GXD4_UNITY_droop_corr.h5		Fake

2 strip HGXDs

HGXD1T

N150122_HGXD1T_150V_250ps_droop_corr.h5

N150213_HGXD1T_150V_200ps_droop_corr.h5

HGXD3T

N140121_HGXD_100V_250ps_droop_corr.h5

N150122_HGXD3T_150V_250ps_droop_corr.h5

N141014_HGXD3T_200V_250ps_droop_corr.h5

HGXD2F

HGXD2F_4X_droop_corr.h5

N170315_HGXD2F_100V_0ps_droop_corr.h5
(CL_HGXD_13330002_DROOP_100100100100V_0000000000000000ps_000ID_20170405104000.h5)

N170330_HGXD2F_100V_0_400_150_425ps_droop_corr.h5
(CL_HGXD_13330002_DROOP_100100100100V_0000040001500425ps_000ID_20170405104000.h5)

N170110_HGXD2F_150V_0ps_droop_corr.h5

N160510_HGXD2F_150V_250ps_droop_corr.h5

N160829_HGXD2F_150V_250ps_droop_corr.h5

HGXD6F

NIF 23

N170315_HGXD6F_150V_0ps.h5
N150428_HGXD_150V_250ps_droop_corr.h5

N160829_HGXD6F_150V_2DConA_droop_corr.h5 delays=(450,0,225,700)

CL_HGXD_13330006_DROOP_150150150150V_0000000000000000ps_000ID_20160405104000.h5

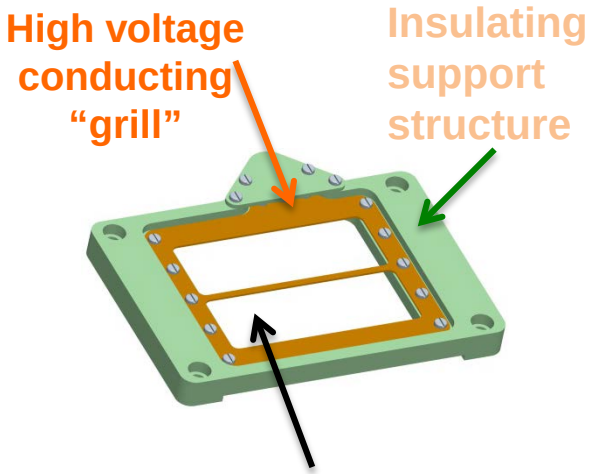
N170330_HGXD6F_150V_0_400_150_425ps_droop_corr.h5

ERASER mitigates the effect of early x-rays

ERASER **E**arly **R**adiation **A**rtifact **S**uppression **E**lectrode **R**ig

ERASER suppresses artifacts by attracting electrons before the camera is triggered.
High-voltage surface installed ~1cm above framing camera active area (microstrips)
Changes E-field to attract electrons that arrive before amplifying voltage

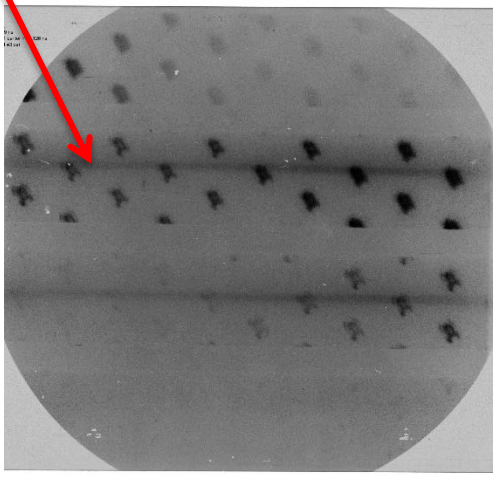
ERASER Schematic



Open above MCP to avoid interference with x-ray data

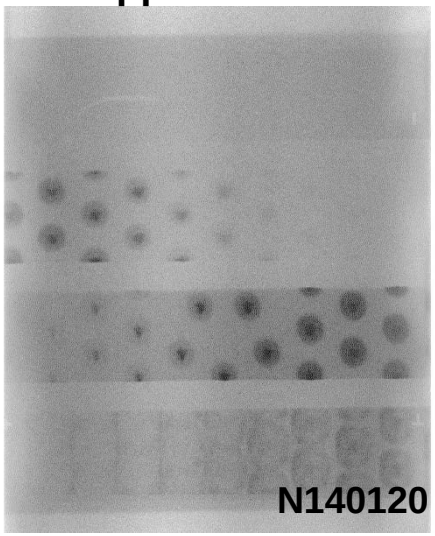
HGXI1 without ERASER

Artifacts due to x-rays that arrive before camera is triggered



HGXD2F with ERASER

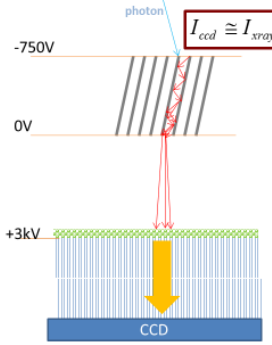
No apparent artifacts



Need newer cartoon –may have issues with circuity on perimeter that bias ERASER

DC Image built up of detected photons

DC MCP (simplified model)



$$I_{ccd} \cong I_{xray}\left(\eta_{xray} G_{mcp}\right)\left(k_{ph}(V_{ph} - V_{dead})\right)\left(T_{ph\_to\_ccd}\,\eta_{ccd} K_{adu}\right)$$

MCP — Phosphor — CCD

$$\langle G_{mcp} \rangle \cong \left(\frac{|V_{mcp}|}{V_1}\right)^{\gamma} \qquad \gamma \sim 10$$

η=X-ray to electron conversion efficiency

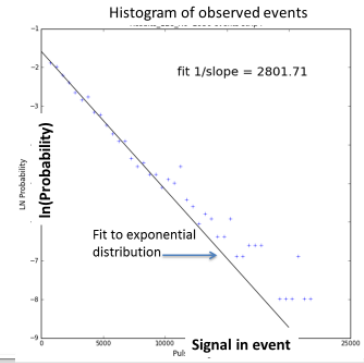
G_{mcp} =Electron amplification Gain
G_{det} = gain mcp + phosphor +ccd
we measure this

X-ray Photon-> "star event" of CCD counts

Expect exponential-like distribution of pulse heights (in CCD counts) of single x-ray detection events

Lawrence Livermore National Laboratory

We do observe that the GXDs display an exponential distribution in amplified single events



All events observed in strip 4; 2936 events

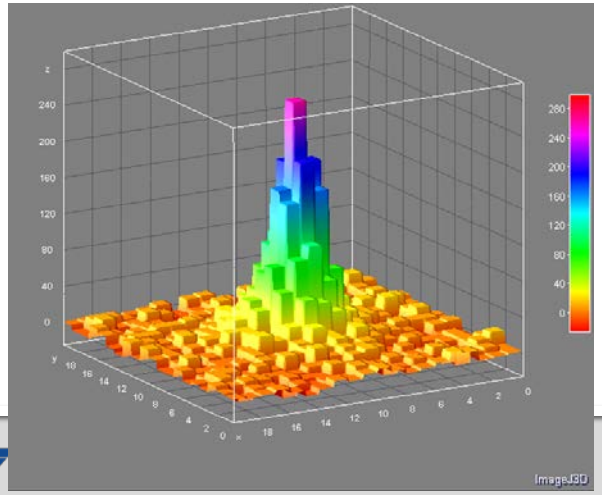
Fitted expectation, mean, standard deviation, median/ln2 are all ~ 3000 counts -- consistent with exponential distribution

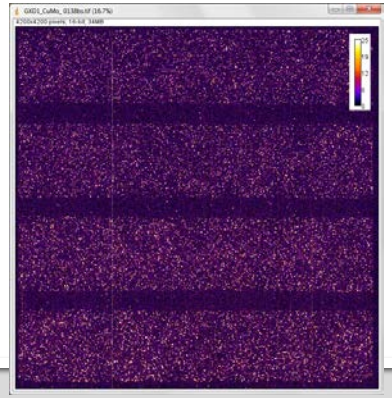
Mean	3445
Standard Dev	3167
Median/ln(2)	3460

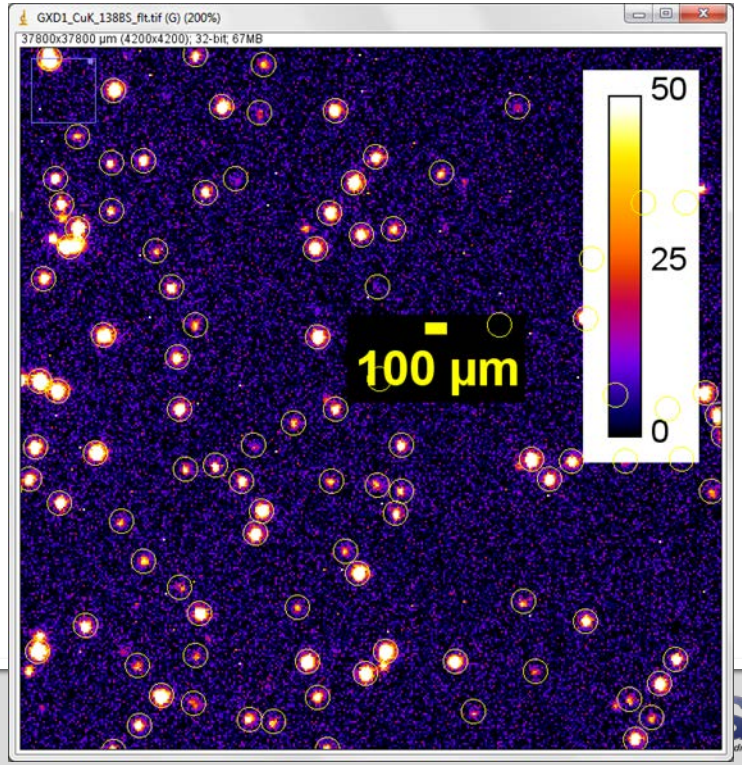
X-rays ~ 8.243keV
MCP set -750V DC
Phosphor 3kV DC

Lawrence Livermore National Laboratory

Conversion and gain both can depend on x-ray energy and angle







X-ray Detection Mostly in MCP Pb glass

Per Energy

REVIEW OF SCIENTIFIC INSTRUMENTS 77, 10E323 (2006)

Energy dependent sensitivity of microchannel plate detectors

G. A. Rochau, J. E. Bailey, G. A. Chandler, T. J. Nash, and D. S. Nielsen
Sandia National Laboratories, Albuquerque, New Mexico 87185
G. S. Dunham, O. F. Garcia, and N. R. Joseph
Ktech Corporation, Albuquerque, New Mexico 87123
J. W. Keister
SFA Inc., Brookhaven National Laboratory, Upton, New York 11973
M. J. Madlener, D. V. Morgan, K. J. Moy, and M. Wu
Bechtel Nevada, Las Vegas, Nevada 89193

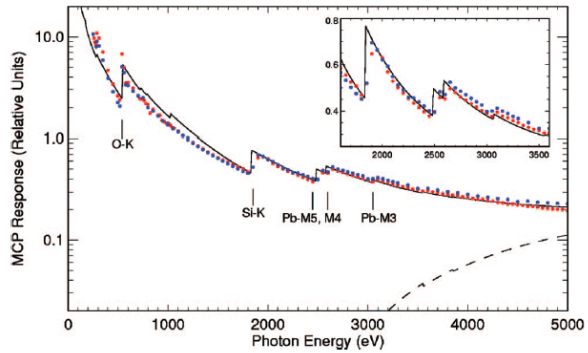
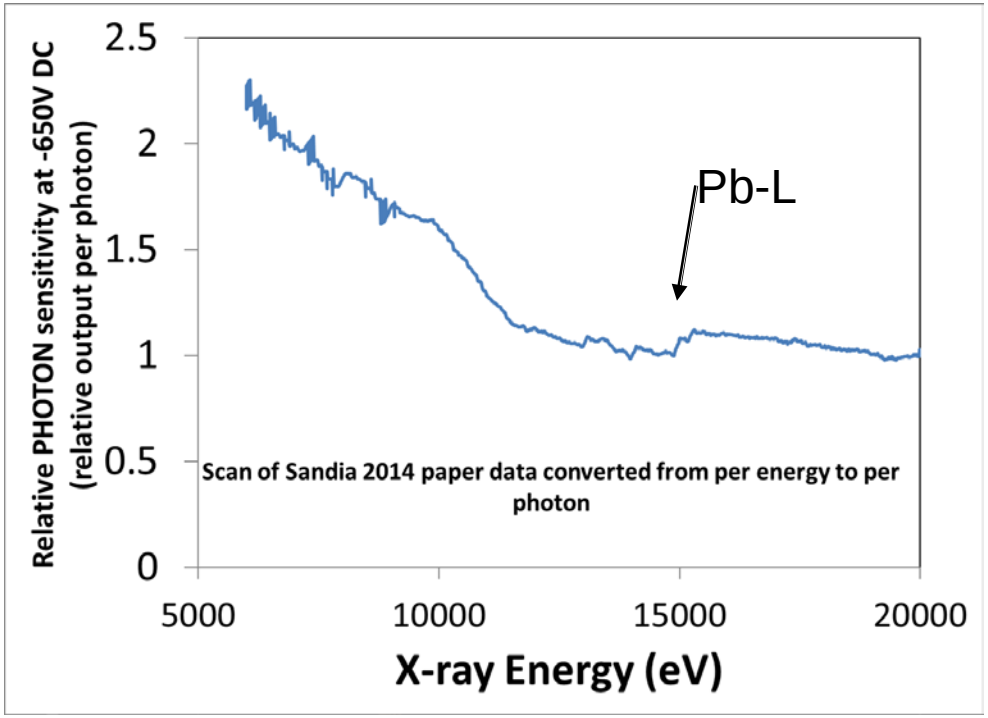


FIG. 3. (Color) Relative MCP response as measured for two separate detector systems (red and blue dots) and as calculated from the model in Eq. (5) (solid line) using the material fractions determined from XPS analysis of the MCP composition. The dashed line gives the calculated contribution to the MCP response from electrons produced everywhere, except the front surface of the first channel wall.

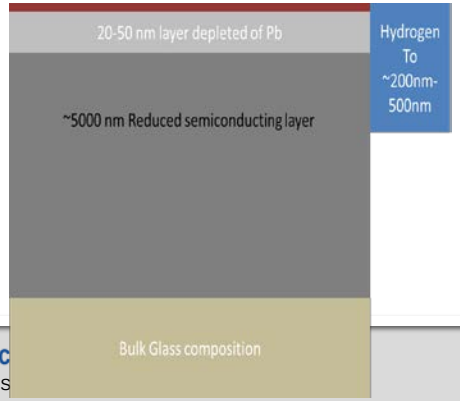
Characterizations of MCP performance in the hard x-ray range (6–25 keV)a)

Ming Wu, Ken Moy, Craig Kruschwitz, and Greg Rochau

Citation: Review of Scientific Instruments 85, 11D607 (2014); doi: 10.1063/1.4890293



10nm alkali enhanced surface layer

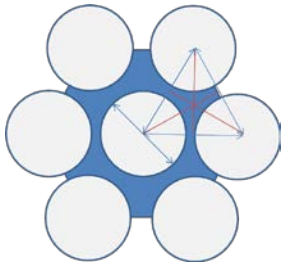


Original lead glass ~50% Pb by weight

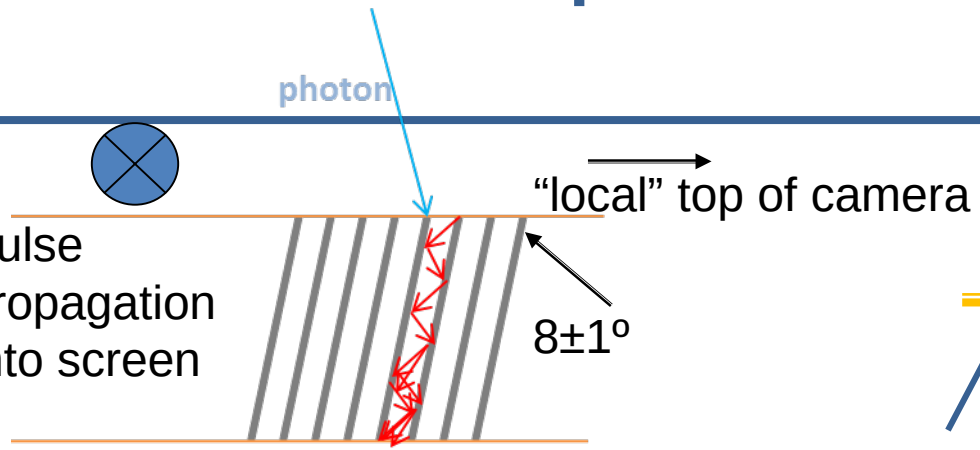
MCP pulled cut polished etched H-fired and treated

Our conductive coatings
100nm Au
500nm Cu
Cr or Nb adhesion layer

Pores – surfaces walls and speed



Nominal MCP



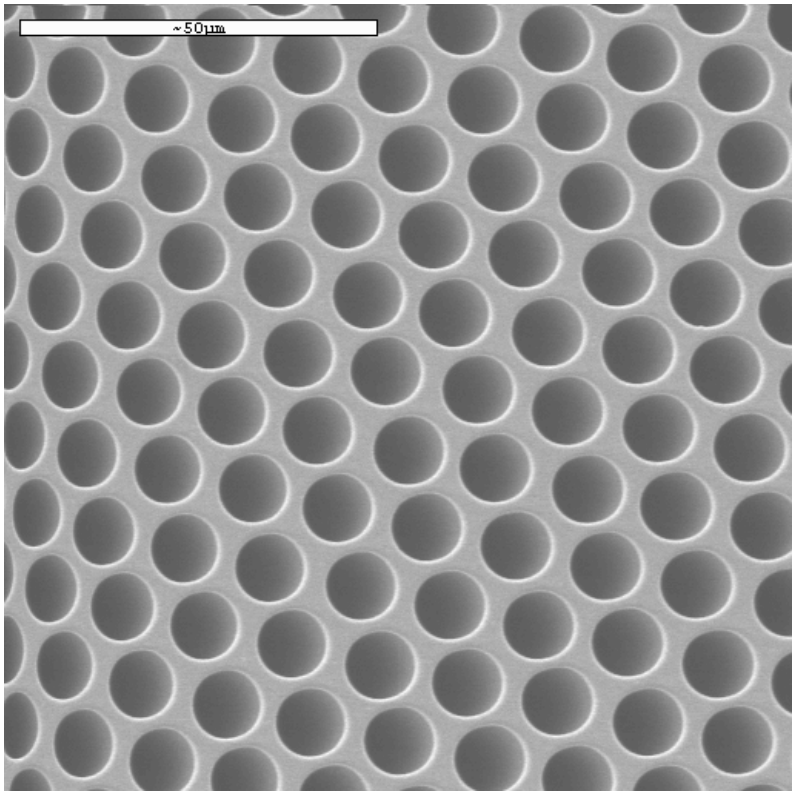
GXD early batchs MCP (assume spacing)

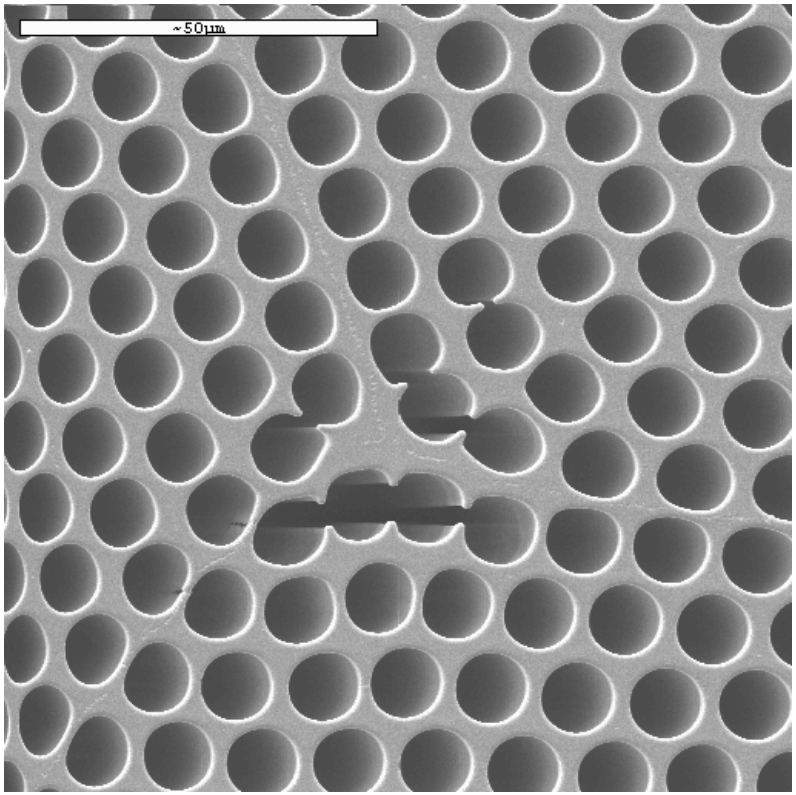
$$D_{pore} = 10\mu m$$
$$d_{c-c} = 12\mu m$$
$$A_{pore} = 78.54(\mu m)^2$$
$$A_{hex} = 374.1(\mu m)^2$$
$$A_{per\_pore} = 124.7(\mu m)^2$$
$$OAR = 0.63$$
$$t_{wall\_\min} = 2\mu m$$
$$t_{wall\_1D\_ave} = 4.13\mu m$$
$$L/D \cong 43$$

$$D_{pore} = 11\mu m$$
$$d_{c-c} = 12\mu m$$
$$A_{pore} = 95\cdot(\mu m)^2$$
$$A_{hex} = 374.1\cdot(\mu m)^2$$
$$A_{per\_pore} = 124.7\cdot(\mu m)^2$$
$$OAR = 0.76$$
$$t_{wall\_\min} = 1\mu m$$
$$t_{wall\_1D\_ave} = 2.68\mu m$$
$$L/D \cong 39$$

Note that at multi-bundle boundaries this went to 0 um or actually less

Early GXD MCP





Take away

- Use similar shots to scale
- Wiki table of relative sensitivities
- Try to use configuration with flat field data
- X-rays make electrons when you are not trying to look at them
- More gain on “photon-y” image just makes larger “photons”
- Several

Backup etc

X-ray Framing camera overview

- **X-ray framing cameras use microchannel plates (MCPs) as photocathode and amplifier**
  - X-rays make electrons
  - Electrons that reach a microchannel (or pore) are accelerated by an applied voltage that directs the electron along the channel where it is likely to hit the wall of the pore, creating more (low energy) electrons. The above process repeats, creating an avalanche of electrons, that exits the channel.
  - Avalanche Gain proportional V^{gamma} where gamma ~10 for <20> collisions
  - Unity gain ~ 300 to 400 V for our plates (~10um channel diameter, ~13um hex pitch,~430um thick)
- **A short electrical pulse is propagated along the conductive coatings on the MCP (microstriplines), applying voltage to the pores**
  - Speed of propagation depends on MCP material and fraction that is vacuum
  - For GXD1 with 77% Open Area Ratio this is ~ c/2
  - For standard 4 strip camera 7.5 mm wide line ~10 ohm transmission line, relatively thin coatings since need to leave open channels so have voltage losses, power law 5% Voltage change is ~ 50% change in gain
  - Fixed amplitude pulse so apply +DC bias voltage to lower effective voltage
  - For 200ps FWHM electrical pulses get gain pulse width ~100 ps – transit time limits
- **Electrons exiting the MCP are accelerated to a phosphor**
- **CCD (GXD, HGXD in test) or Film used to record light image transferred by fiber optic block(s) from phosphor**

Issues

Each channel plate batch is different– Glass – note speed related to OAR

For our plates that means the variation in wall thickness is
a factor of 2..

~<4keV x-rays interacting with thin coatings and “cooked” lead glass layers
~>8keV x-rays interacting with entire walls – layers and substrate glass

Detection, Yield and Gain are coupled and dynamic ….
Extreme example is AXIS detector –
low gain front plate to maximize volume detection

Each strip is biased and driven differently – real parts, de-embedding
difficult 5-10 ohm high voltage high speed measurements of nonlinear system
At best a 1% -> 10% gains in “zero thickness” approximation

note modern scope specifications for “eye” diagrams
Have to optimize everything to get ~128:1 single shot

Phosphors….Optical Couplings…Film/CCD -conversions

Gating

HGXD-002-AUG15 GATE PROFILE ANALYSIS, GATE PROFILE 2A

Imager in Gated Operation, 50V Bias, 200ps PFM's

Interstrip Delays, Chan.1: 0 ps, Chan.2: OFF , Chan.3: OFF , Chan.4: OFF

Page 2/9

National Security Technologies

Example Data and Fits

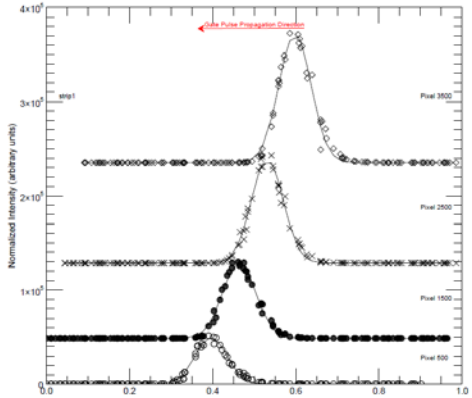
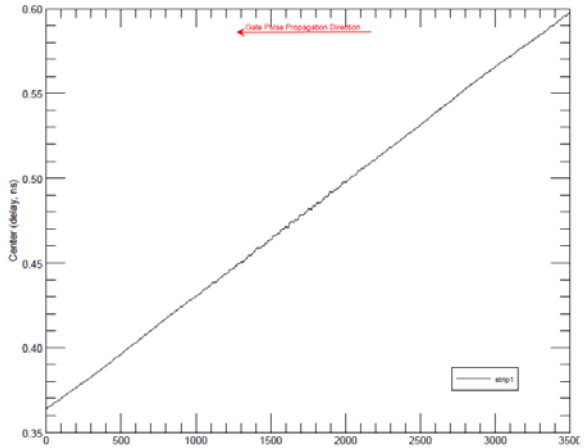


Figure 1: Plot shows (4) Gate Profiles for each strip. Each Profile shows measured data points and a Gaussian fit to these points. Each data point shows the relative intensity at a given pixel location as a function of Gated Imager trigger delay. The amplitude, width, and peak location in subsequent analysis are determined by the Gaussian fit.

Gate Pulse Velocity and Strip Separation



Gate Width

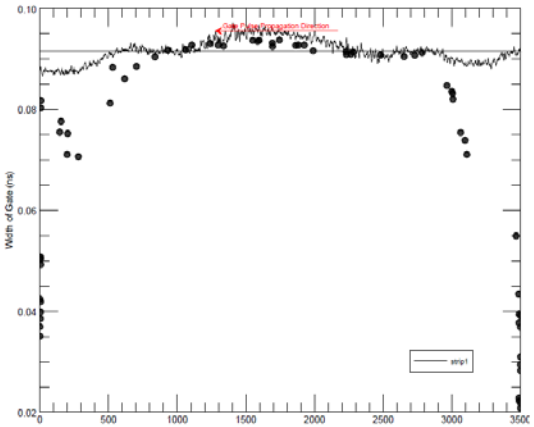


Figure 8: Fitted gate width at each pixel. These values are averaged to produce the best-estimate gate width (horizontal lines). Individual circle markers indicate FWHM values for individual droop-corrected images that contained a pulse sufficiently well-centered to determine its width. These values determined from single images should be consistent with the ensemble fitted width.

Pulse Amplitude

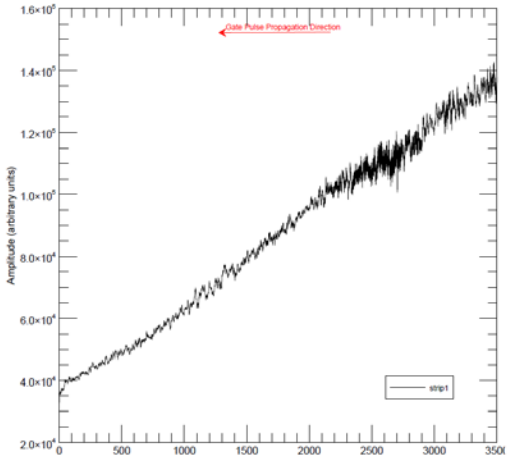


Figure 3: Fitted gate pulse as a function of location along the strip line (pixel number).

Gain