X-Ray Framing Camera Sensitivity Notes

Presented to NIF user Forum

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Framing Camera RS & X-ray Diagnostic Campaign co-lead
2 strip HGXD with ERASER
Gain Shutter transit speed $\sim c/2$

**Microstripline**

Propagate a high-voltage gate pulse across a microchannel plate deposited on the front surface of a Microchannel Plate.

Pb glass blocks X-rays (mostly) w/o pulse with pulse MCP Amplifier / transit shutter $v_{\text{shutter}} \sim c/2$

$Z \sim 12.5$ Ohms for L/D 40 ~6mm

$\sim 1000V \ 10^5$ Watts launched on microstrip – less than 5 ns

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

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

![Diagram of Microstripline Cross section](image)

**Synthetic UV and NIF X-ray FF**

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

- Strip 1
- Strip 2
- Strip 3
- Strip 4

![Graphs showing intensity over X Position](image)
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

\[ \text{signal}_{\text{shot2}} = \text{gain}_{\text{ratio}} \times \text{camera}_{\text{ratio}} \times \text{spectral}_{\text{ratio}} \times \text{imaging}_{\text{ratio}} \times \text{signal}_{\text{shot1}} \]

Also have per photon numbers later in presentation

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

<table>
<thead>
<tr>
<th>Camera</th>
<th># strips</th>
<th>DIM</th>
<th>Add'l INFO</th>
<th>Gain Rel¹</th>
<th>Pulse Vel (mm/ns)</th>
<th>Gate width (ps)@bias V</th>
<th>Some Actual Interstrip Timings (UV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGXD1F</td>
<td>4</td>
<td>00-00 &amp; 90-315</td>
<td></td>
<td>31</td>
<td>150</td>
<td>104 (150V)</td>
<td>ISD0:0/-3/1/2 average, ISD200:0/176/383/604, ISD300:0/293/590/911</td>
</tr>
<tr>
<td>GXD3F &amp; RGXD3F</td>
<td>4</td>
<td>90-78</td>
<td></td>
<td>5</td>
<td>142</td>
<td>115 (50V)</td>
<td>ISD200:0/187/391/611</td>
</tr>
<tr>
<td>RGXD4F-200</td>
<td>4</td>
<td>0-0 &amp; 90-78</td>
<td>200 ps electrical</td>
<td>11</td>
<td>137</td>
<td>100 (100V)</td>
<td>ISD200:0/197/376/595</td>
</tr>
<tr>
<td>RGXD4F-600</td>
<td>4</td>
<td>0-0 &amp; 90-78</td>
<td>600 ps electrical</td>
<td>176 (16x of -200 config)</td>
<td>139</td>
<td>228 (100V)</td>
<td></td>
</tr>
</tbody>
</table>

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

\[ 4000 \times \frac{S_{\text{gxd3}}}{S_{\text{gxd1}}} = 4000 \times \frac{5}{31} = 645 \]
- want to be 4000-6000 counts
- Change bias to 100 V \( 9 \times 645 \sim 5800 \)
Also HGXDs

<table>
<thead>
<tr>
<th>Camera¹</th>
<th># Strips</th>
<th>DIM</th>
<th>Add'l INFO</th>
<th>Gain Rel²</th>
<th>Pulse Vel (mm/ns)</th>
<th>Gate width (ps)@bias V</th>
<th>Actual Interstrip Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGXD1T</td>
<td>2</td>
<td>0-0 &amp; 90-78</td>
<td>ERASER; reduced phosphor at 1800V</td>
<td>0.8*</td>
<td>154</td>
<td>106 (50V) 95 (150V)</td>
<td>0/2, 0/194, 0/247</td>
</tr>
<tr>
<td>HGXD2F</td>
<td>4</td>
<td>0-0 &amp; 90-78</td>
<td>ERASER; phosphor at 1800V setting</td>
<td>2</td>
<td>132</td>
<td>~92(50V)/~82(200V)</td>
<td>0/250/514/743@200V</td>
</tr>
<tr>
<td>HGXD3T</td>
<td>2</td>
<td>90-78</td>
<td>ERASER; phosphor at 1800V setting</td>
<td>~0.8</td>
<td>135</td>
<td>~105(50V)/94(150V)</td>
<td>0/1, 0/194, 0/266</td>
</tr>
<tr>
<td>HGXD6F</td>
<td>4</td>
<td>90-78</td>
<td>ERASER; phosphor at 1800V setting</td>
<td>2</td>
<td>135</td>
<td>~80(50V)/~72(250V)</td>
<td>0/264/514/743@200V</td>
</tr>
</tbody>
</table>

a) HGXD3T pulser replaced (March 2015), Head(MCP/Phosphor) and PFM nominally the same. Similar sensitivity to previous build expected.
b) HGXD6F is four strip framing camera first used in April 2015 using new taper transformer drive head design
c) HGXD2F was rebuilt Aug 2015 to be like HGXDs, 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

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Lawrence Livermore National Laboratory
LLNL-PRES-739764
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 $400 \pm 100$ 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 $4 \pm 0.4\%$ (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)

$6655\pm674$ CCD counts/(det photon)

Integrate.. “equivalent FWHM square gain”… 1.07*P

Average response $285 \pm 60 \pm \text{model}$ 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)

<table>
<thead>
<tr>
<th>delay2</th>
<th>measured</th>
<th>bias</th>
<th>strip1 center</th>
<th>strip2 center</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2</td>
<td>50</td>
<td>1.065</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>194</td>
<td>50</td>
<td>1</td>
<td>1.366</td>
</tr>
<tr>
<td>250</td>
<td>245</td>
<td>50</td>
<td>1</td>
<td>1.263</td>
</tr>
<tr>
<td>250</td>
<td>250</td>
<td>150</td>
<td>1</td>
<td>1.167</td>
</tr>
</tbody>
</table>
Flat Field/ Droop Corrections – SAVI automated and standalone tools

GXD1F droop corrections available

GXD1_F_100V_0ps_NSTECgate_droop_corr.h5
GXD1_F_100V_0ps_NSTECgate_droop_corrRenamed.h5

Shot TCO000-0000_RGXD1F_150V_0ps_Fe_Drop_AutoSphere_Keys_829_82B
TC060-006_GXD1_150V_200ps_N11010_150V_droop_corr.h5
TC060-315_GXD1_150V_200ps_N11010_150V_droop_corr.h5
TC080-008_GXD1_200V_250ps_N18090_200V_droop_corr.h5
TC080-008_GXD1_200V_250ps_N18090_200V_droop_corr.h5
TC080-008_GXD1_200V_250ps_N111010_200V_droop_corr.h5
TC080-008_GXD1_200V_250ps_N111010_200V_droop_corr.h5

GXD3 droop corrections available

GXD3_N130319_60V_350ps_droop_corr.h5
GXD3_N150616_100V_200ps_droop_corr.h5
TC090-070_N142008_GXD3_100V_350ps_droop_corr.h5
TC090-315_GXD3_150V_350ps_N11010_150V_droop_corr.h5
GXD3_N140404_200V_350ps_droop_corr_55.h5
GXD3_N140404_200V_350ps_droop_corr_55.h5

GXD4F-200 droop corrections available

N140515_GXD4_100V_200ps_droop_corr.h5
- TOO BRIGHT
N140626_GXD4_250V_200ps_droop_corr.h5
N140626_GXD4_250V_200ps_droop_corr.h5
N140627_GXD4_250V_250ps_droop_corr.h5
N140627_GXD4_250V_250ps_droop_corr.h5
GXD4_UNITY_droop_corr.h5
Fake

2 strip HGXDss

HGXD1T
N150122_HGXDT_150V_250ps_droop_corr.h5
N150213_HGXDT_150V_200ps_droop_corr.h5

HGXD3T
N140121_HGXD3_T_150V_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_150V_0ps_droop_corr.h5
(CL_HGXD_133300032_DROOP_150V_150V_0ps_0ps_0ps_0ps_0ps_20170409104000.h5)
N170330_HGXD2F_150V_0ps_400_150_425ps_droop_corr.h5
(CL_HGXD_133300032_DROOP_150V_150V_0ps_0ps_0ps_0ps_0ps_20170409104000.h5)
N170110_HGXD2F_150V_0ps_droop_corr.h5
N160510_HGXD2F_150V_250ps_droop_corr.h5
N160829_HGXD2F_150V_250ps_droop_corr.h5

HGXD6F

N170315_HGD0F6F_150V_0ps.h5
N160428_HGXDF6_150V_250ps_droop_corr.h5

N160829_HGXD6F_150V_2DCmoA_droop_corr.h5
delays=(450,0.225,700)
(CL_HGXD_13330003_DROOP_150V_150V_0ps_0ps_0ps_0ps_0ps_0ps_20170409104000.h5)
N170330_HGXD6F_150V_0ps_400_150_425ps_droop_corr.h5
ERASER mitigates the effect of early x-rays

**ERASER** Early Radiation Artifact Suppression Electrode Rig

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

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ERASER Schematic

High voltage conducting “grill”

Insulating support structure

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

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Need newer cartoon –may have issues with circuity on perimeter that bias ERASER
DC Image built up of detected photons

DC MCP (simplified model)

\[ I_{\text{out}} \approx I_{\text{in}} \eta \cdot G_{\text{exp}} \left( V_{\text{ph}} - V_{\text{dead}} \right) I_{\text{ph to cc}} \eta \cdot G_{\text{ph}} K_{\text{ph}} \]

\[ \langle G_{\text{exp}} \rangle \approx \left( \frac{V_{\text{exp}}}{V_{\text{i}}} \right)^n \quad n \approx 10 \]

\( \eta = \) X-ray to electron conversion efficiency

\( G_{\text{exp}} = \) Electron amplification gain

\( G_{\text{ph}} = \) gain mcp + phosphor + ccd

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

Histogram of observed events

All events observed in strip A, 29086 events

Fitted expectation, mean, standard deviation, median/IQR are all \( \sim 3000 \) counts -- consistent with exponential distribution

Mean 3445
Standard Dev 3167
Median/IQR 3460

X-rays \( \sim 8.24 \text{keV} \)
MCP set - 750V DC
Phosphor 3kV DC

Conversion and gain both can depend on x-ray energy and angle
X-ray Detection Mostly in MCP Pb glass

**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 87123

*G. S. Durham, G. F. Graese, and N. R. Joseph*
Rockwell Corporation, Albuquerque, New Mexico 87123

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

*Ming Wu, Ken Moy, Craig Krachtelis, and Greg Rochau*

*Sandia National Laboratories, Albuquerque, New Mexico 87123*

**Original lead glass ~50% Pb by weight**

**MCP pulled cut polished etched H-fired and treated**

**Per Energy**

- **10nm alkali enhanced surface layer**
- **20-50 nm layer depleted of Pb**
- **~5000 nm Reduced semiconducting layer**
- **Bulk Glass composition**

**Our conductive coatings**

- 100nm Au
- 500nm Cu
- Cr or Nb adhesion layer

**Relative PHOTON sensitivity at ~650V DC**

(relative output per photon)

**Scan of Sandia 2014 paper data converted from per energy to per photon**

**X-ray Energy (eV)**

**Pb-L**
Pores – surfaces walls and speed

Nominal MCP

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

GXD early batches MCP (assume spacing)

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

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

- Photon pulse propagation into screen
- “local” top of camera
- Coatings
- $8 \pm 1^\circ$
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 $\gamma \sim 10$ for <20> collisions
  - Unity gain $\sim 300$ 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 $\sim c/2$
  - 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 $\sim 50\%$ change in gain
  - Fixed amplitude pulse so apply +DC bias voltage to lower effective voltage
  - For 200ps FWHM electrical pulses get gain pulse width $\sim 100$ 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

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

Figure 2: Pulse velocity and delay separation.

Figure 3: Fitted gate width at each pixel. These values are averaged to produce the best estimate gate width (horizontal line). Individual circles indicate FWHM values for individual data set resolved to determine its width. These values determined from single images should be consistent with the ensemble fitted width.

Figure 4: Pulses amplitude of location along the strip line (pixel number).