Title: Burst-mode 4 MHz CMOS-hybrid imaging system for multi-frame proton radiography

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Burst-mode 4 MHz CMOS-hybrid imaging system for multi-frame proton radiography

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Proton Transmission Radiography

- **Probing particles**: high-energy protons $E = 800$ MeV to 70 GeV
  - highly penetrating, long mean free path ($\lambda_0 = 194$ g/cm$^2$, 17 cm in Pb)
- **Proton flux attenuation**: nuclear collisions dominant at high energies, and multiple Coulomb scattering dominates at 800 MeV.
- Protons being charged particles can be focused in magnetic fields.
- **Magnetic lenses** form 1:1 Image of the Object on scintillator plate, or
- **Magnifier** magnets provide $\times 3$ and $\times 7$ magnification
- **Multiple beam pulses** serve as strobe pulses: 2-to-1000 bursts; each ~ typ. 50 ns wide; (can be adjusted 0.3 ns - 100 ns → motion blur); multiple views of a fast-evolving object (a movie); or tomography of static object
- Needed **camera system** with large multi-frame capability (burst mode), flexible precise triggering (independently vary inter-frame time and shutter width), high-resolution ~1-2 Mpx, high QE, large pixels, radiation resistance

Proton radiography (pRAD) beam transport schematic layout

pRAD experimental set-up at LANSCE
**x7 Magnifier**

Made up of four 1"-DIA bore permanent magnet quads

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**Seven Gated-CCD System**

- **Tiled LSO Scintillator**: 2mm thick (12cm x 12cm)
- **25k ph/MeV, 22.5k/p**: Turning Mirror (6µm thick pellicle)
- **Nikon 105mm/ F#2.0**
- **10kV Gated Planar Diode**: Cooled CCD (1Mpx or 2.5Mpx)
- **F.O. bundle**: 0.3 ph
- **DQE = 1/(1+1/n)**
  - \( = 1/(1+1/0.6) \)
  - \( = 0.4 \)
- **Full Well Saturation**: @ 3 x 10^10 p / burst or 10^7 p / mm^2
- **Resolution**: ≥ 2.5lp/mm (≤ 200µm)**
Camera arrangement at Imaging Station #1

Development of Hybrid-CMOS camera

- Early on pRAD used 11 OE-gated single-frame CCD cameras, and two low-resolution 9-frame Framing cameras (all suffered from low DQE, limited number of frames, min. shutter width ~320ns, FPN noise due to FOB)
- in 2004 designed and fabricated CMOS-hybrid 720x720 px, high-QE, three-frame imager
- Hybrid CMOS ⇒ high QE and optical fill factor, well established fast CMOS and bump bonding technology, radiation resistant
Imager as Two-Component Hybrid Focal Plane Array (FPA)

- Independent optimization of detector and readout IC
- ≥100% optical fill factor
- Arbitrarily large well depth

(1) Photo-Sensor Pixel Array (photon-charge conversion)

(2) CMOS Readout IC (ROIC): charge-to-voltage conversion, signal storage & processing, logic and A/D conversion; SoC: photons-to-bits

Pixel Design Provides 3-Frame Storage and Correlated Double Sampling (CDS)

Saturation charge determined by node capacitance: \( C_0 \)
Voltage droop on C2, C3 by FET leakage (sub-threshold) and quality of oxide
ROIC Pixel layout, Metal Layer-4

Charge storage capacitors (Metal-Insulator-Metal)
- size dictated by S/N and rate of charge leakage.
- 26μm pixel footprint allows 3-frame storage, but 22mm CMOS reticle limits the ROIC size and array resolution to 720 x 720 px to bump bonding pad

ROIC: Rockwell Scientific

Wafer to Hybrid FPA Chip

200mm - dia. wafer with 48 CMOS ROIC dies. Foundry delivered 12 wafers

21.4mmx22mm FPA is 2-side buttable - makes possible 1440x1440 px imager in a tiled assembly
System-on-Chip (SoC) Architecture Simplifies Camera Integration

- FPA chip needs only external power, master clock and trigger signals.
- The imager requires dual (3.3V and 2.5V) power supplies, "high voltage" detector bias (15V)
- The chip sends out 12 bit digital video data.
- Readout timing and biasing are generated on-chip and can be programmed through a serial interface.

Imager block diagram

Rockwell/ Teledyne pRAD Cameras

CMOS ROIC fabrication worked on 1st iteration (cost $1.16M)

Jan 2005, prototype—in Alu housing
Sizable volume taken up by TEC cooler and fan

Camera in stainless-steel Dewar
Silicon PD Array Has Advantages Over Monolithic CMOS or CCD’s

- 100% Fill factor (back-side illuminated)
- >95% Peak QE (AR coating)
- Good spatial and fast temporal response (fully depleted)
- Low inter-frame cross-talk / good extinction ratio (storage node isolation)
- Broad band spectrum response (depletion depth ~100μm)

Hybrid Burst Mode Imager

- Number of frames: 3
- Min. shutter time: 150 ns (40ns)
- Inter-frame time: 250 ns
- Array Size: 720×720
- Dynamic Range: 11-bit (12-bit ADC)
- Read Noise: 98 e−
- Well depth: >200ke−
- QE: 84% (at 415nm)
- Pixel size: 26 μm
- Chip size: 21.4mm×21.9mm
- CMOS technology: 250 nm
Beam and Camera Trigger Timing

Proton Beam Time Pattern

Corresponding Camera Trigger Pattern (FPGA gen.)

- 19 images at first station
- 22 images at second station
Typically 180 ns to 400 ns exposure times w/ LSO; and w/ CsI(Tl) 5 µs

Effective Shutter Gate Profile

Data taken with 70 ps wide, blue laser pulse λ=404 nm.
Shutter gate 400 ns wide, at two detector bias voltage settings.
Effective Shutter Gate at Minimum Width

**TUV:** 180ns Gate, 404nm 70ps Laser Scan
**ORS:** 100ns Shutter Gate, 404nm Laser Scan

9px's VB=17V; 20-Apr-2011
2 Frames compared; Sensor bias = 16V; 10-Feb-2011

Camera response to laser scan at 180 ns shutter gate (= min width as per design specs), and shorter at 100 ns

Leading Edge Dependence of Shutter Gate

The effective rising edge is longer than the expected carrier collection time (16ns, 11.8 ns and 10.1 ns for 11V, 15V, and 17.5V bias). Carrier plasma and trapping effects in detector.

However, the detector bias has remarkably little effect on the spatial resolution, as long as \( V_{\text{full depletion}} \leq V_{\text{bias}} \).
PSpice simulations of pixel response 400ns gate

Response at nominal SF current: CDS ckt. included, but not 100μm detector. Sample-node slew limited (large caps).

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System Resolution as a function Scintillator Type and Thickness

Decay times: CsI(Tl) 1us, LSO = 42ns, and EJ-208 plastic scintillator - 2.3ns

pRAD-1 Hybrid CMOS Cameras - limitations

- **spatial resolution** (at IL1) at 720x720 px and 12x12cm FOV camera is limiting the spatial resolution (in the image/scintillator plane: $\sigma = 180\mu$m)
- **exposure time** and inter-frame time are both scintillator- and camera-limited (beam intensity)
  (2.3ns plastic scintillators help, but poor spatial resolution)
- **number of views** high-resolution frames pRAD is camera limited to 23 (19-frames at IL1, 4-frames at IL2)

⇒ New hybrid CMOS imager is to address those issues (e.g., no. frames at IL1 for 6 cam's ×10 = 60)
### Hybrid CMOS Imager: 1st vs. 2nd generation

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>pRAD-1 Imager</th>
<th>pRAD-2 2nd Gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum integration time (Global shutter)</td>
<td>150 ns</td>
<td>50 ns</td>
</tr>
<tr>
<td>Nominal min. inter-frame time</td>
<td>350 ns</td>
<td>150 ns</td>
</tr>
<tr>
<td>Effective Dynamic Range</td>
<td>11.4 bits</td>
<td>12 bits</td>
</tr>
<tr>
<td>Read noise</td>
<td>100 e-</td>
<td>~ 37 e-</td>
</tr>
<tr>
<td>Imaging array size</td>
<td>720x720 px</td>
<td>1100x1100 px</td>
</tr>
<tr>
<td>Number of samples/frames</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>26 μm</td>
<td>40 μm</td>
</tr>
<tr>
<td>Sensor QE @ 415 nm</td>
<td>84%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Chip dimensions</td>
<td>21x22 mm²</td>
<td>~46.5x49 mm²</td>
</tr>
<tr>
<td>Optical Fill-Factor</td>
<td>~100%</td>
<td>~100%</td>
</tr>
<tr>
<td>Saturation charge/Well depth</td>
<td>&gt;200 ke-</td>
<td>~ 150 ke-</td>
</tr>
</tbody>
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### 10-frame In-Pixel Storage: Larger Pixels & Advanced CMOS

Original 26μm pixel. New 40μm pixel together w/ more advanced 180nm CMOS process (larger capacitance /μm²) allow to pack 10 MIM storage caps per pixel. ⇒ Large IC chip = 46.5x48.7 mm², will need reticle stitching. Impacts cost and yield.
Summary

- Burst mode 4 MHz high-resolution, high QE, 3-frame, 720×720 px, hybrid CMOS imager successfully fabricated on 1st iteration. System-on-chip (SoC) approach produced a compact, reliable and low power imager.
- Six cameras built and operated for several years in radiation environment.
- Thick (~100 μm) detector provides high QE from 380 nm to 900 nm, but affects time definition of the shutter. Photo-sensors and circuits generating shutters under 100ns (50ns) need more tuning.
- LSO scintillator optimal resolution and radiation resistance, plastic scintillator faster, but worse spatial resolution (ZnO ?)
- New 50 ns, 10-frame, 1Mpx imager in design close to completion.
- Future radiography and FEL facilities need high-resolution sub-ns imagers.


Two Proton Radiography Experiments:
shaped-charge jet penetration of HE and polymer cylinders

~ 9 km/s copper jet generated by a shaped charge; (Left panel) impacting a cylinder of high-explosives and triggering detonation wave; (Right) an inert Teflon cylinder.