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Compressed Time-Resolved X-Ray Imaging

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Rice University, December 2, 2015

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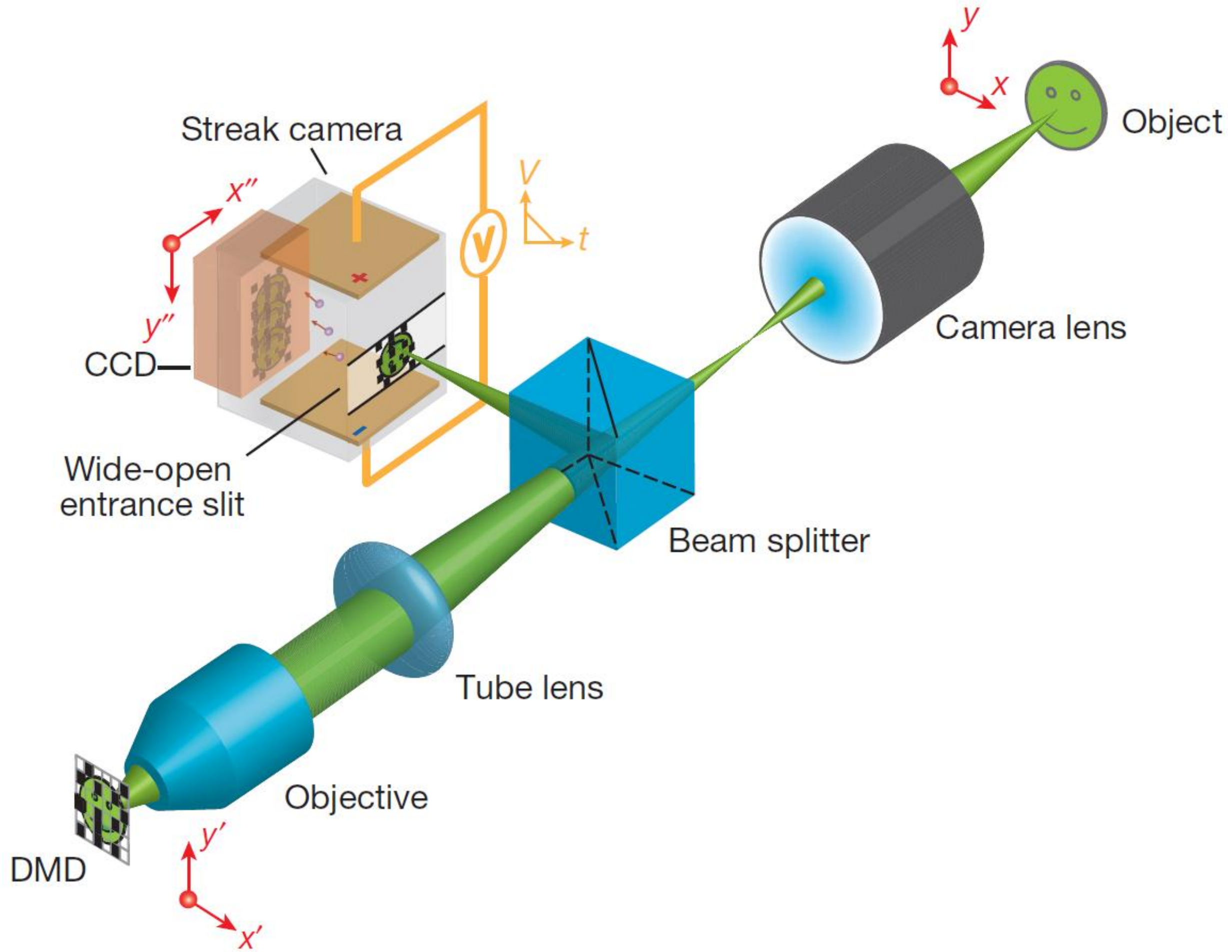
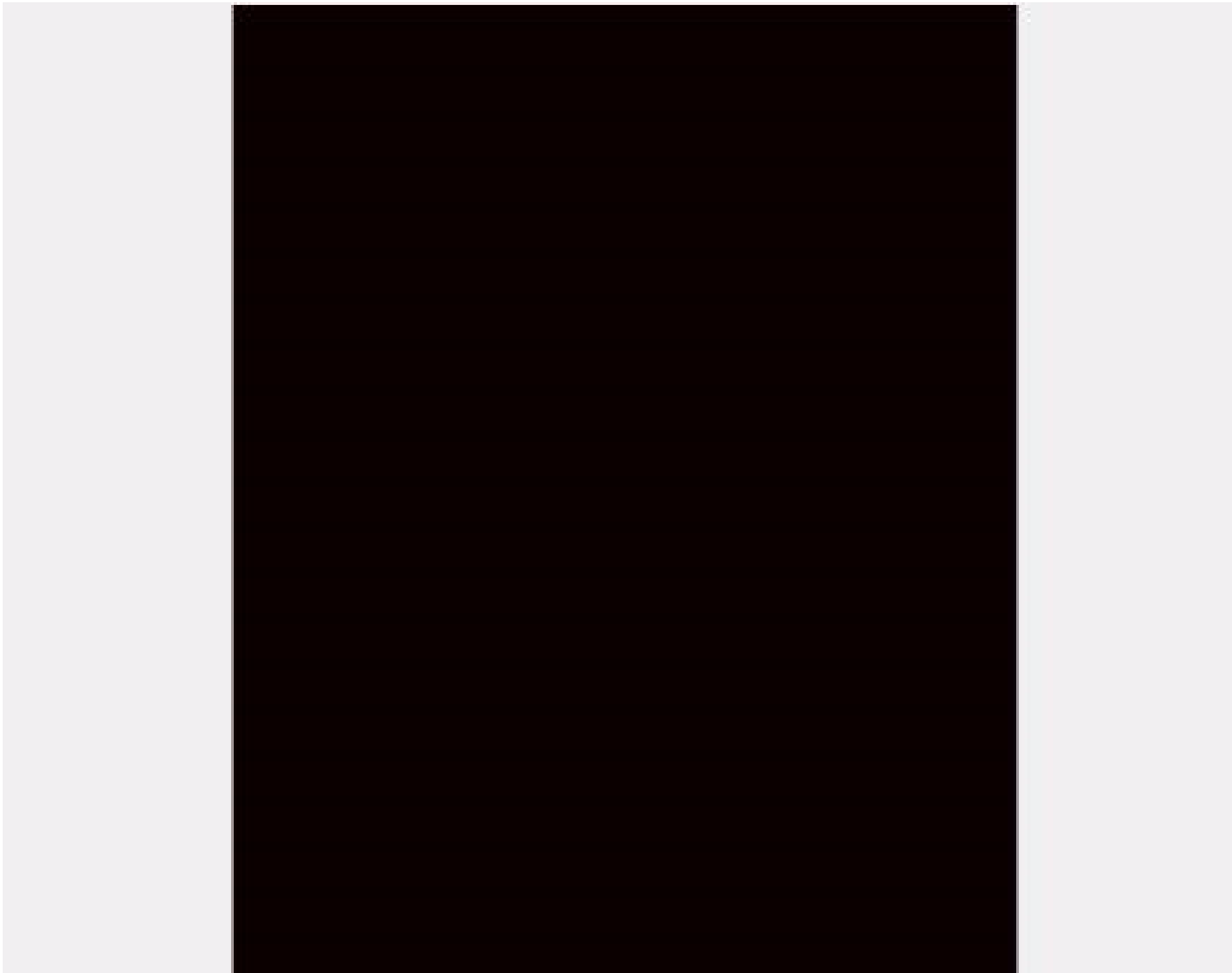
National Security Technologies

Compressed Ultrafast Photography (CUP)

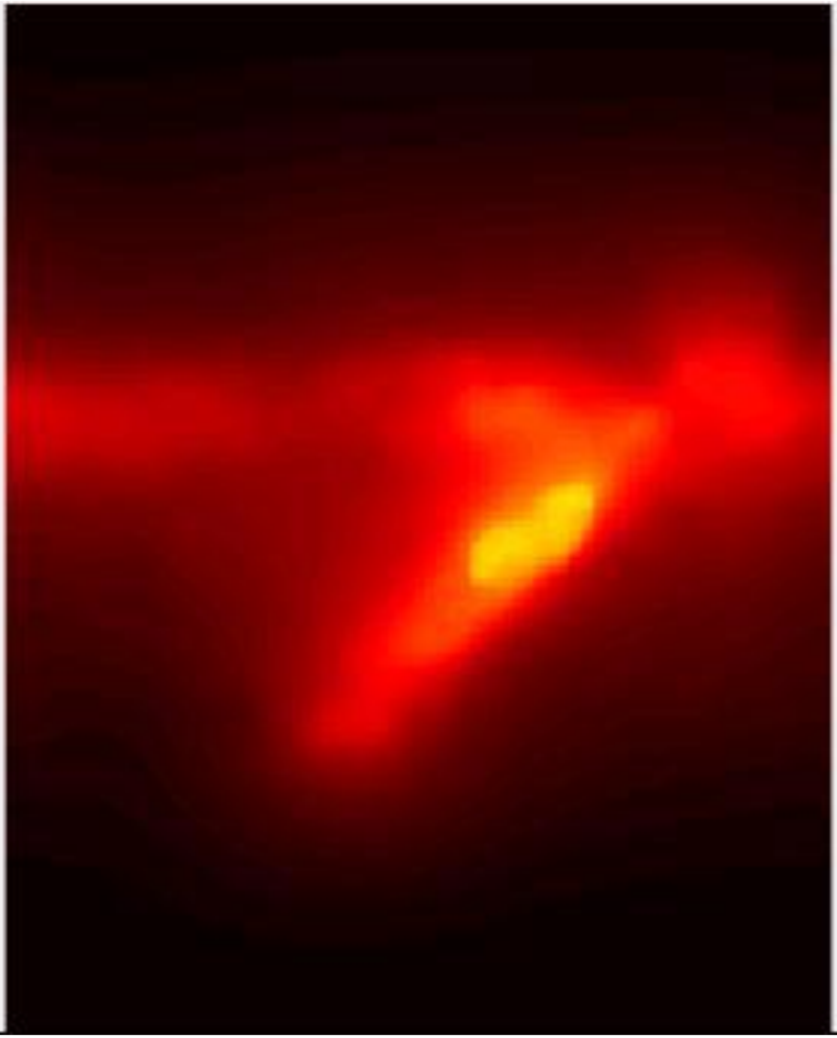
Gao, Liang, Jinyang Liang, Chiye Li, and Lihong V. Wang, "Single-shot compressed ultrafast photography at one hundred billion frames per second," Nature 516 4 December 2014, 78.



Reconstruction of Light Bouncing From Mirror



Reconstruction Without Subtracting First Frame or Thresholding



NSTEC is Pursuing Three Applications of CUP

I. High-Speed Beam Imaging Diagnostic for Radiography Machines

Simulations were done, development may take place in future to support development of future radiography machines

II. Compressed Time-Resolved X-ray Imaging

A fully funded R&D project which has just started, with option to continue for up to 3 years

III. Compressed Timed All-Optical Mapping Photography

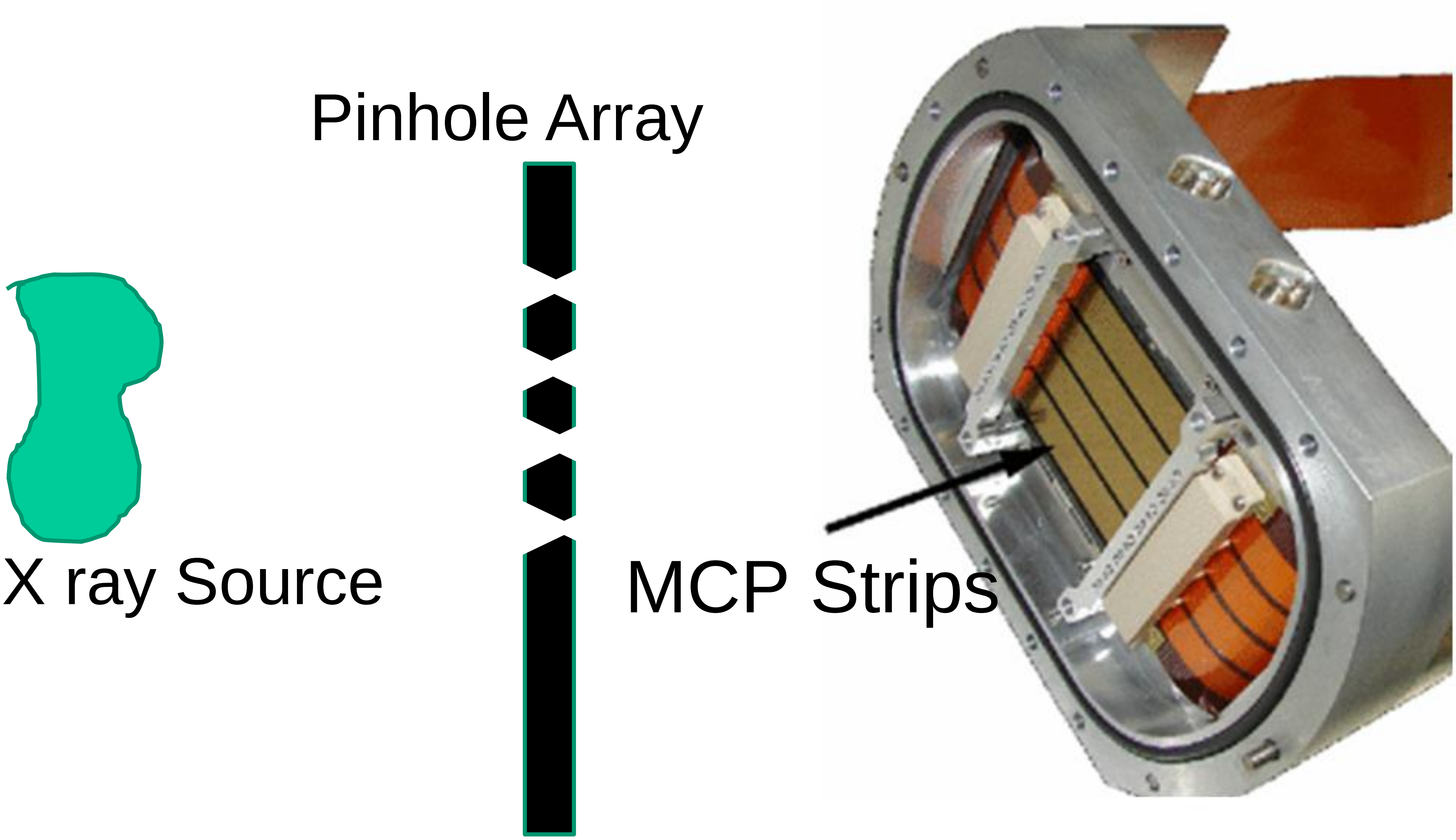
A side project we are pursuing under our x-ray R&D project in collaboration with UT Austin

Survey of Multi-Frame High-Speed Imaging Applications

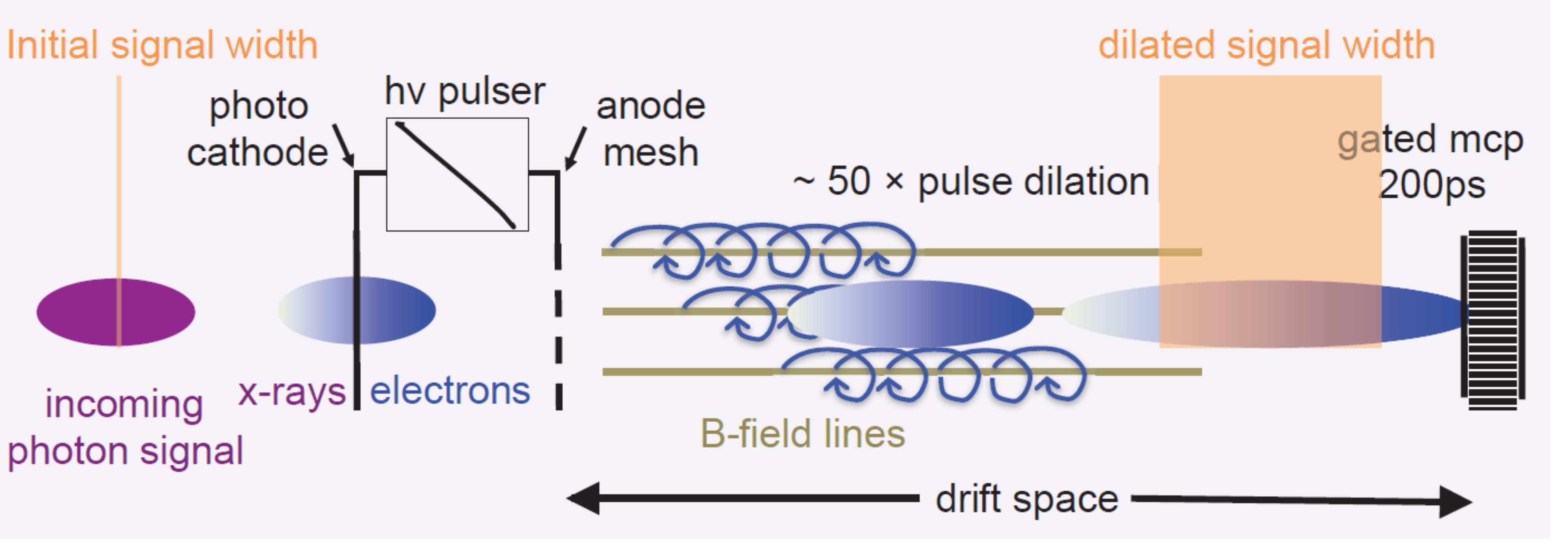
	Radiation	Time Resolution	1D/2D	Works for Self-Luminous
Multi-MCP	Optical/X-ray	50 ps	2D	Yes
DIXI	X-ray	10 ps	2D	Yes
Streak Camera	Optical/X-ray	0.5 ps	1D	Yes
CUP	Optical/X-ray	0.5 ps	2D	Yes
STAMP	Optical	200 fs	2D	No

[1] Gao, Liang, J. Liang, C. Li, and L. V. Wang, "Single-shot compressed ultrafast photography at one hundred billion frames per second," *Nature* **516** (December 4, 2014) 78.

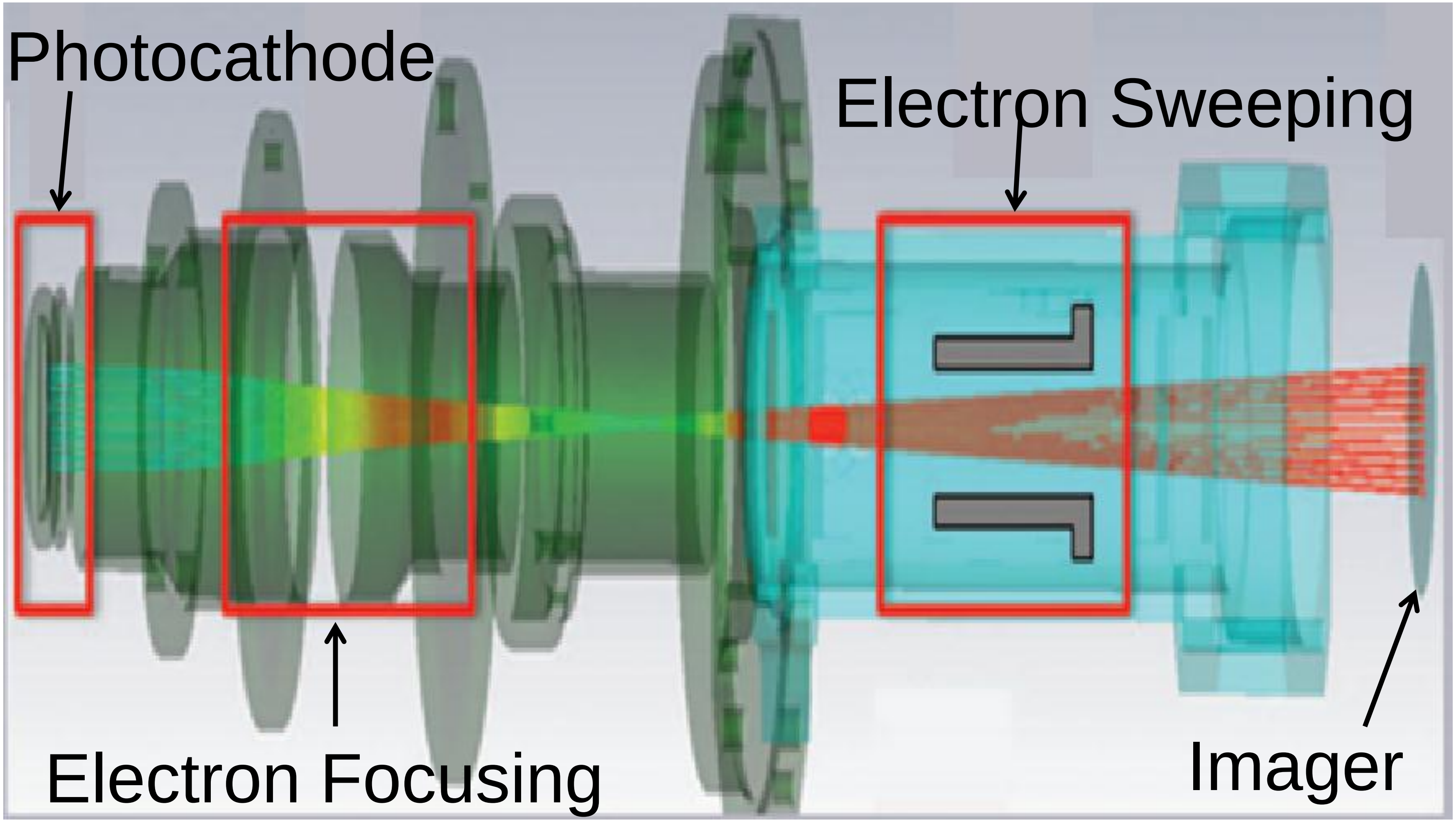
Multiple Micro Channel Plates



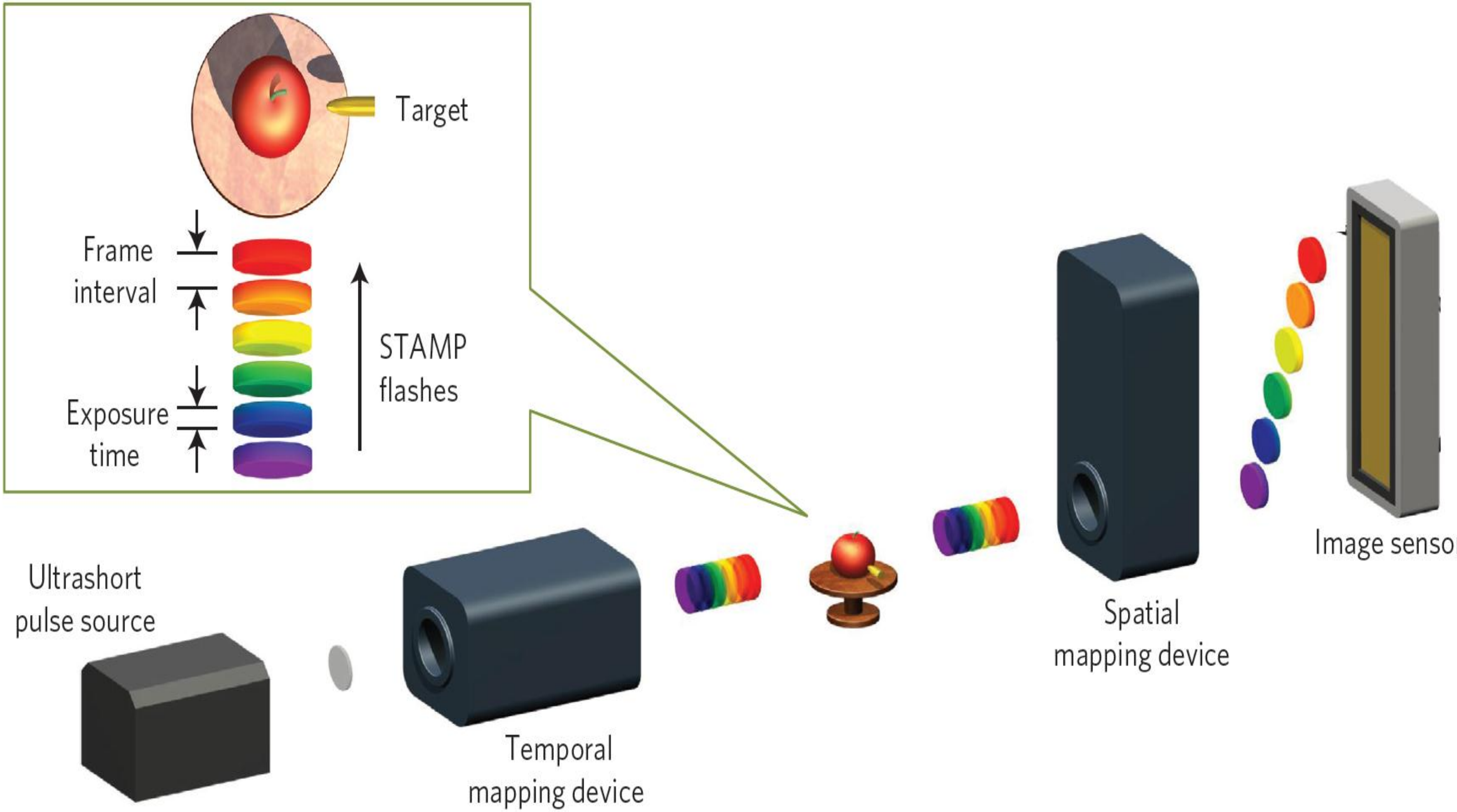
Dilation X-ray Imager (DIXI)



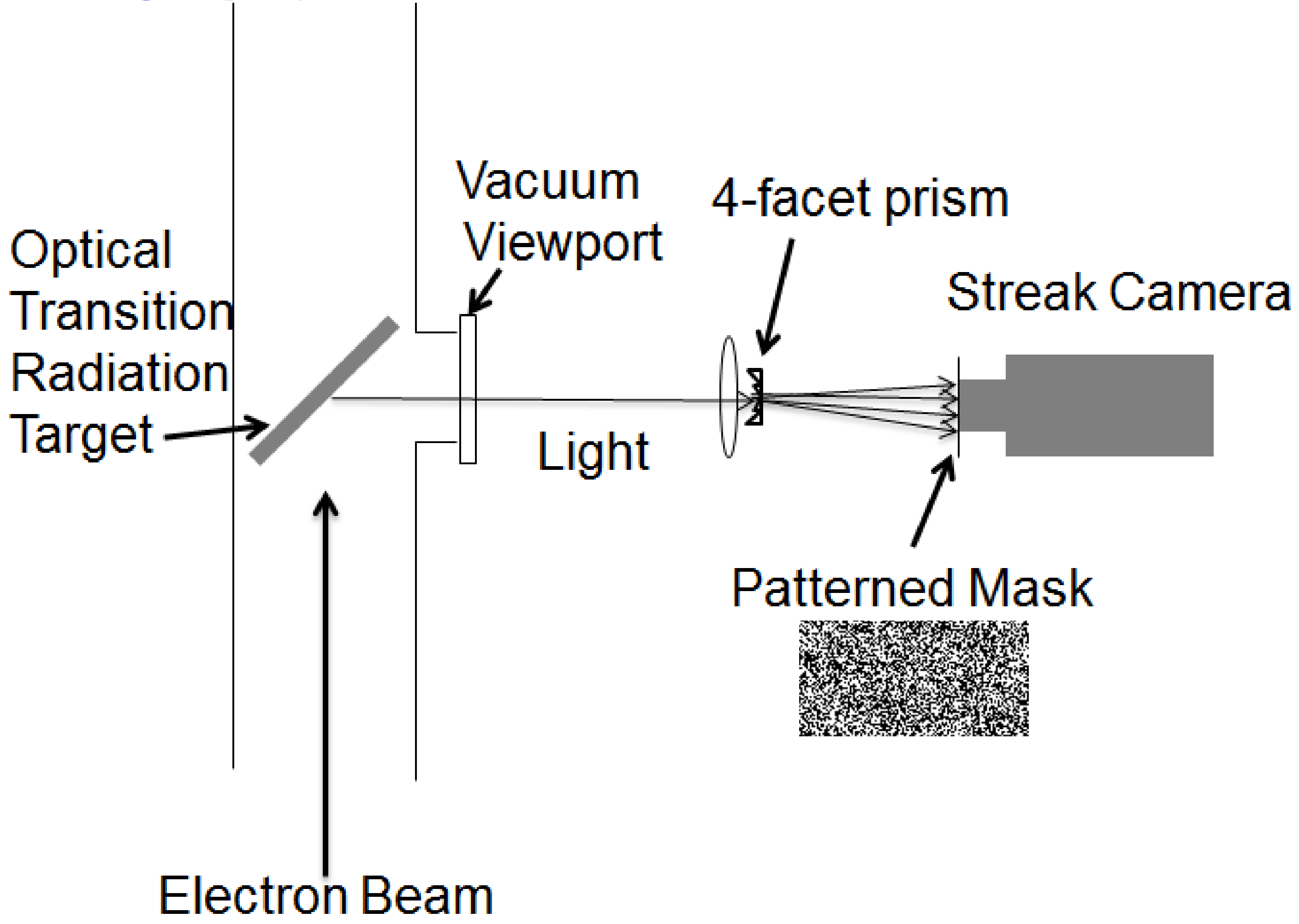
Streak Camera



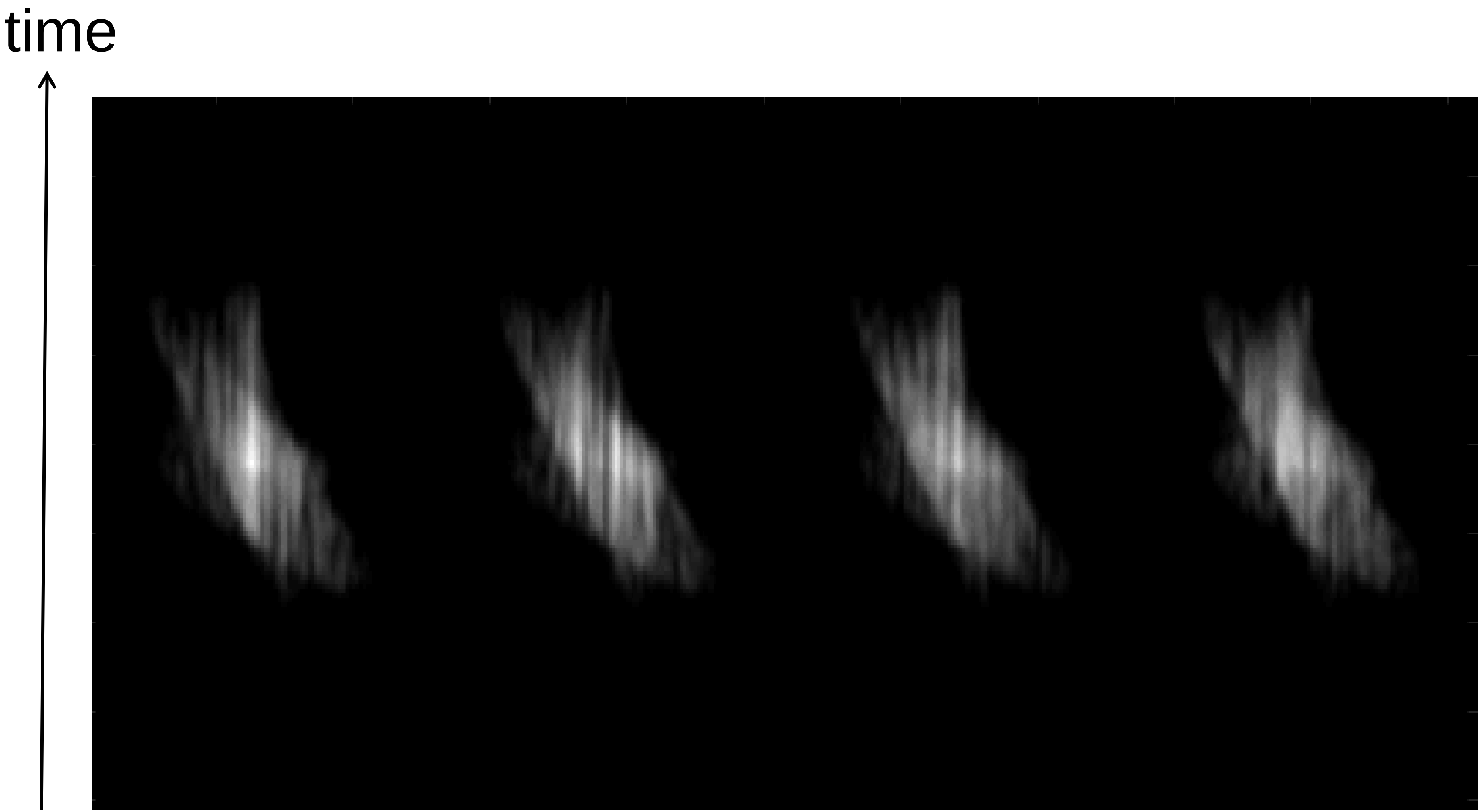
Sequentially Timed All Optical Mapping (STAMP)



I. High-Speed Beam Imaging Diagnostic for Radiography Machines



Data From Four Streaked Pinhole Image



TwIST Algorithm for Reconstructions

Iterative Twist[2] Algorithm, used in the original paper by Gao *et al.*[1]

$$G_{i+1} = (1-\alpha)G_{i-1} + (\alpha - \beta)\, G_i + \beta \Psi[G_i + K^T\{D - K(G_i)\}]$$

α,β= constants
D = Measured data, which consists of streak images
G_i = *O*bject reconstruction at i*th* iteration
K = Projection operator, which generates simulated images from G_i
K^T = Back-projection operator
Ψ = Smoothing operator, total variation for this case

Reconstruction

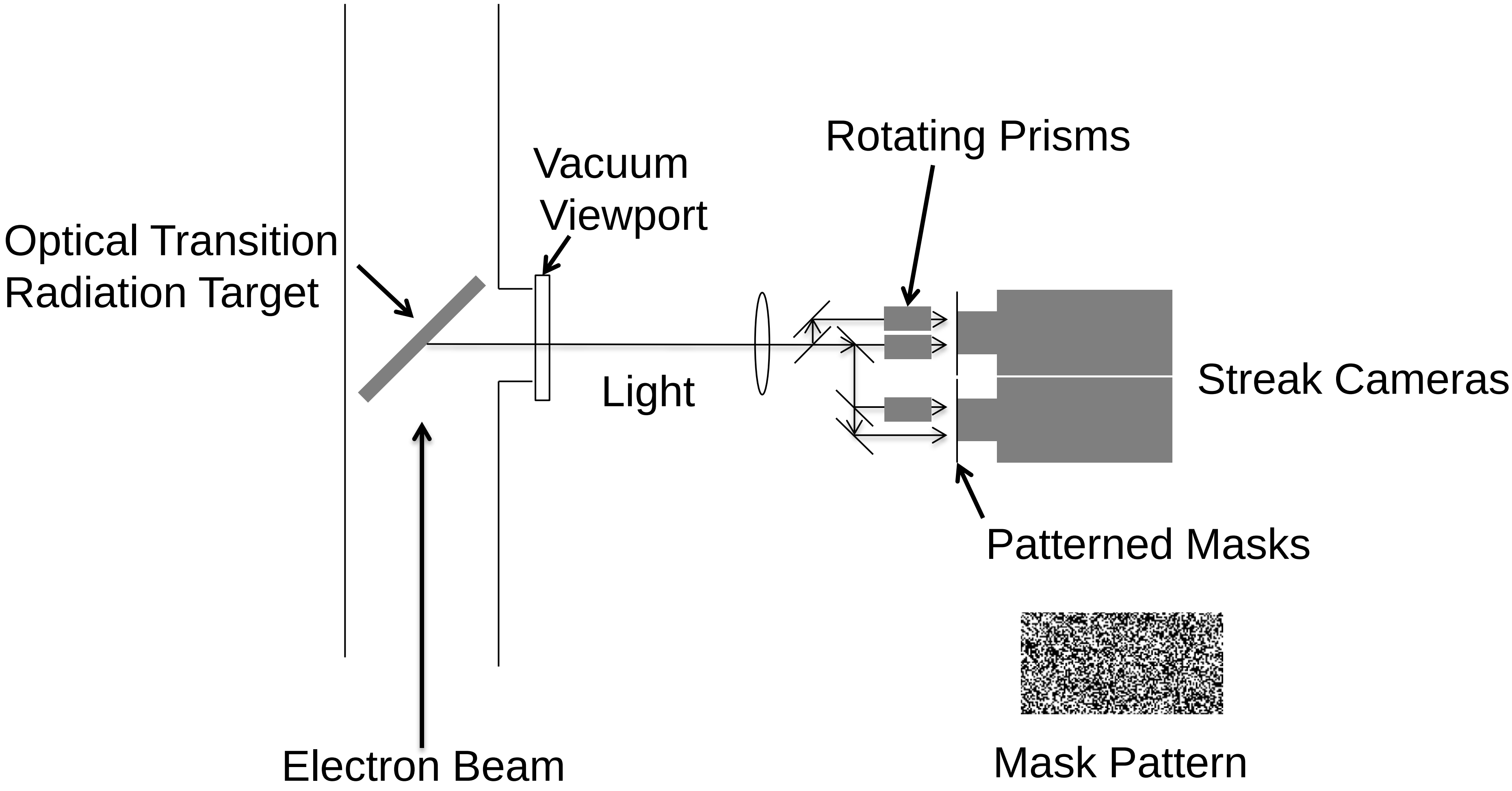
Modified Algorithm

$$G = G - \lambda \mathbf{S}\,(K^{T}(G))$$

G= Object Reconstruction
S = Gaussian smoothing operator
λ = constant

Reconstruction With Modified Algorithm

Beam Imaging Diagnostic With Rotated Images



Reconstruction From Rotated Images

II. Compressed Time-Resolved X-ray Imaging

- $310k/yr internally funded R&D project started Oct. 1, 2015
- Can reapply for funding for up to 3 years
- Apply to self-luminous plasmas and radiography of dynamic experiments
- Rotation of images is not possible.
- We could have multiple rotated cameras, but this is too expensive and introduces significant parallax

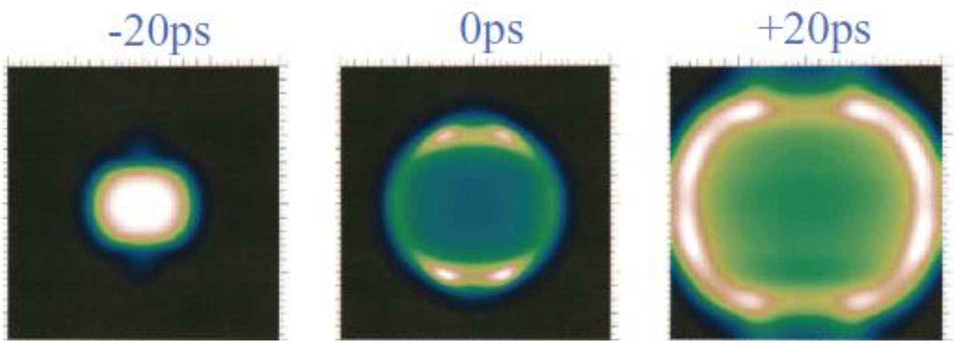
Convert 1D to 2D Imager

- Cost of x ray streak camera is over $300,000
- Cost of patterned photocathode is less than $4,000

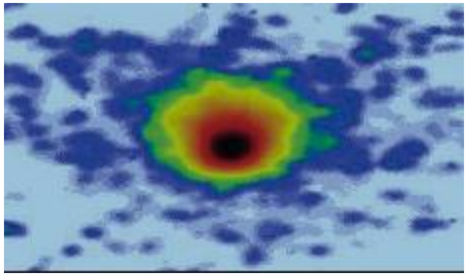
Convert 1D to 2D imager for very little expense and no further complication in the experimental setup.

Experiments

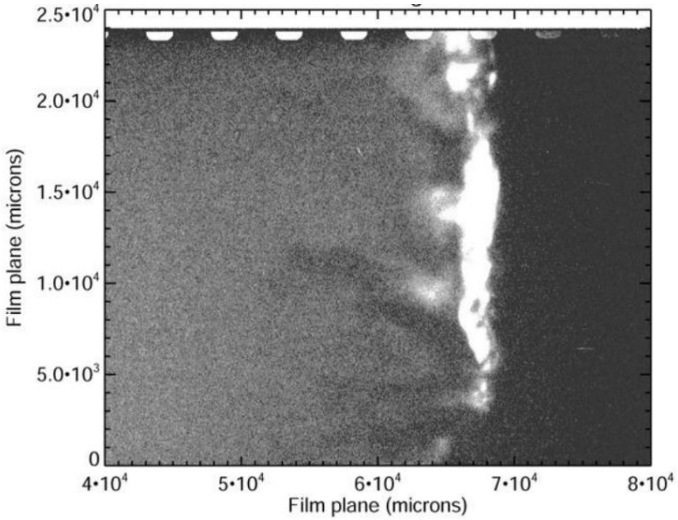
National Ignition Facility



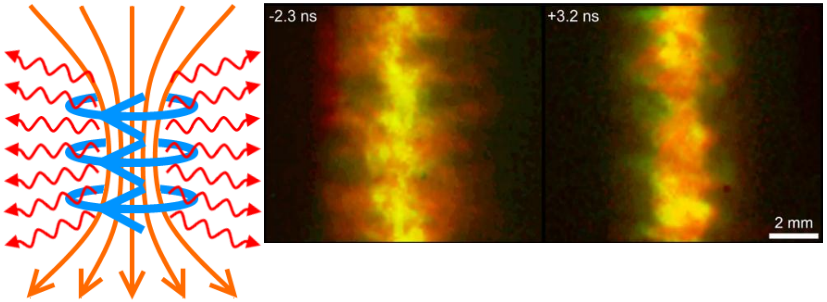
TITAN
Laser-Induced Plasma



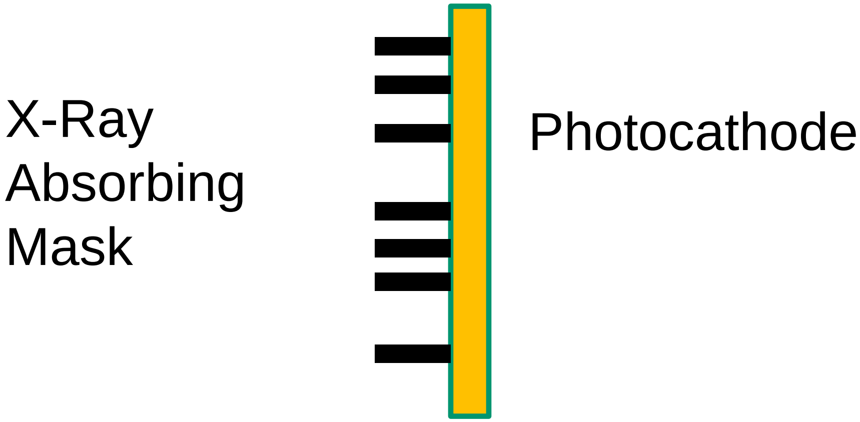
Z-Machine Radiography

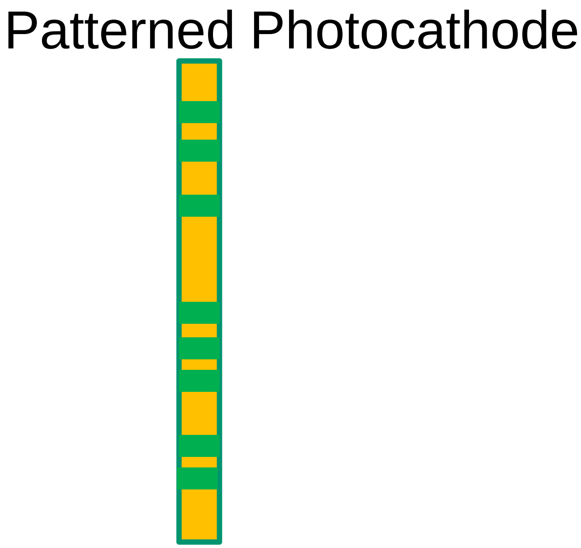


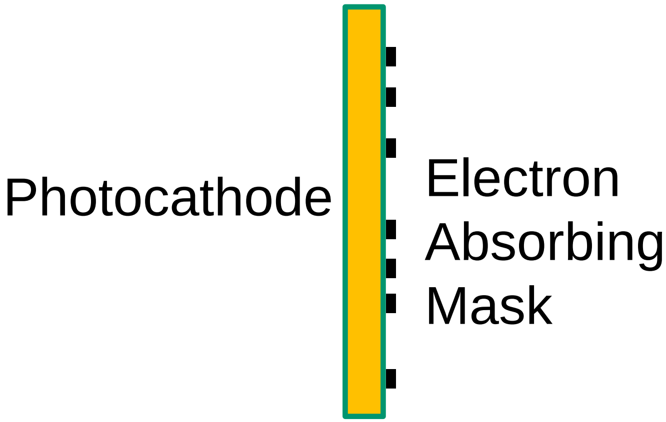
Z-Machine Plasma



Three Options for Patterning



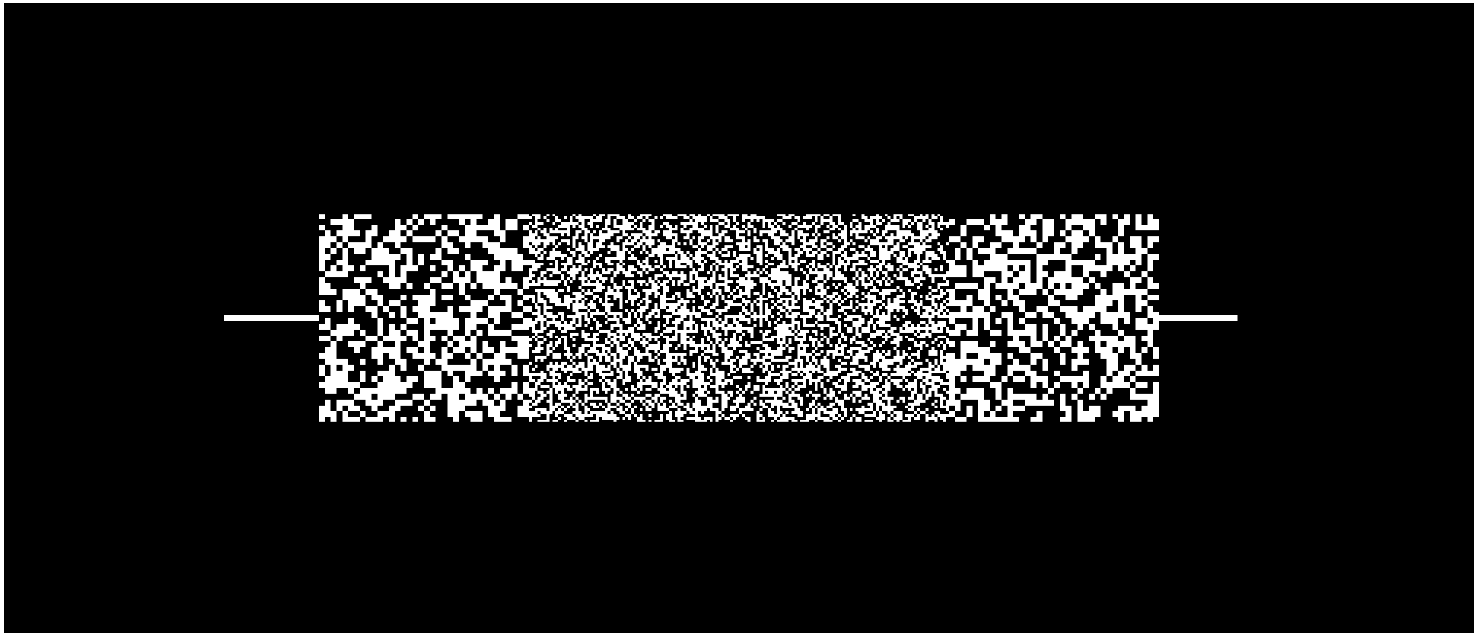




Patterned Photocathode

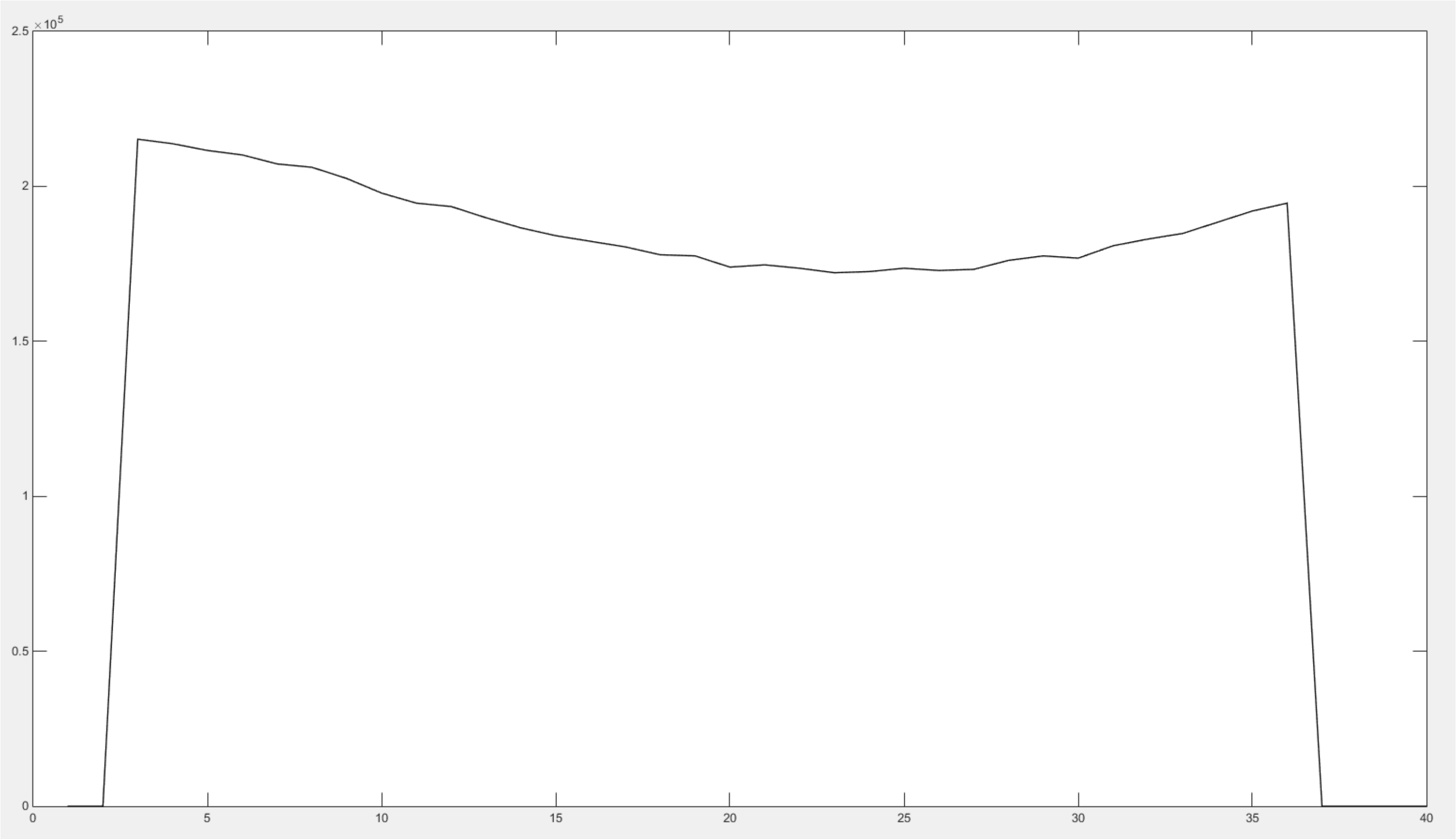
- 70 μm pattern in center, 140 μm pattern on edges due to changing camera spatial resolution
- Accommodate four 5x5mm images
- Slits at ends could be used for collecting a record of the total x-ray flux to help constrain the reconstruction

Photocathode Pattern (White is Active Area)



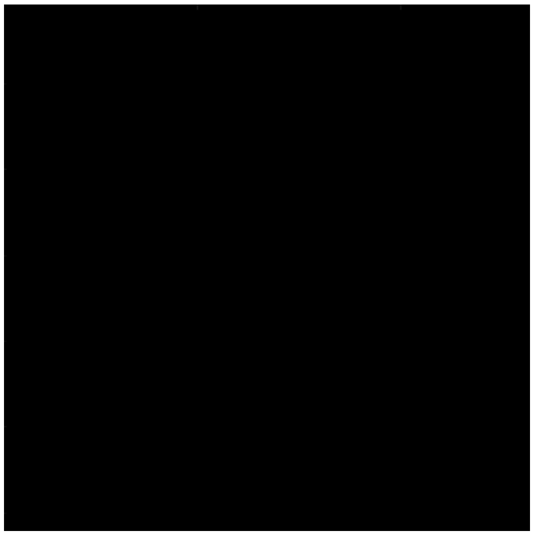
Flux Monitor

Total Flux

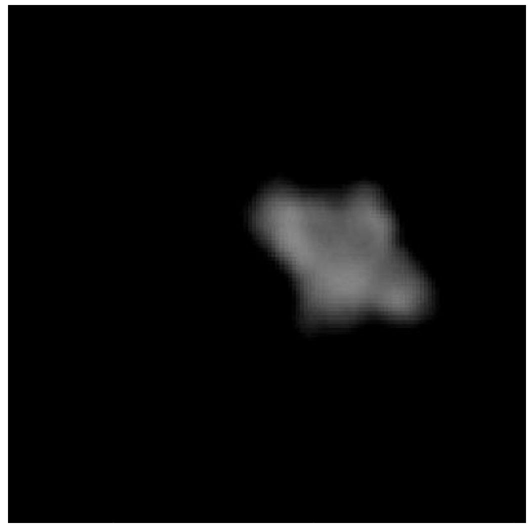


Time

Reconstruction Using Flux Monitor



Object (Frame 38/40)



Reconstruction Without Flux Monitor

Reconstruction With Flux Monitor

Photocathode Materials

Aluminum: Sensitive to UV light, low x ray sensitivity

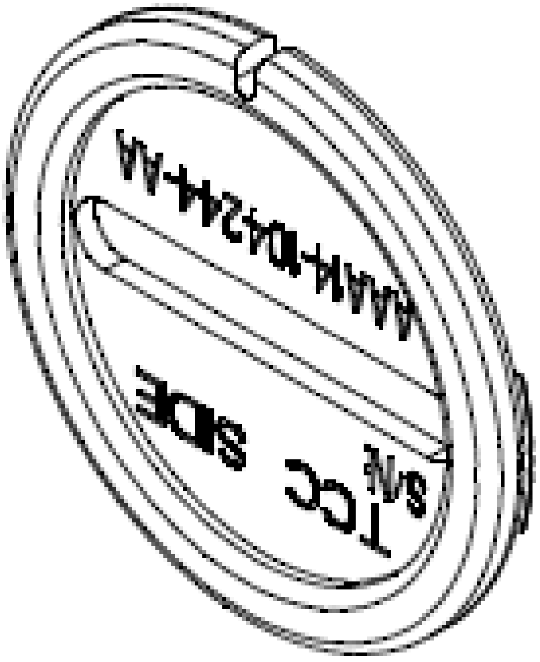
Gold: Sensitive to x rays up to 10 keV, Quantum efficiency maximum of 0.08 photoelectrons/photon. Easy to handle and etch.

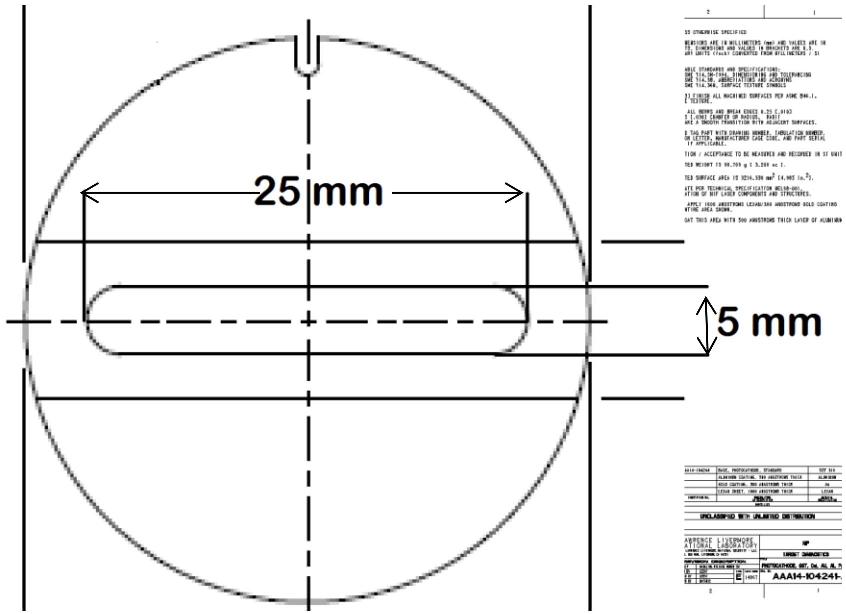
CsI: Sensitive to x rays up to 10keV, can go to higher energy with special microstructures. Quantum efficiency can be >0.4. Delicate material, difficult to etch. Degrades with exposure to air, limited lifetime.

We have chosen to use gold, but using CsI in the future with an electron absorbing mask is possible.

Limited Size of Photocathode

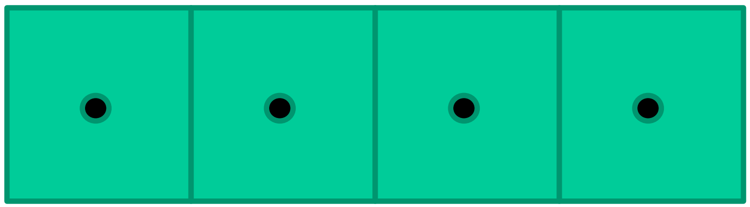
- Height (sweep direction) is limited to 5 mm by the photocathode holder and the size of the accelerating mesh behind it
- Enlarging the holder should be easy
- Enlarging the mesh may be more difficult



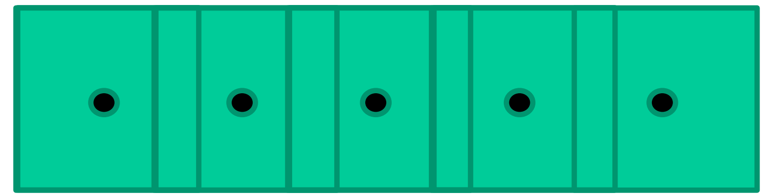


Pinhole Patterns

5mm Height Photocathode

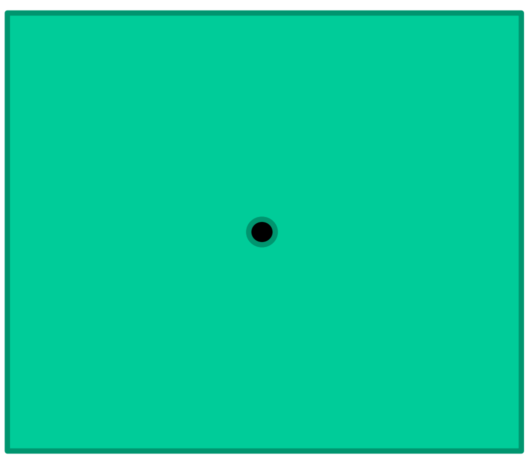


4 Images

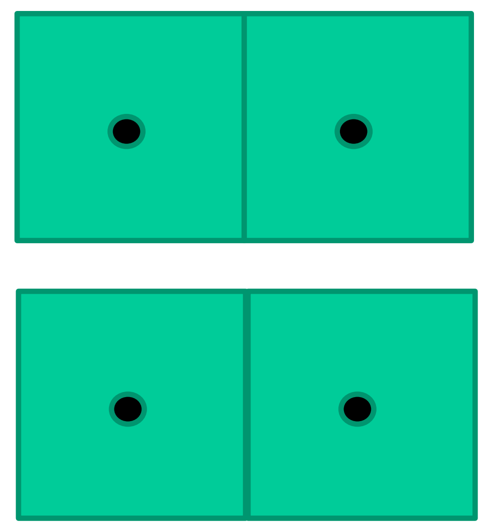


Overlapping Images

20mm Height Photocathode

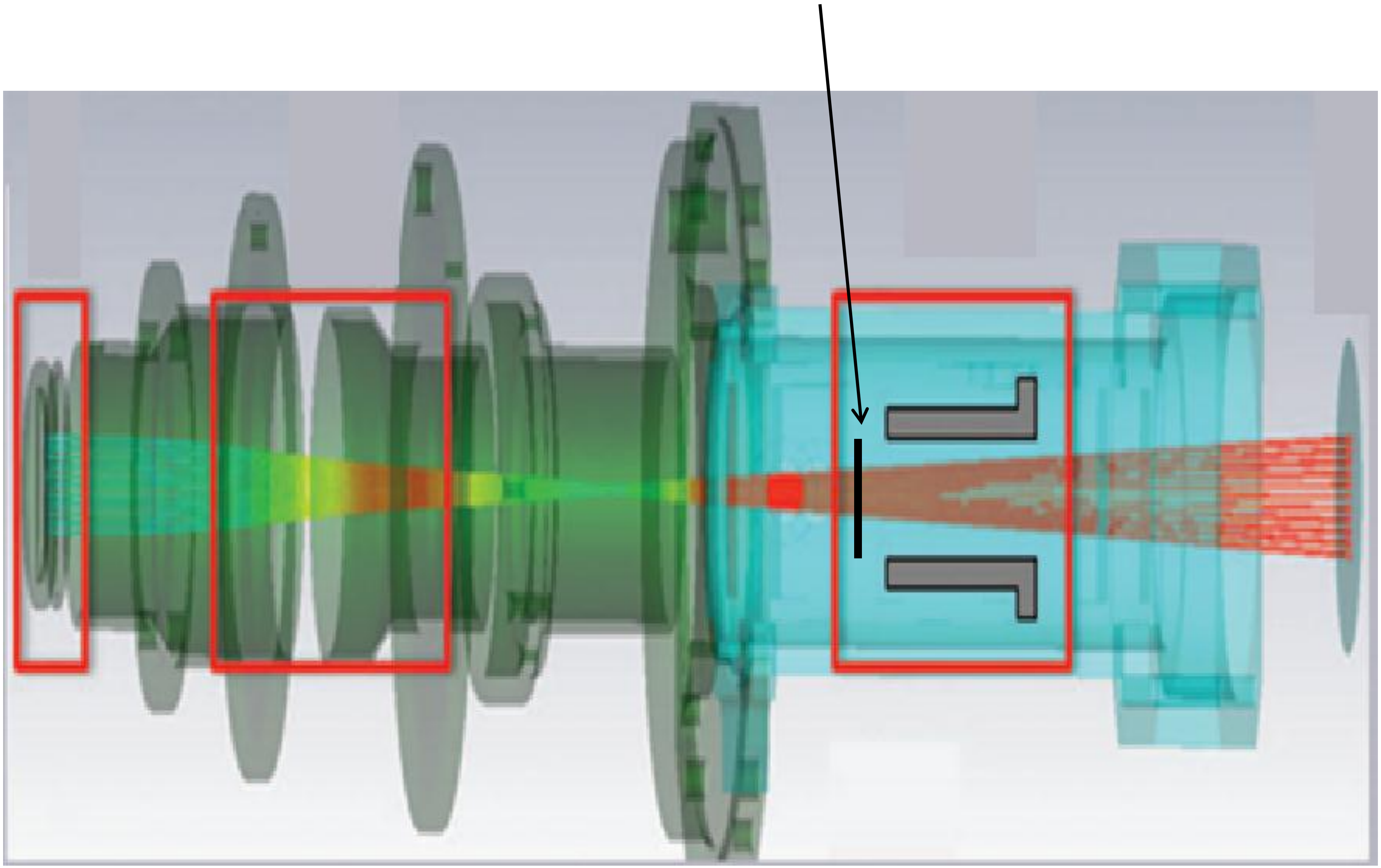


One Image



4 Images

Put Pattern Later in Electron Beam



Downstream Electron Beam Patterning

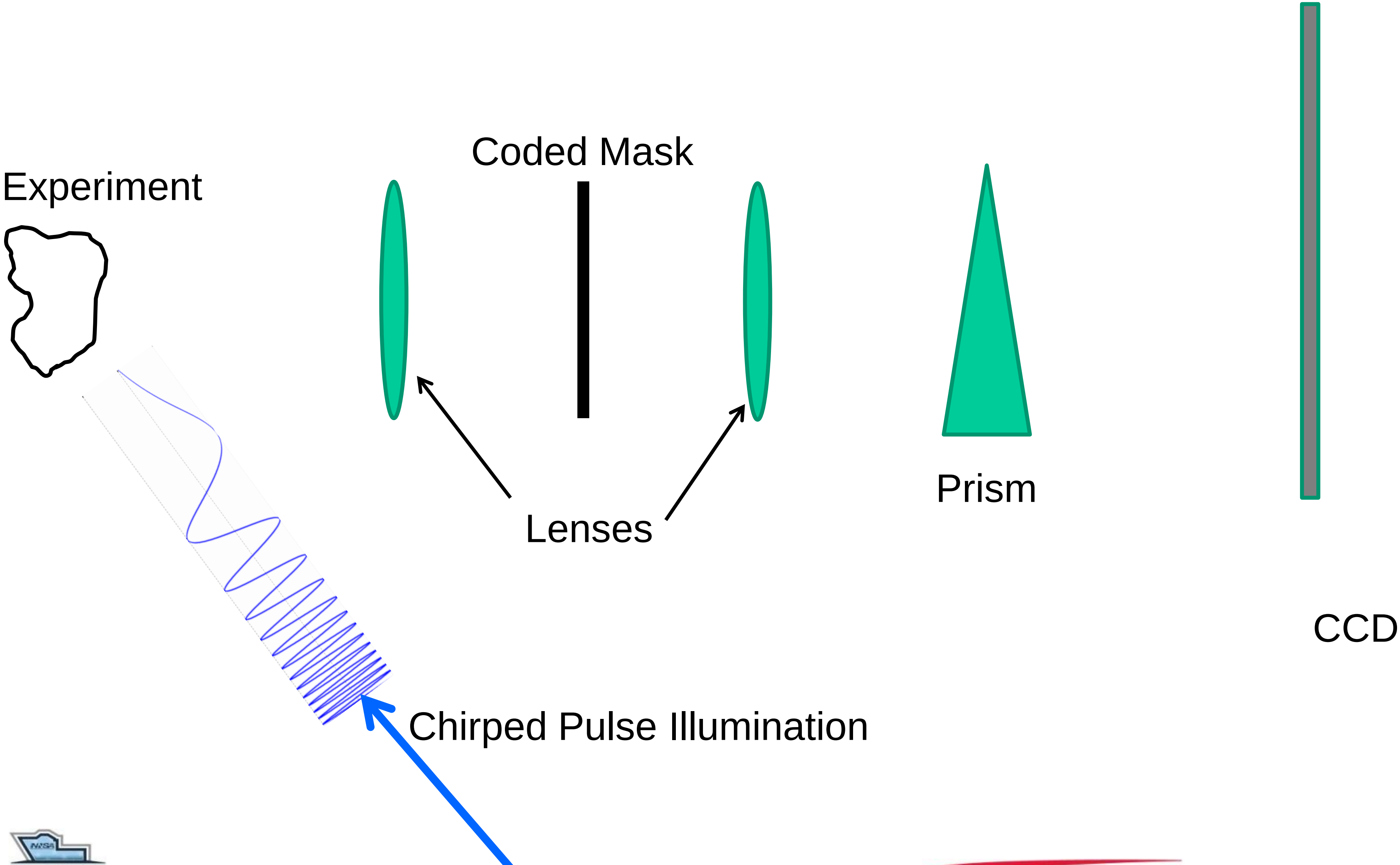
Advantage

- Most of the system blur occurs before this point, so a higher resolution pattern could be imposed
- Even with system blur before the pattern, a higher resolution pattern will enable higher resolution reconstructions.
- Multiple patterns at different locations could make compression closer to the ideal of random sampling of the object space

Disadvantages

- Pattern must be many times smaller than final desired resolution
- May be impossible to mount
- Must be thick enough to stop 15 keV electrons
- Space charge effects may be significant
- Material may be destroyed by beam?
- May be impossible to build pattern with desired resolution (3 μm)

II. Compressed Timed All-Optical Mapping Photography

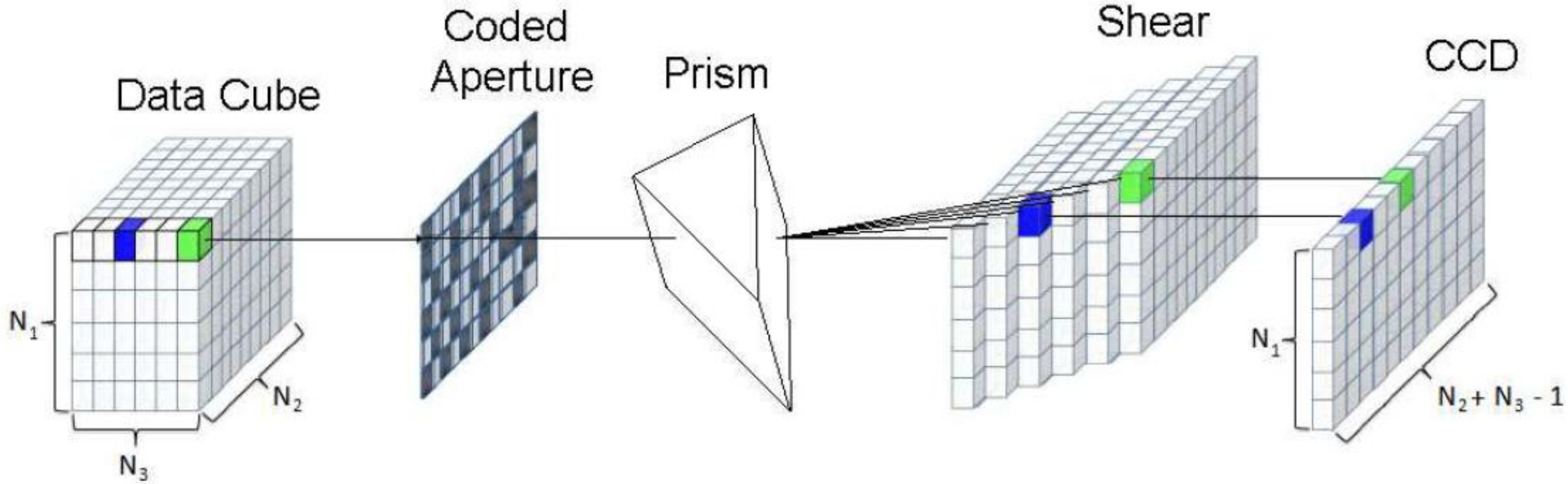


Collaboration with UT Austin

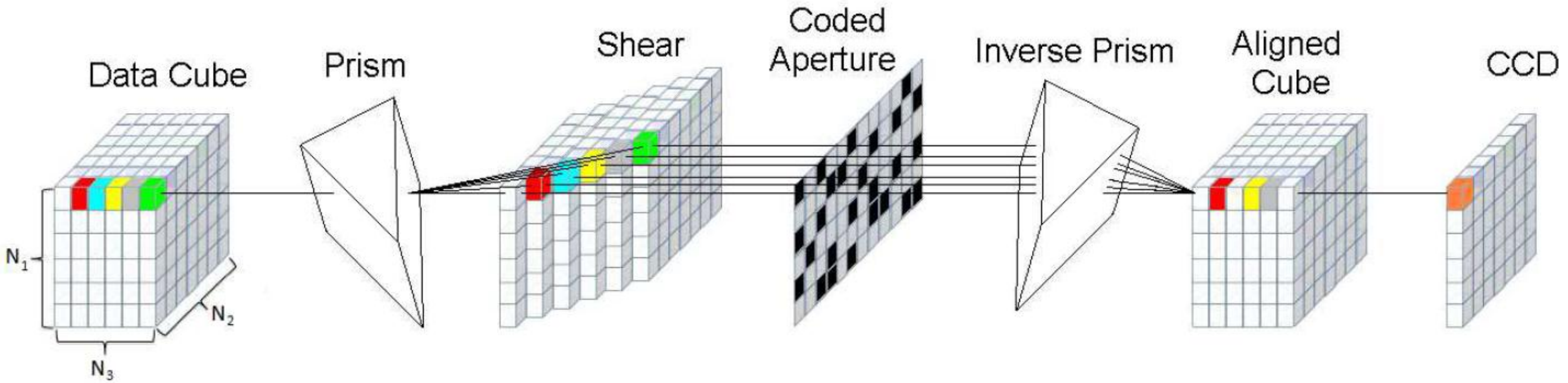
- Use the Texas Petawatt Laser at the Center for High Energy Density Science. Produce nonlinear optical effects on a time scale of less than 1 ps.
- Use a pump laser to produce non-linear effect, then probe with the chirped pulse.

Could Use Dual Disperser Configuration

Single Disperser



Dual Disperser



Conclusion

- Compressed Sensing enables us to push cameras into new time domains
- Compressed Sensing can make a cheaper camera than other fast cameras, such as the DIXI camera.
- Compressed Sensing enables us to get double use out of expensive pieces of equipment, converting 1D streak camera to a 2D time-resolved camera for little cost.
- Significant improvements in our reconstruction algorithms are needed, especially in the case of an x-ray system that does not allow rotations.