Image Processing and Control of the NIF Beam Profile with Programmable Spatial Shapers

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Matthew Rever, John Heebner, Jean-Michel Di Nicola, Barry Fishler, Mitanu Paul, Eddy Tse, Abdul Awwal, Charles Orth (LLNL)

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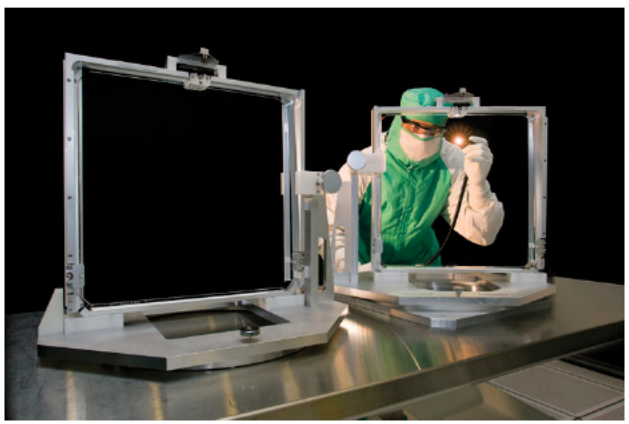
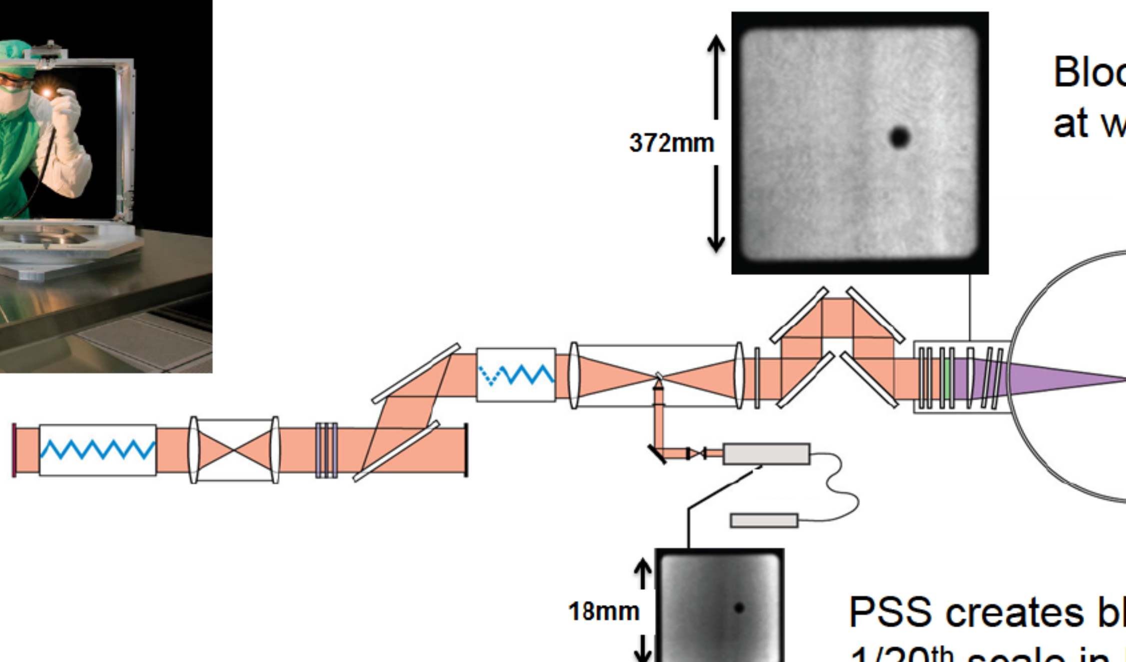
The ability to program the NIF beam profile started in 2010

- NIF has 192 beamlines into target, each with valuable optics at the end
- A system of Programmable Spatial Shapers (PSS) was installed in 2010 to create small blocker obscurations used to shadow a small number of optics flaws. These would be susceptible to grow under repeated laser illumination.

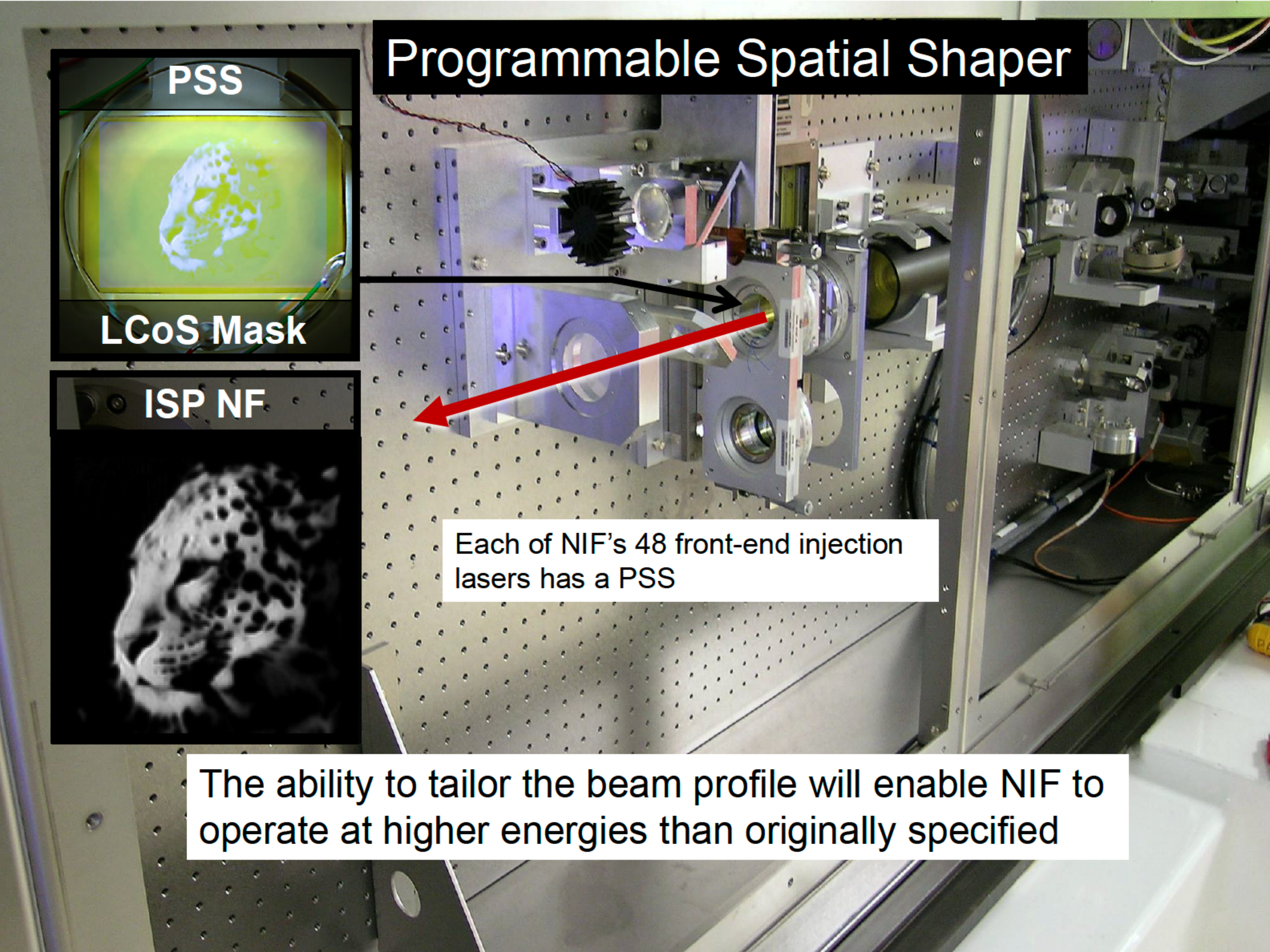


Final optics (wedged focus lens)



Blocker obscuration at wedged focus lens

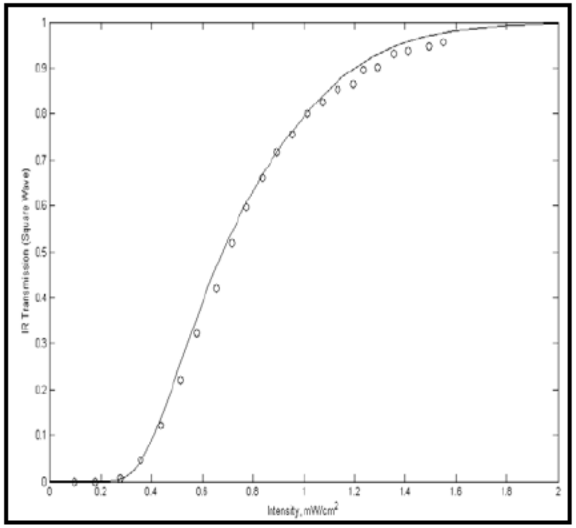
PSS creates blocker at 1/20th scale in NIF front-end


Programmable Spatial Shaper
PSS
LCoS Mask
ISP NF
Each of NIF's 48 front-end injection lasers has a PSS
The ability to tailor the beam profile will enable NIF to operate at higher energies than originally specified

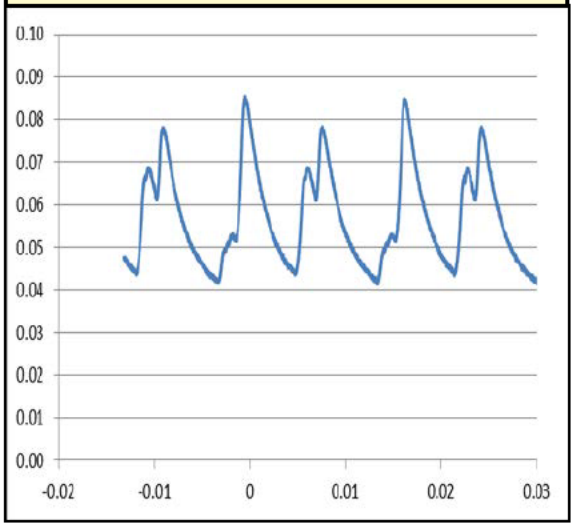
Challenges for PSS Control

- The LCoS transfer function is nonlinear. Moreover, it varies from device to device, and over time.
- The grayscale response is unstable due to synchronization issues.
- Spatial cross talk (ghost reflections) and hysteresis present additional complications

Nonlinear response-curve

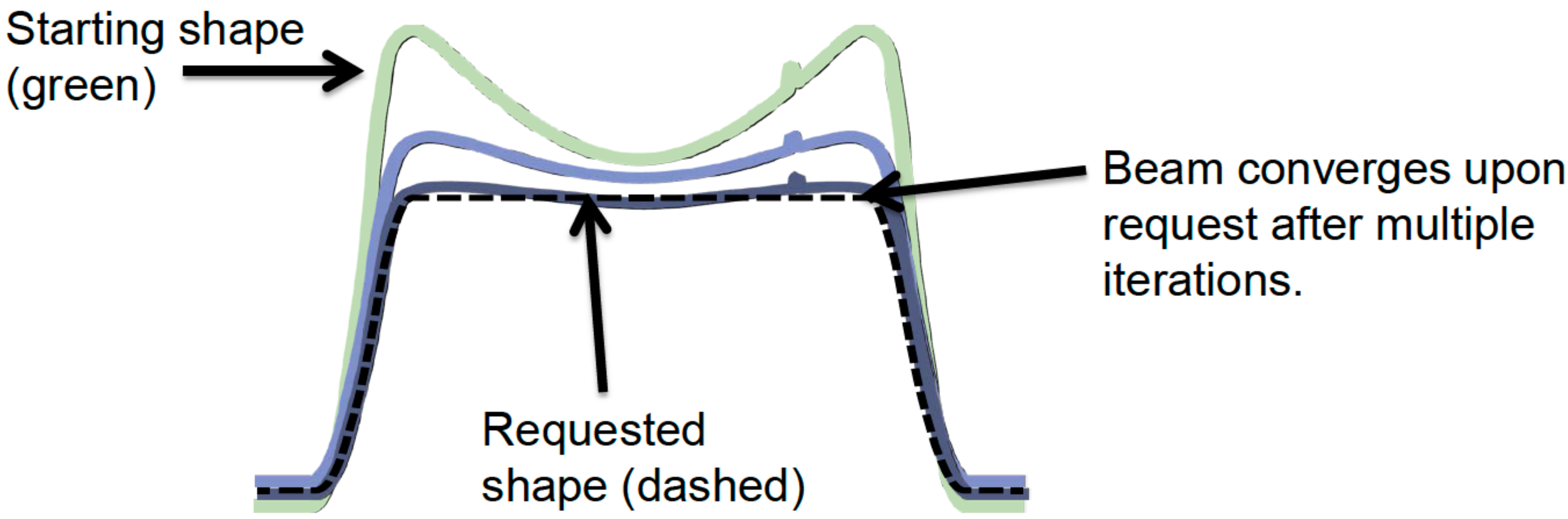


LCoS flicker



A robust, closed-loop, software algorithm can compensate for these

Iterative algorithm used to modify beam to requested shape



$$\mathbf{Control_0} = \mathbf{100\%\ across\ beam}$$

$$\mathbf{Control_{n+1}} = \mathbf{Control_n}\left(\frac{\mathbf{Request}}{\mathbf{Measured}}\right)^{g\sim\mathbf{0.3}}$$

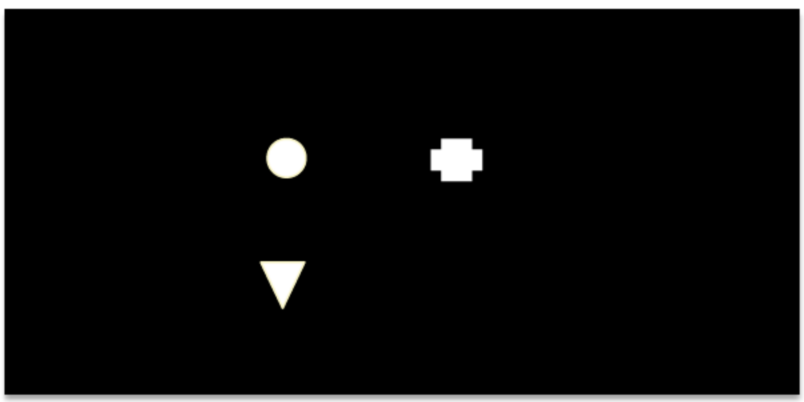
Iterate either a fixed number of times or until error metric is sufficiently small.

Registration between LCoS & ISP

LCoS (control matrix) and ISP (feedback matrix) are in different coordinate systems; (different resolutions, scaling, translation, rotation, shear).

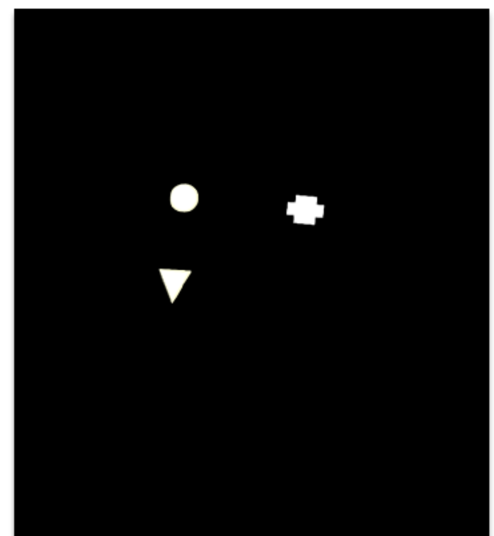
-> Need a mapping between spaces.

1. Write three features on LCoS



→

2. Measure where they correspond to on ISP image via normalized cross-correlation



3. Compute corresponding affine transform matrix:

$$T = \begin{pmatrix} a & b & \Delta x \\ c & d & \Delta y \\ 0 & 0 & 1 \end{pmatrix}$$

Now for every pixel in ISP space we know where to write on the LCoS.

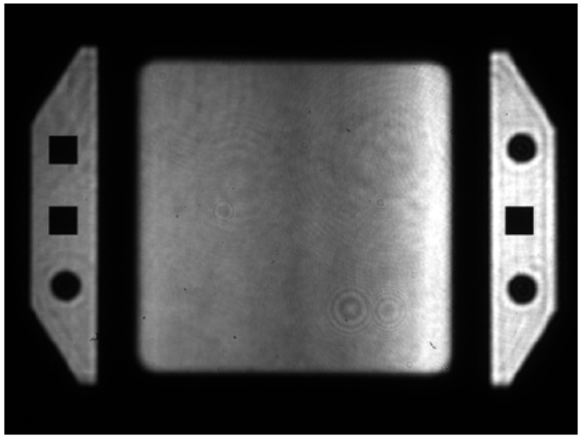
Registration between request & ISP

The requested beam shapes are specified in an ideal space with known dimensions and rotation.

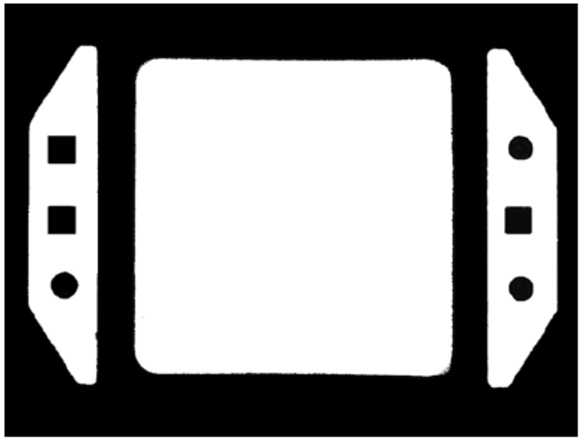
Every beam in the real NIF system has slightly different scaling, translation, and rotation (and possibly shear) on their corresponding ISP cameras.

The request and actual beams need to be precisely aligned.

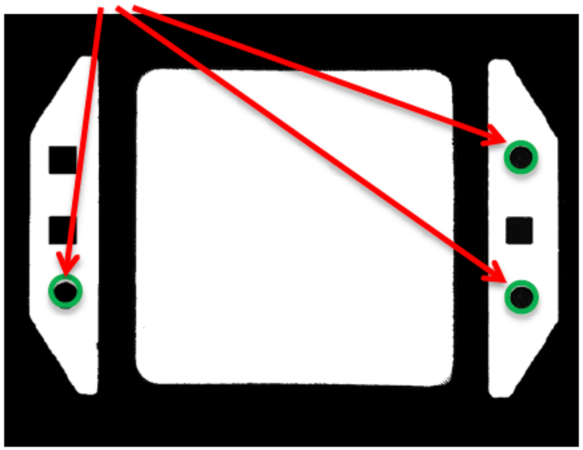
1. Acquire raw ISP image



2. Binarize (low-pass filter then adaptive threshold)



3. Hough transform to find circles in wings



4. Use known circle positions in request image to define Affine transform matrix.

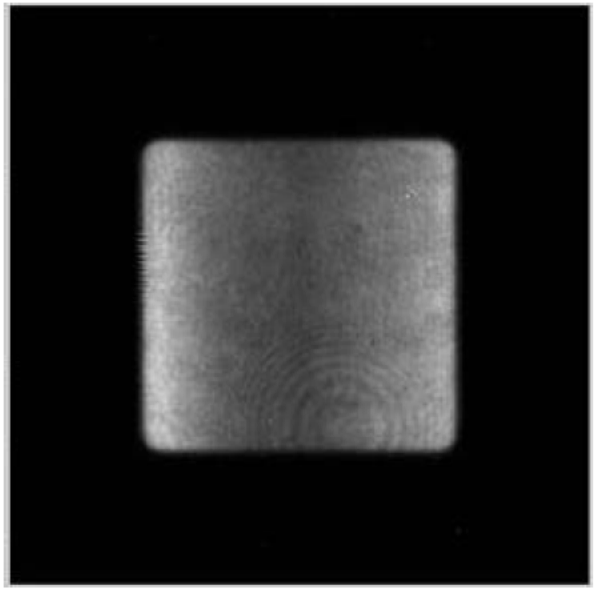
Edge preservation, control matrix extension/inpainting

An abrupt discontinuity at the edge of a control matrix could imprint undesirable features on the NIF beam edges.

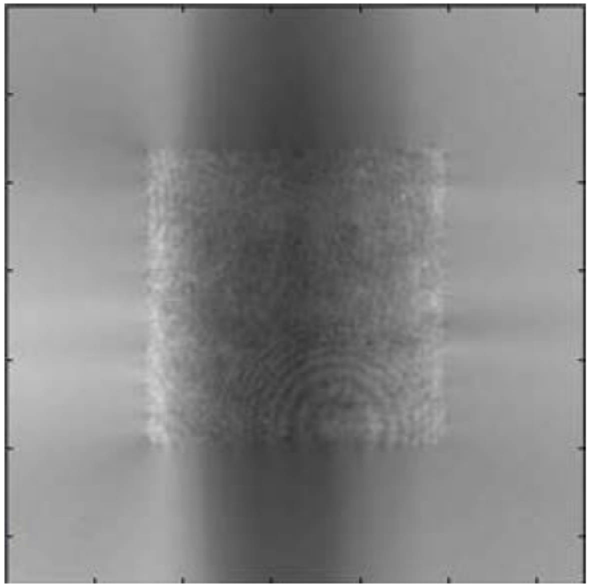
Beams could shift slightly during operation; it is essential that this is handled robustly.

Solution: Extend the control matrix from slightly inside the beam ROI using Telea inpainting algorithm*:

Starting matrix



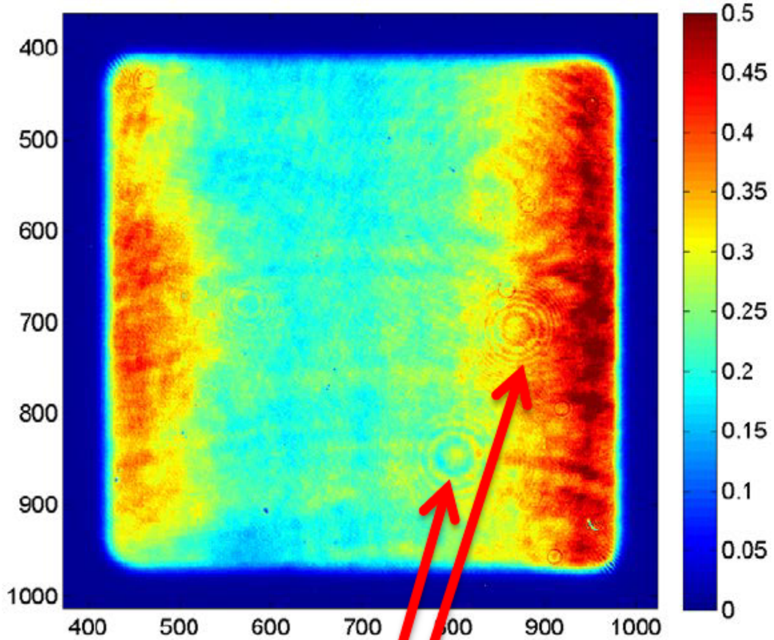
Extended using inpainting



* A. Telea, Journal of Graphics Tools, Vol. 9, No. 1: 25—36, 2003

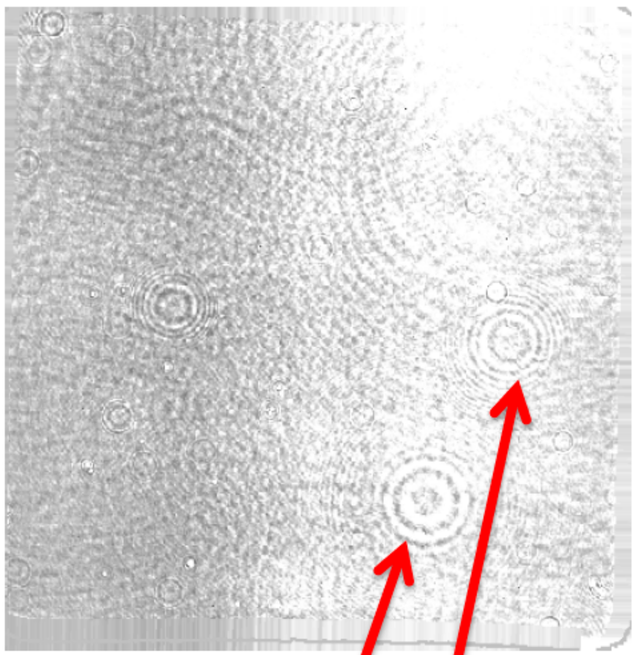
The algorithm will compensate for stray defects on the ISP

ISP-NF Image



Measurement artifacts

LCoS control matrix

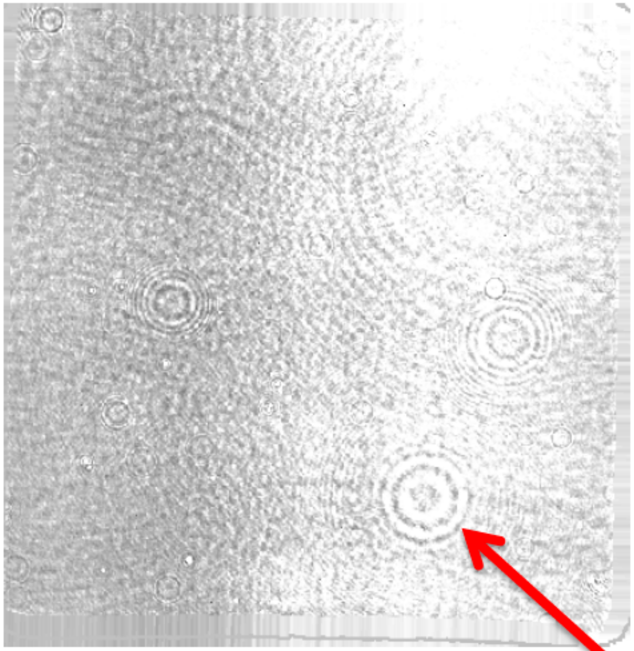


Artifacts will be imprinted on actual beam!

Need a solution to ignore these artifacts

Artifact mitigation: Low-pass filter LCoS image

LCoS output Image

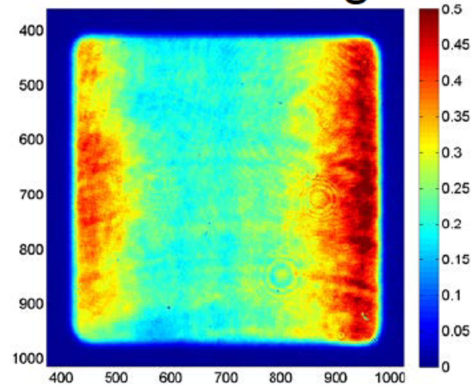


LCoS output Image w/ LPF

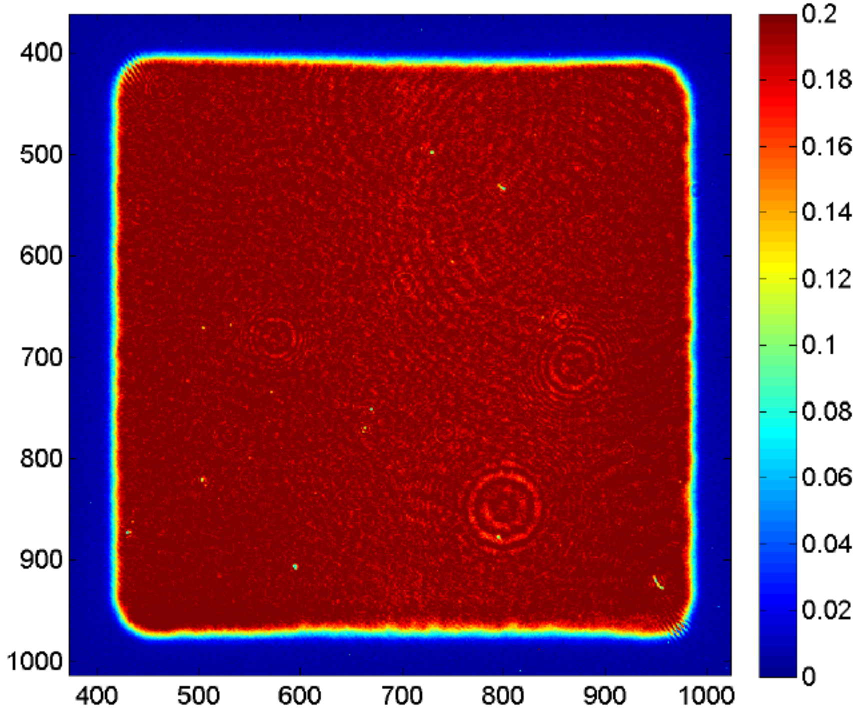
Artifacts smeared out!

Artifact mitigation: Filtering effects on final beam

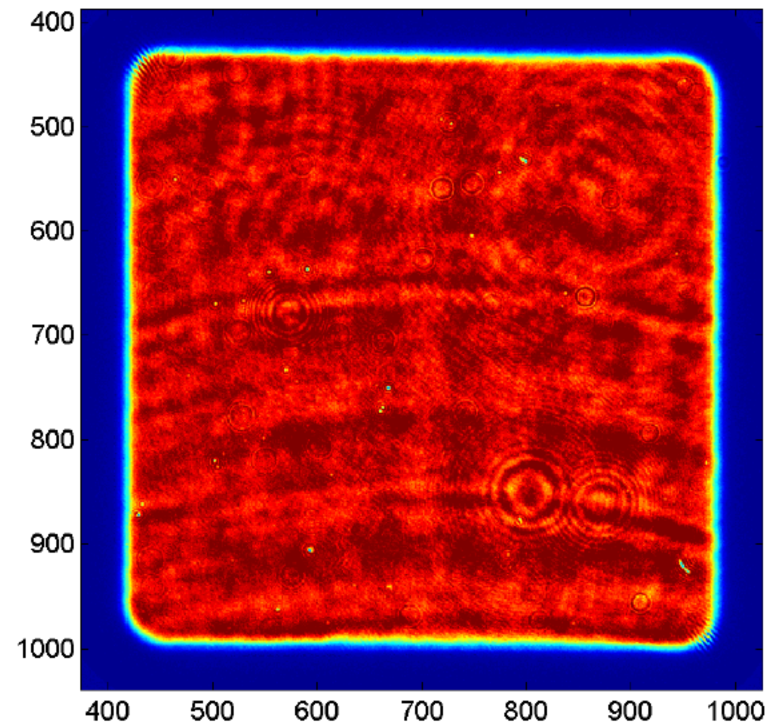
ISP-NF Image



ISP-NF w/ unfiltered LCoS



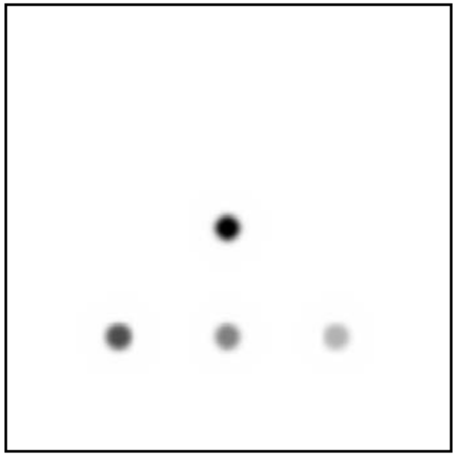
ISP-NF w/ filtered (6 cm LPF) LCoS



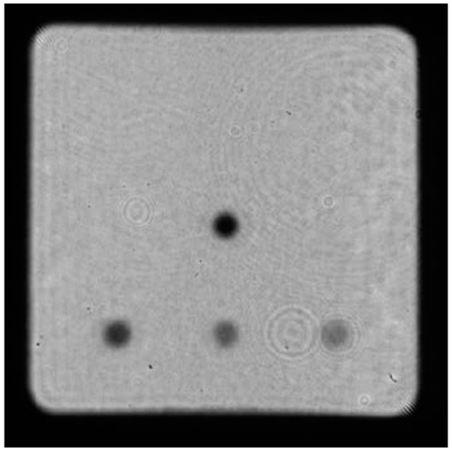
Blockers; control algorithm & registering to the square

Specified blocker transmission

Control algorithm targets a specific transmission rather than specific ISP shape for blockers:



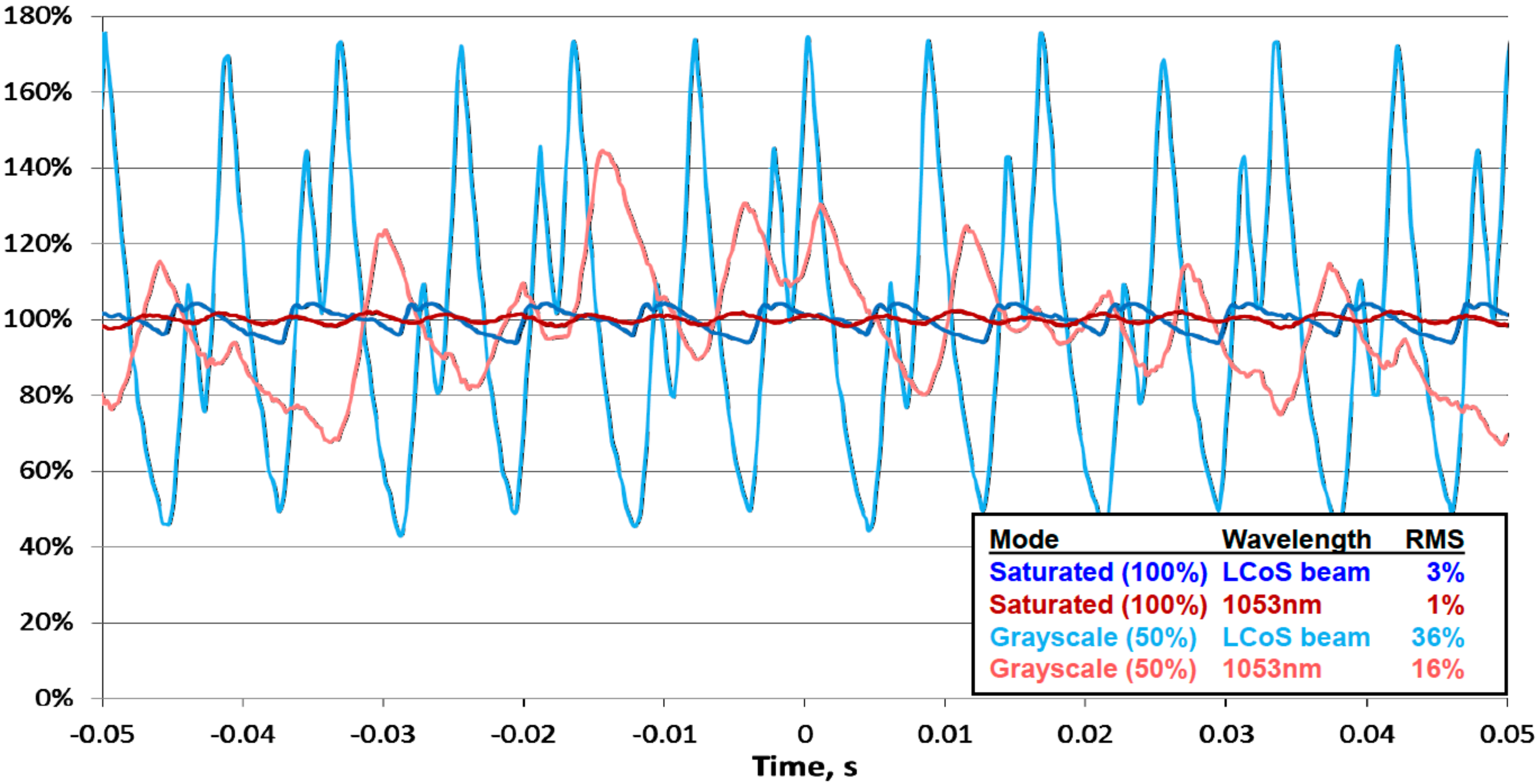
Resulting ISP image:



$$\mathbf{Control_{n+1}} = \mathbf{Control_{n}}\left(\frac{\mathbf{Requested\ Transmission}}{\mathbf{Measured/initial\_beam}}\right)^{g\sim 0.3}$$

- The control matrix is only modified on pixels where blockers are present.
- This allows for low-frequency shaping and blockers to be run in separate loops with different filtering levels.

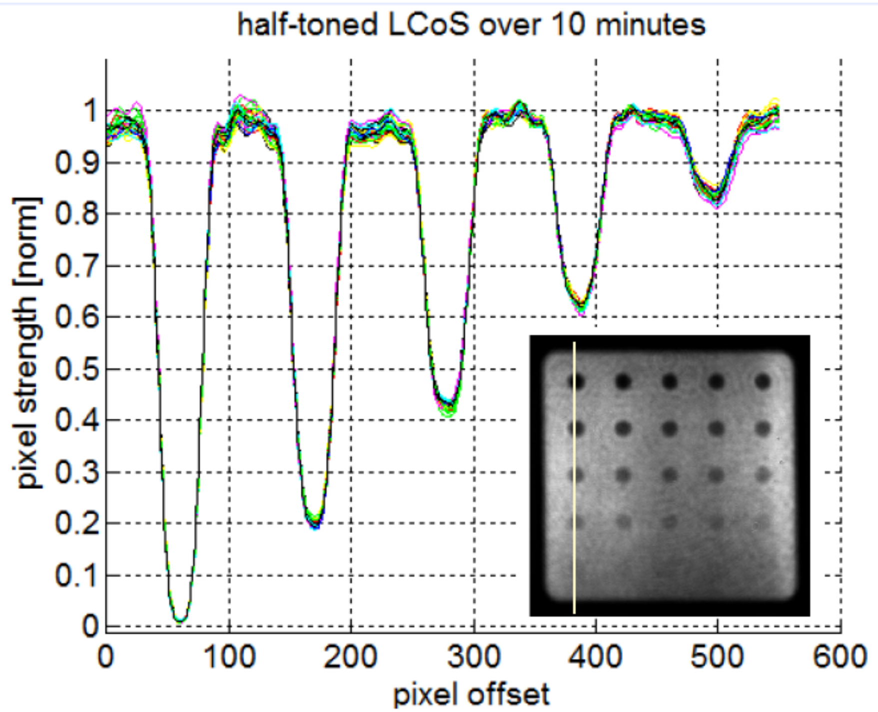
Flicker inherent in LCoS can result in unstable control mask

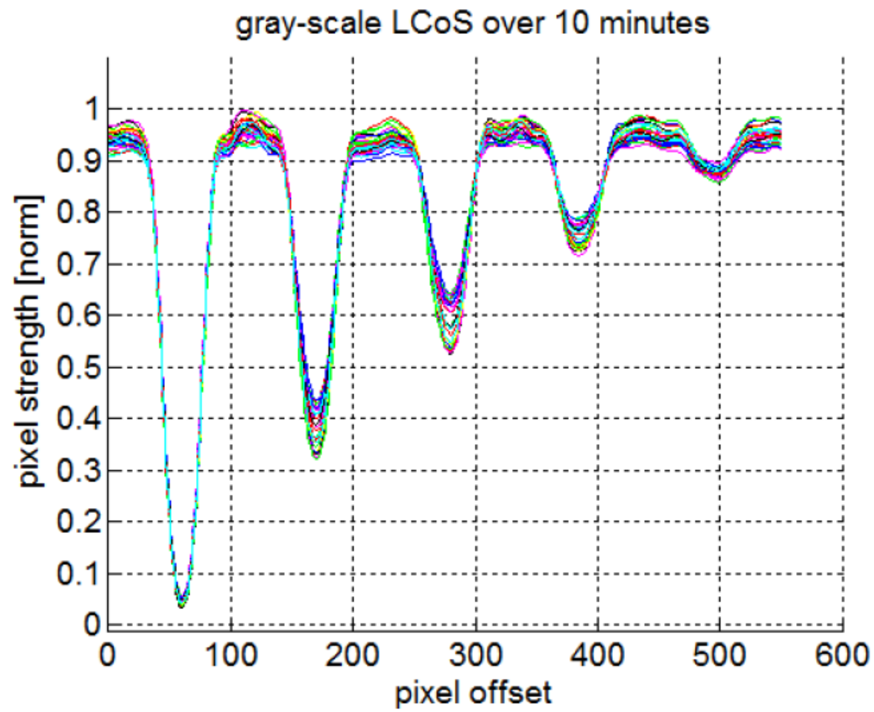


Conclusions:

- The PSS is stable to ~1% when saturated (at 100% = 255)
- At intermediate values, the digital modulation (flicker) of the LCoS is unacceptable

First demonstration of halftone-generated gray blockers in Laser Bay (Q12T) using laptop





For gray blockers, halftoning reduces instability from ~10% to ~2%

“De-glowing” the camera images

Symptom:

There are *two superimposed* copies of the image on the ccd (Actual + Blurred)

Recording, Actual, Blurred

$$r = \underbrace{(1-\varepsilon)}_{95\%}\,\mathrm{a} + \underbrace{\varepsilon}_{5\%}\,\mathrm{b}$$

Hypothesis:

- Silicon ccd is poor absorber at 1053nm
- Leads to double-bounce (blurry) ghost

Blur function

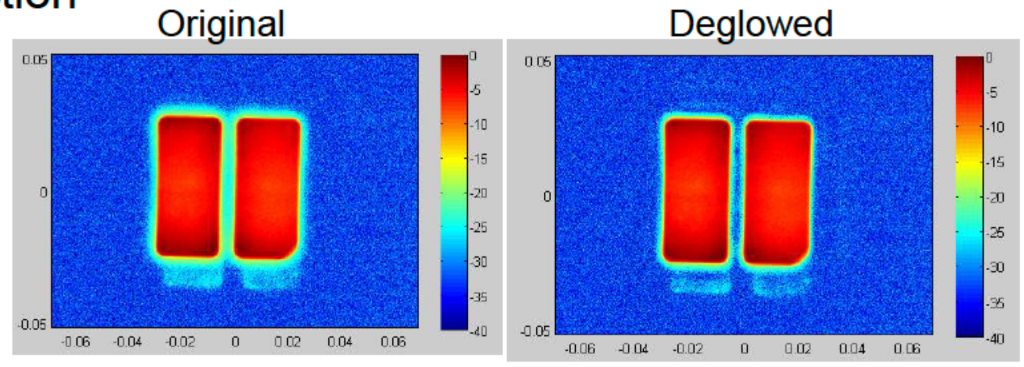
$$\mathrm{b} = \mathrm{h}(x,y) * \mathrm{a}(x,y)$$

$$\mathrm{A} = \frac{\mathrm{R}}{(1-\varepsilon) + \varepsilon\,\mathrm{H}(f_x, f_y)}$$

Transfer function

Solution:

- Empirically determine the form of the blur function (Gaussian)
- Deconvolve the recording with its transfer function

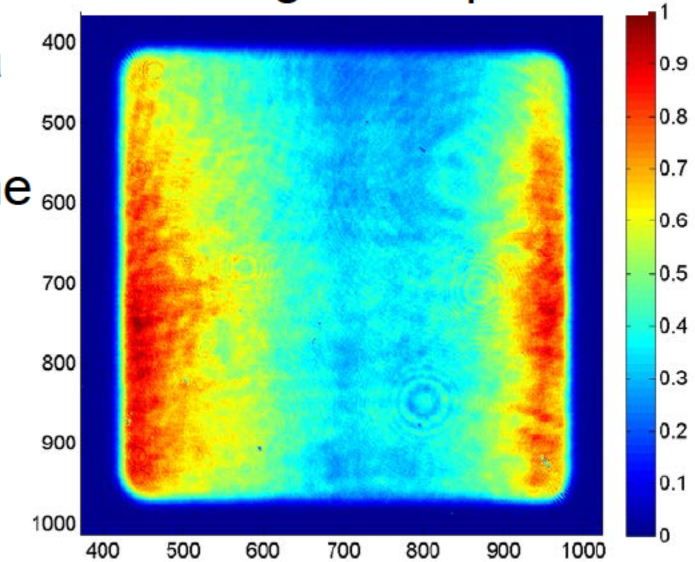


This post-processing step can correct the ISP cameras

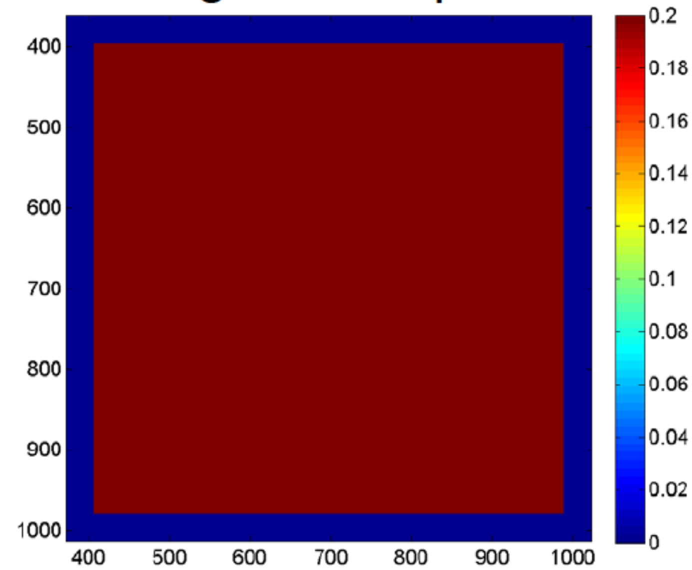
Experimental results (tested in offline front-end replica)

Targeting a flat beam profile at the ISP:

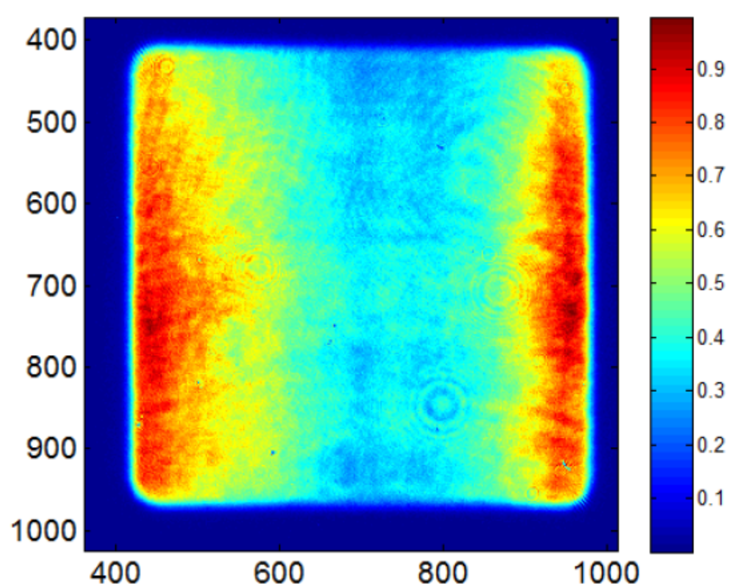
Starting beam profile

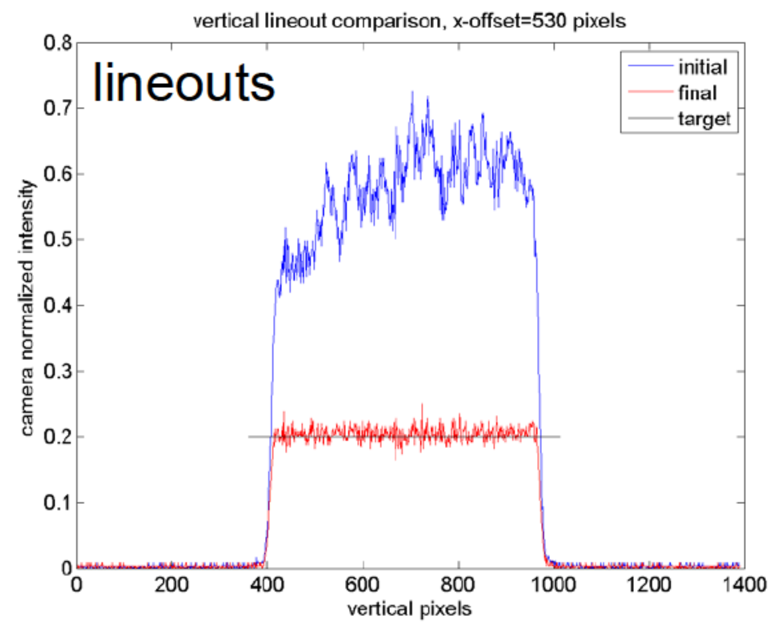


Target beam profile



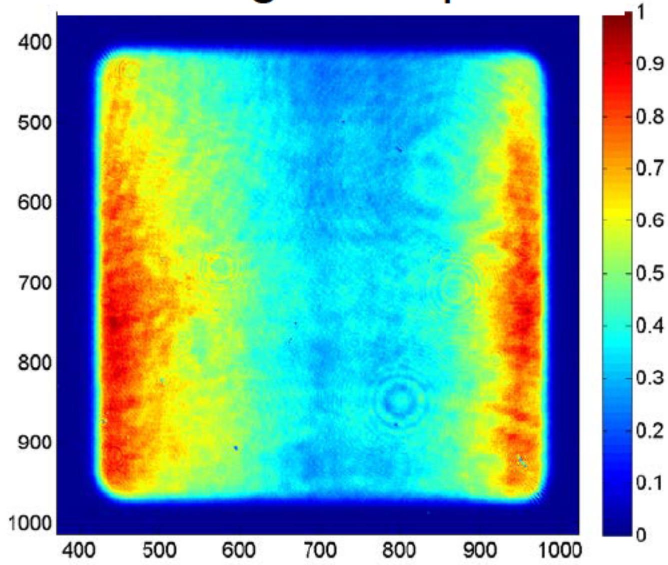
Final beam profile



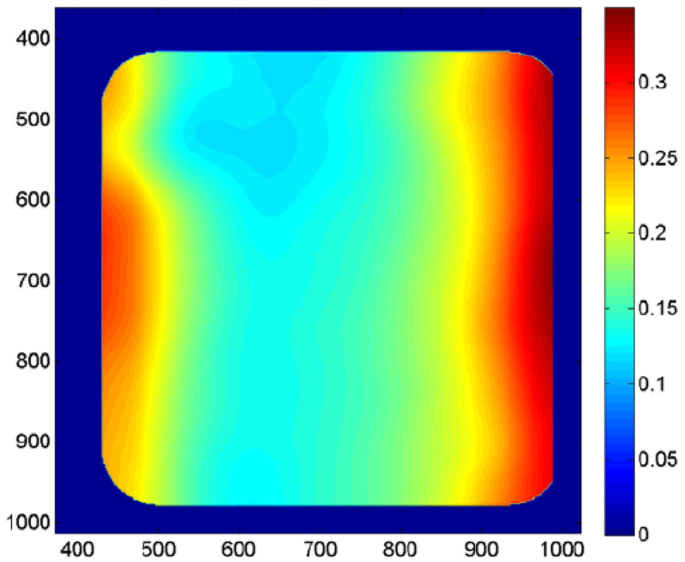


Targeting a flat-profile at Final Optics Assembly

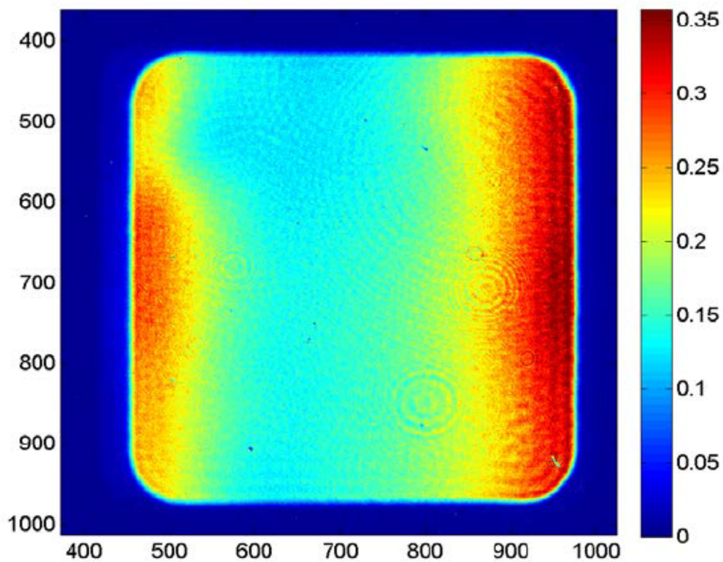
Starting beam profile

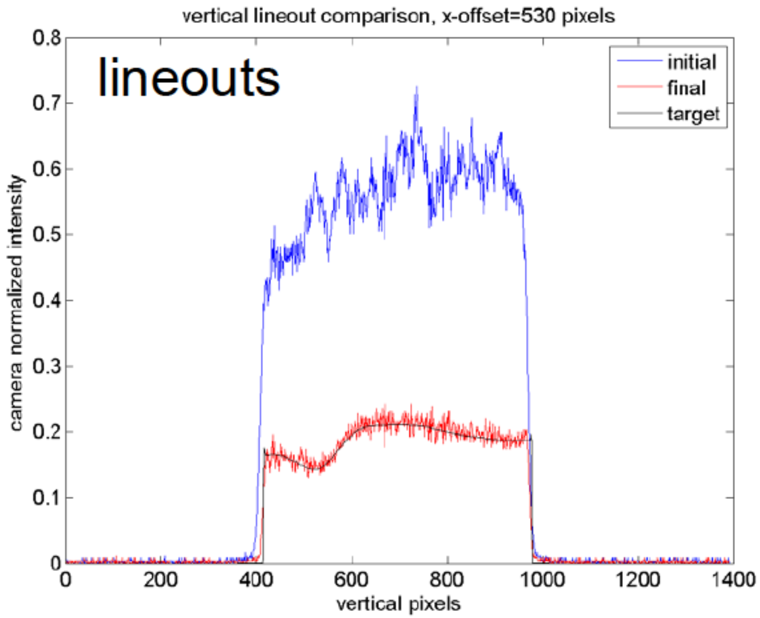


Target beam profile



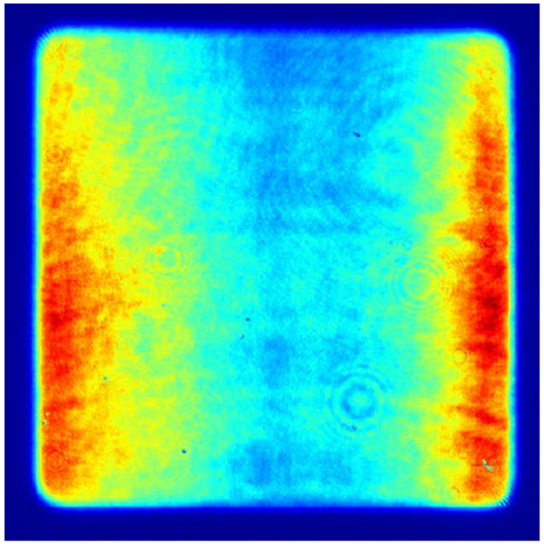
Final beam profile



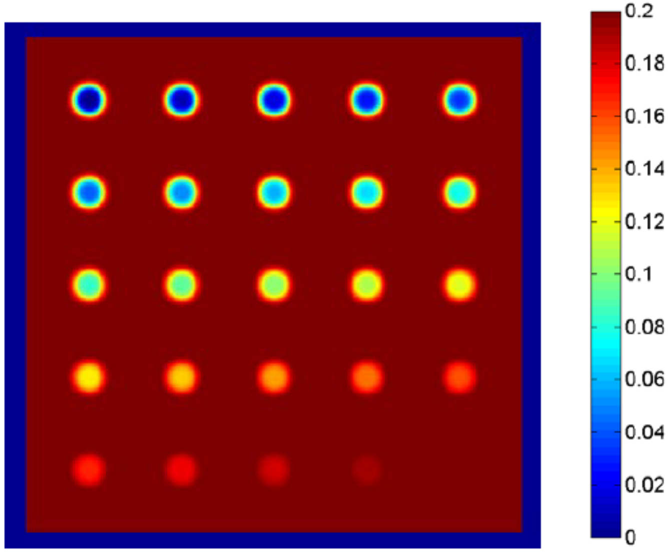


Demonstration of Arbitrary Beamshaping + Gray blockers

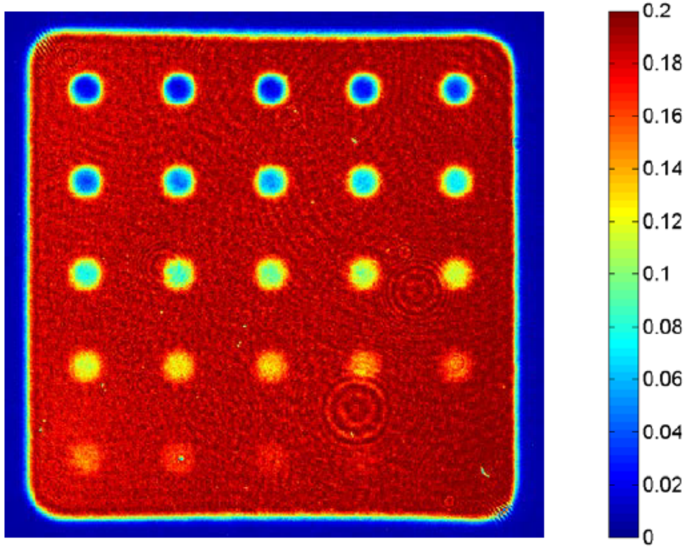
Starting PAM Beam Profile

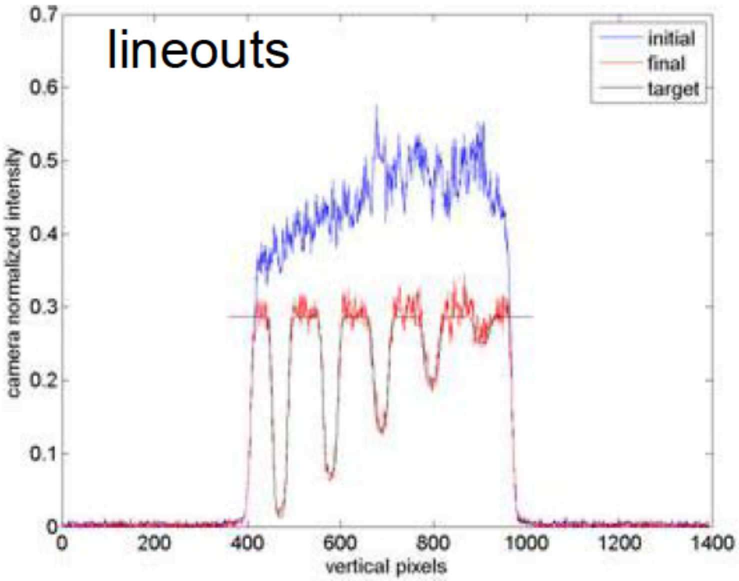


Requested Shape at ISP



Achieved Beam Profile at ISP





Summary

- **Our team developed a control system in C++ (using OpenCV) for NIF that improves on the existing blockers (allows for gray blockers) and adds arbitrary beam shaping.**
- **The software is robust to imperfect alignment and measurement artifacts.**
- **We developed solutions to hardware imperfections (nonlinearity and instability).**
- **The code is currently in the process of being integrated with the existing control software (ICCS).**
- **The ability to tailor the beam profile will enable NIF to operate at higher energies than originally specified.**