An extended-source grating spectrograph for rockets and small satellites

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AXRO

Objective

- Use high-efficiency X-ray gratings to enable higher-resolution spectroscopy of extended sources
  - Supernova remnants
  - Enhancements in the soft-X-ray background (SXRB)
  - SXRB and galactic halo
- First with a sounding rocket instrument
  - Funded through 2022 for design and first launch (Cygnus Loop supernova remnant)
  - Proposing for more NASA funding for additional launches in 2024 and 2026
- Convert instrument to orbital format for new observations of the SXRB
  - $R \approx 100$

The Rockets for Extended-source X-ray Spectroscopy (tREXS)

- Soft X-ray grating spectrograph
  - First observation target: Cygnus Loop supernova remnant
  - ≈10 sq. deg. FOV
  - Spectral resolving power ≈ 40 – 60
  - Primary sensitivity from ≈0.3 – 0.8 keV (≈15 – 40 Å)
  - Optimized for O-VII, O-VIII, N-VI, and C-VI emission

Nahks Tr'Ehnl

tREXS

- Specifications:
  - ≈10 sq. deg. FOV
  - Spectral resolving power ≈ 40 – 60
  - Primary sensitivity from ≈0.3 – 0.8 keV (≈15 – 40 Å)
  - Optimized for O-VII, O-VIII, N-VI, and C-VI emission
- Instrument components:
  - Mechanical beam-shaper modules
  - X-ray reflection gratings
  - Focal plane camera

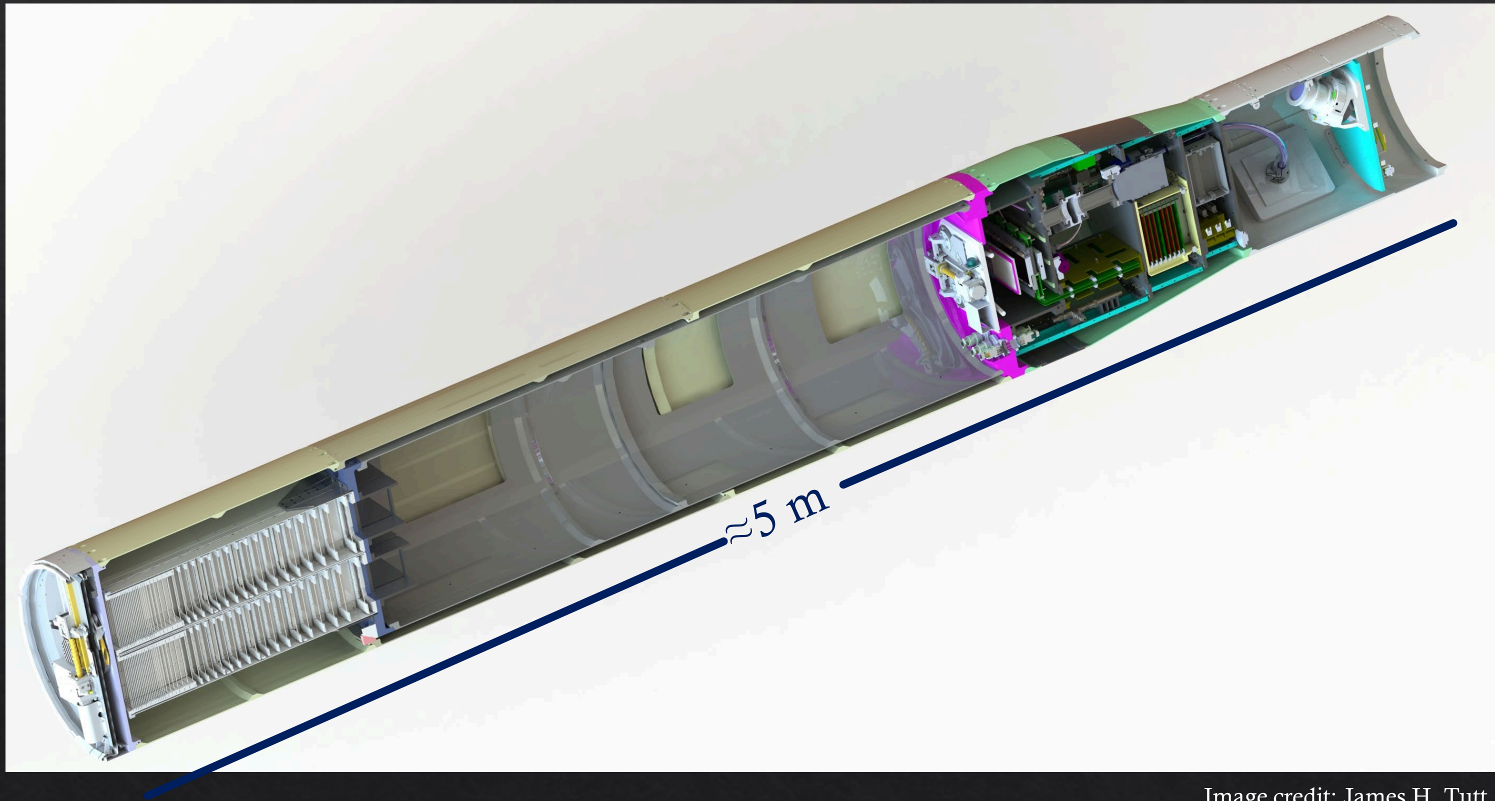
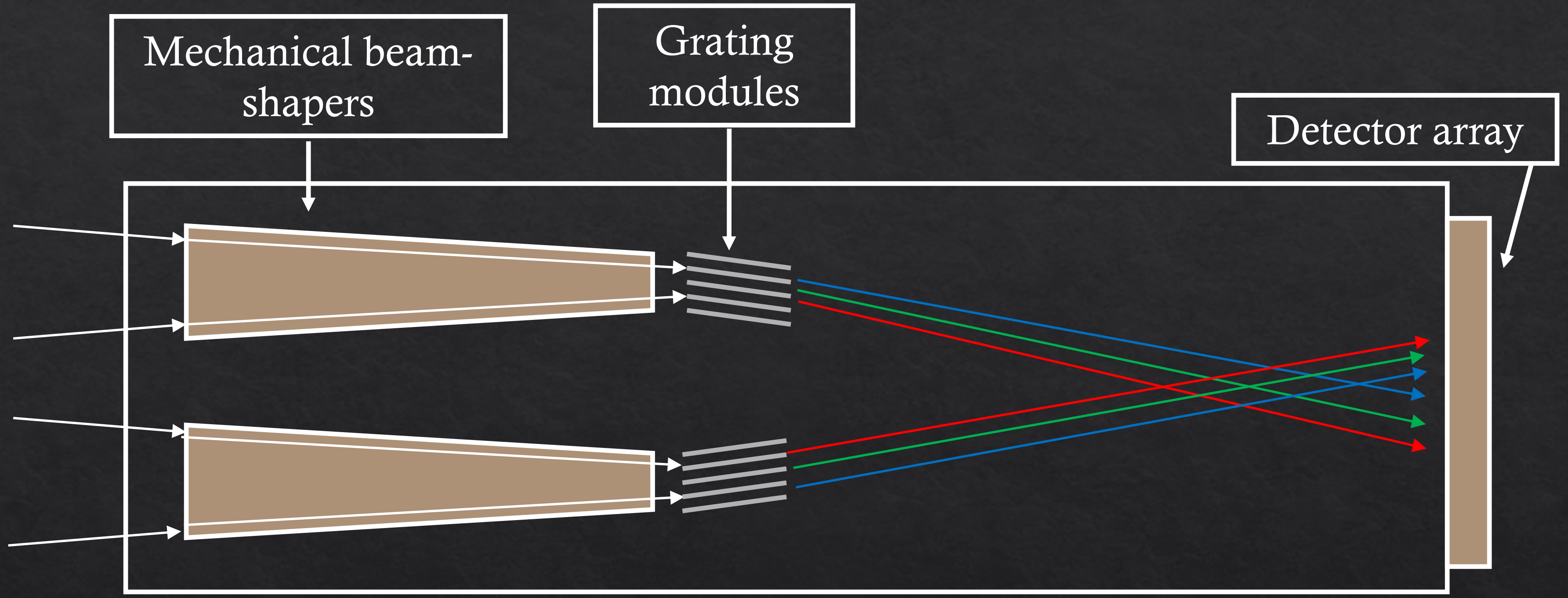
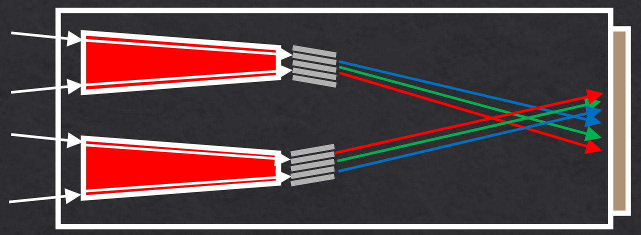


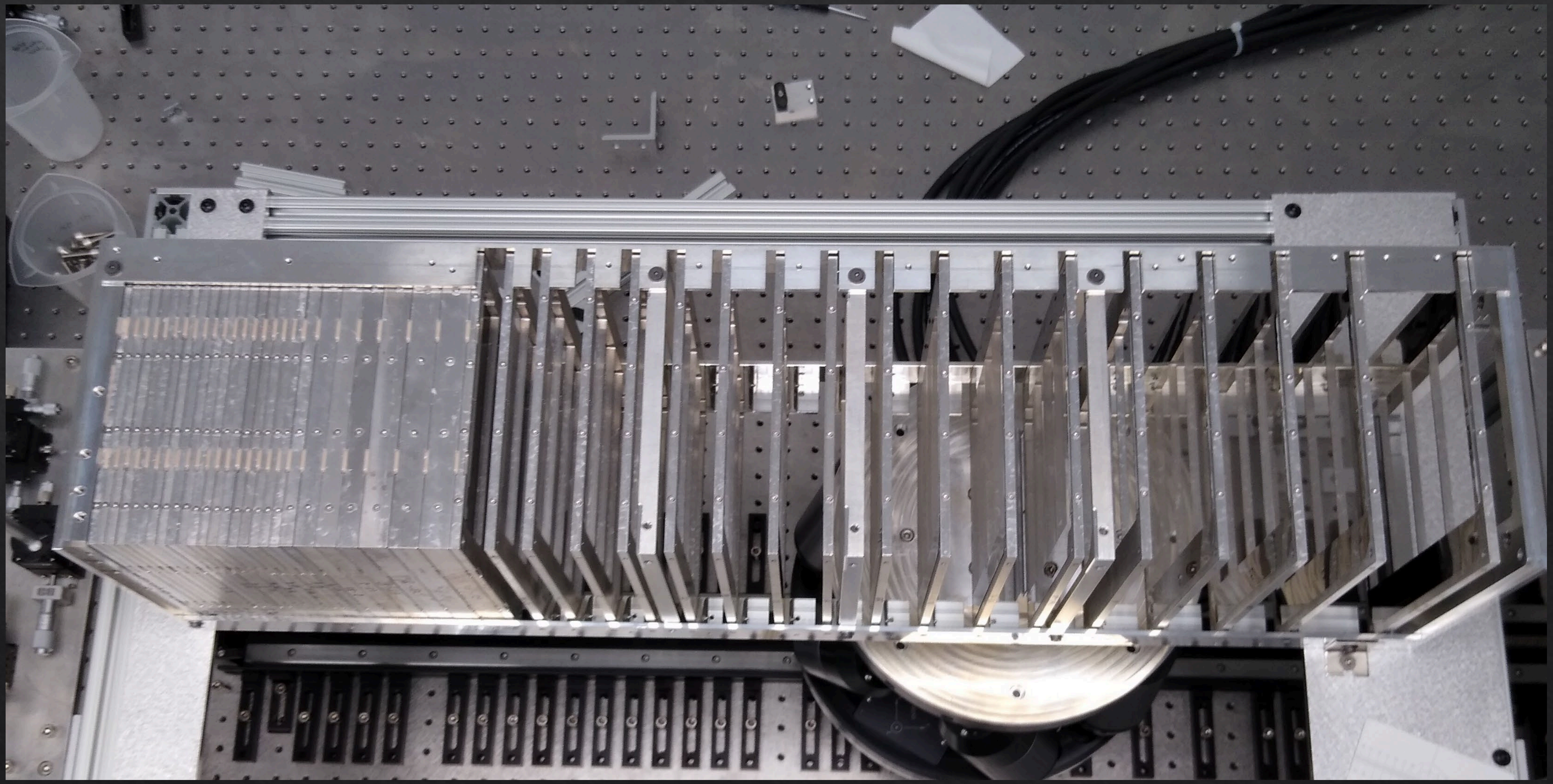
Image credit: James H. Tutt


Mechanical beam-shapers
Grating modules
Detector array

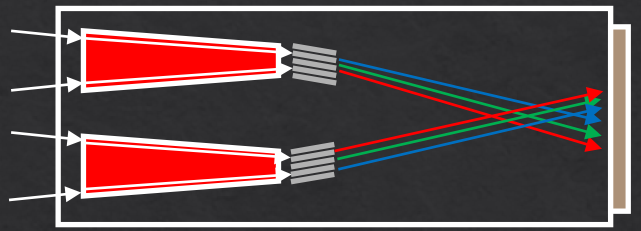


Mechanical beam shapers (MBS)

- Passively sculpt incident light to produce 1D converging beam
- Allows for large FOV (>10 deg^2) and ≈2-3’ LSF
- tREXS:
  - 700-mm long module
  - 45 plates/module
  - 2010-mm focal length



700 mm



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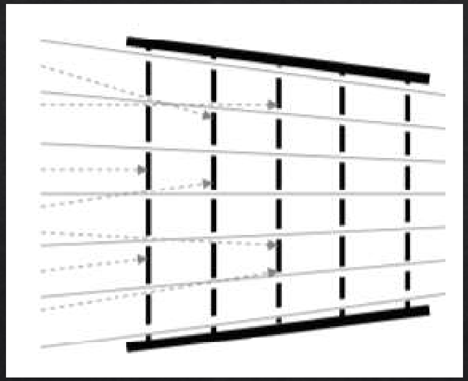
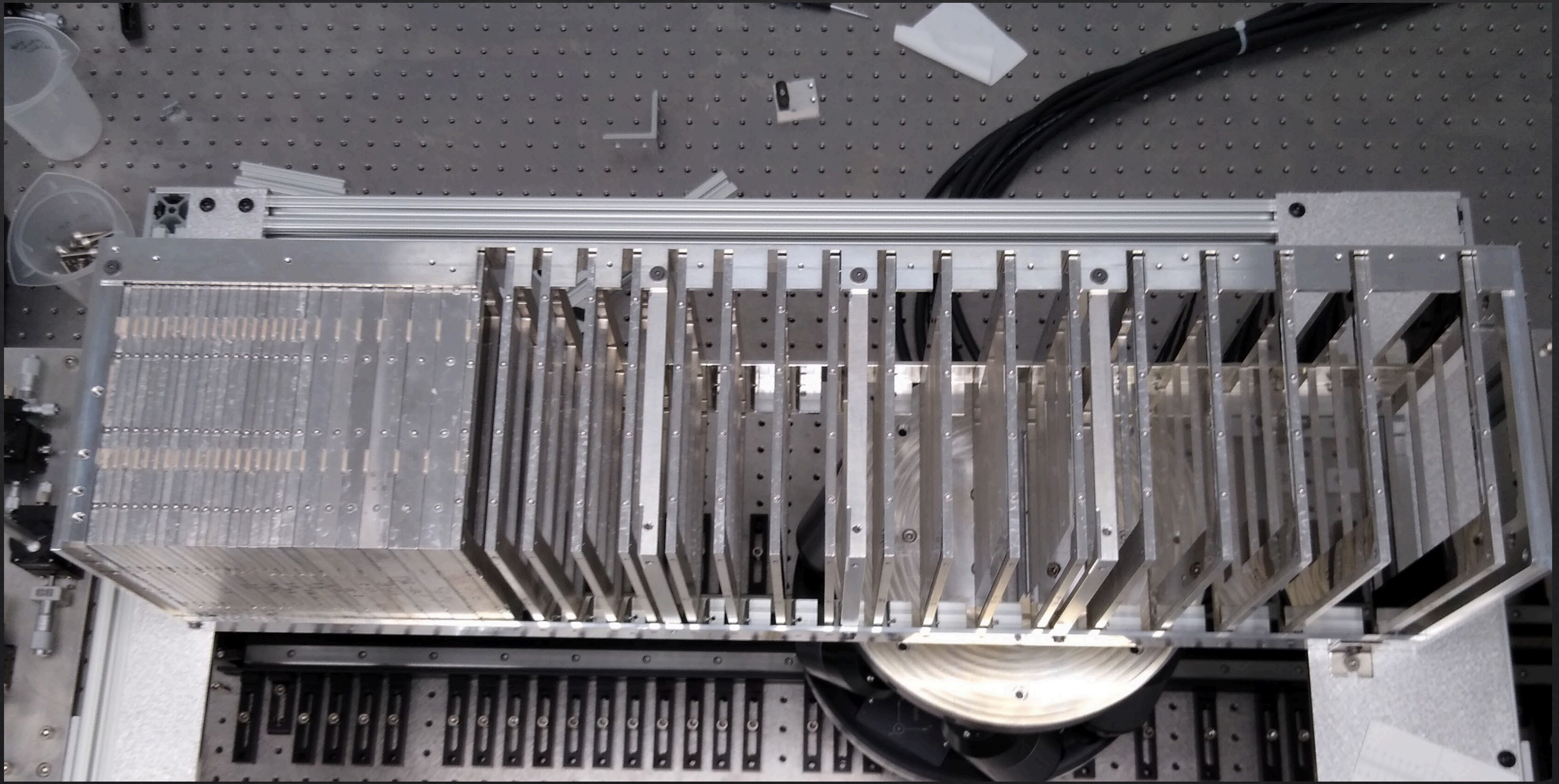
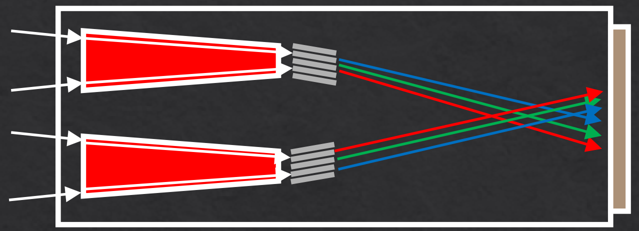


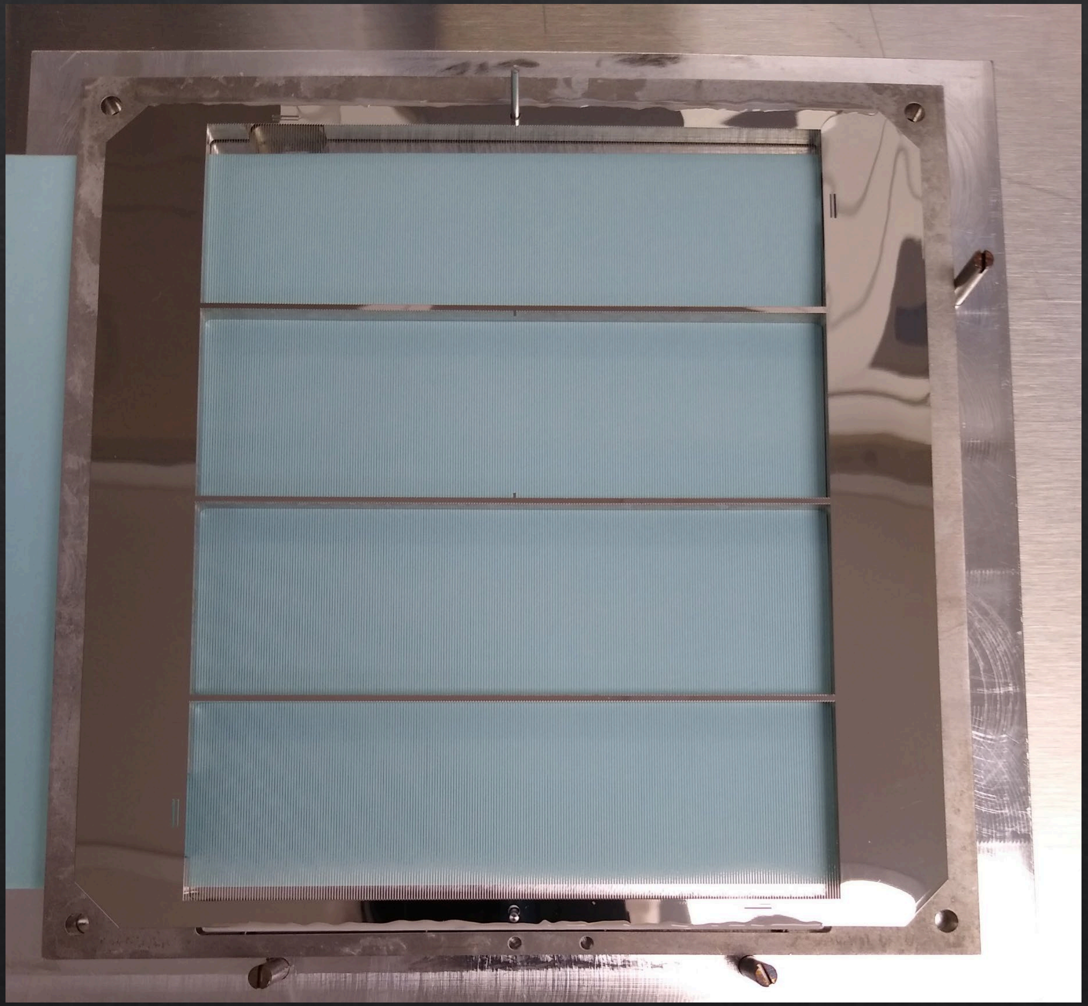
McEntaffer et al. (2007)

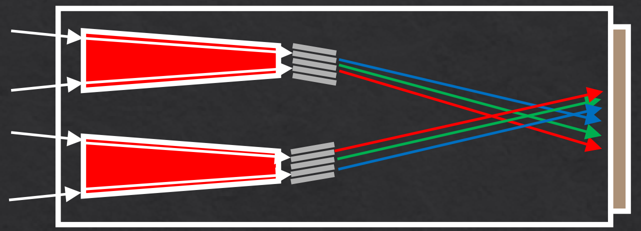


700 mm

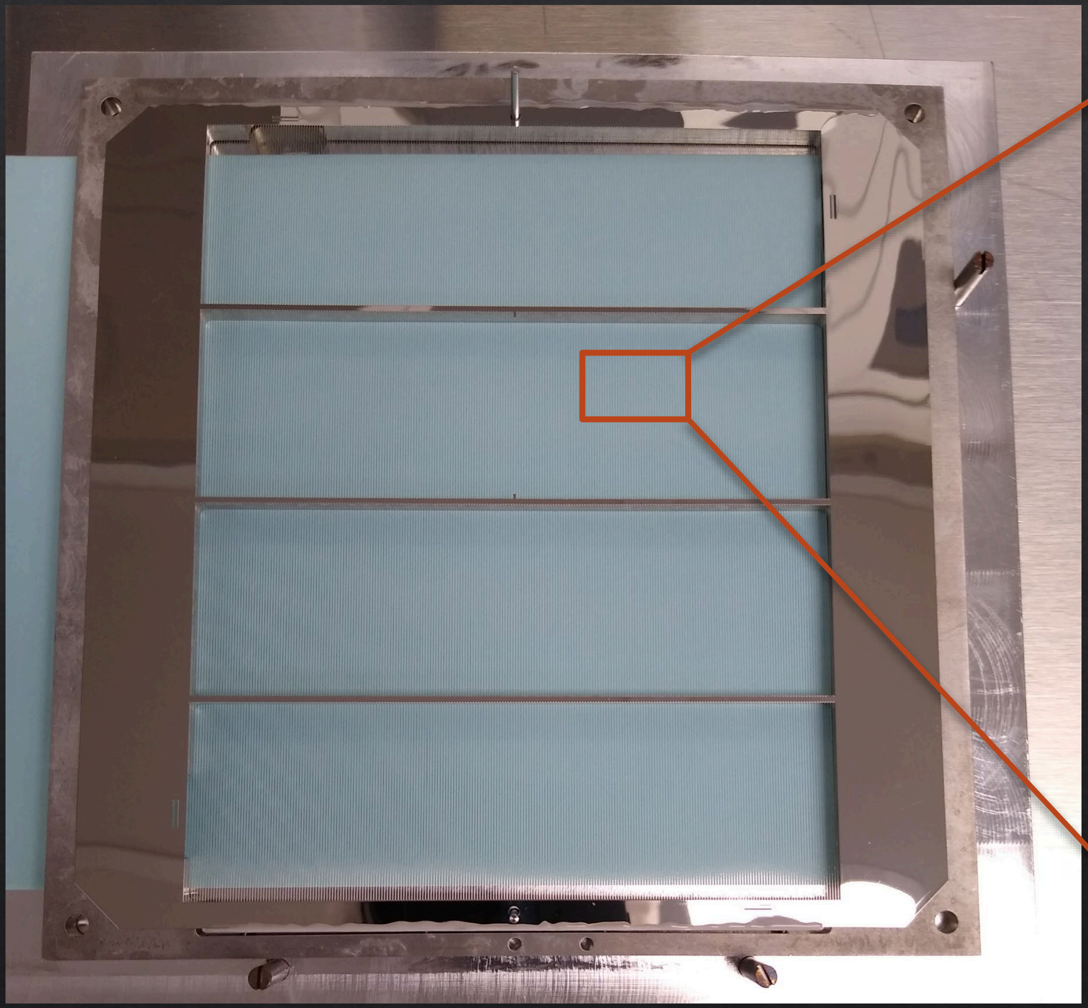
MBS Plates

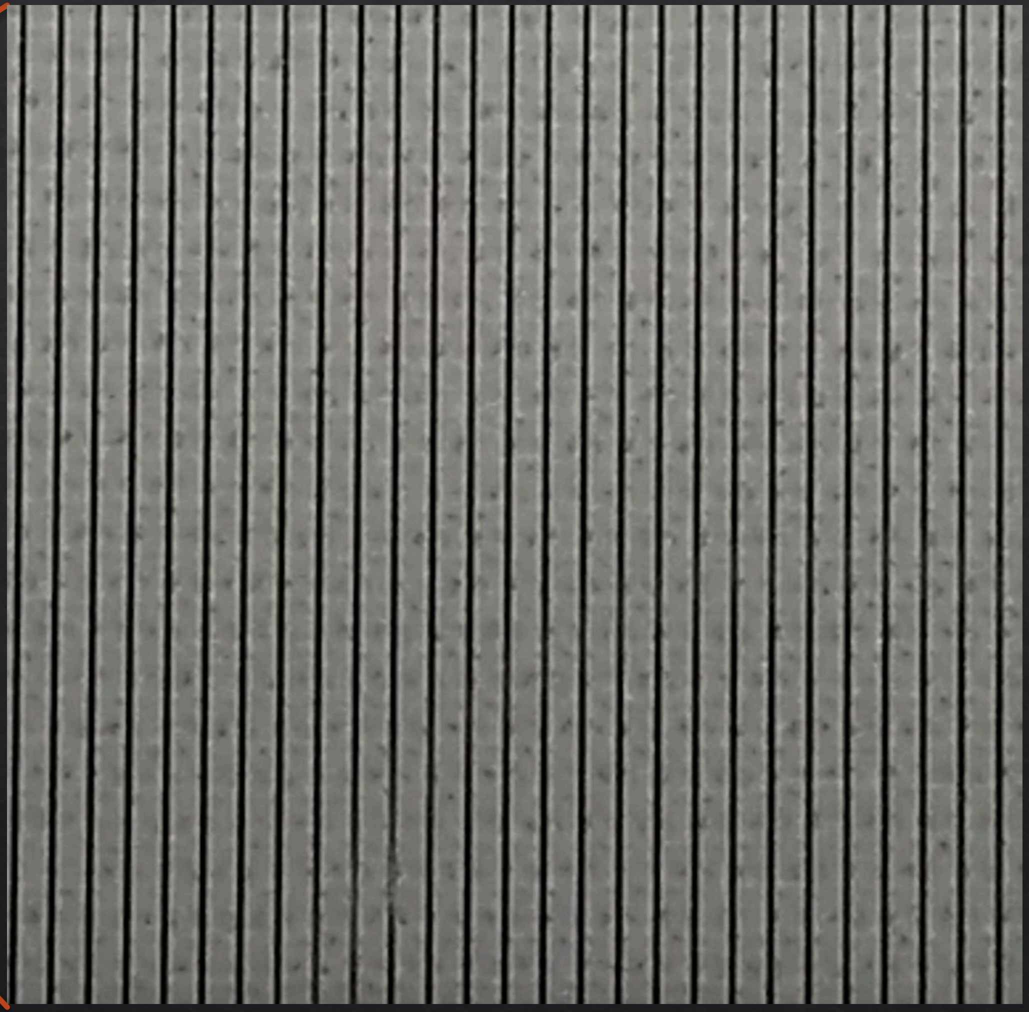






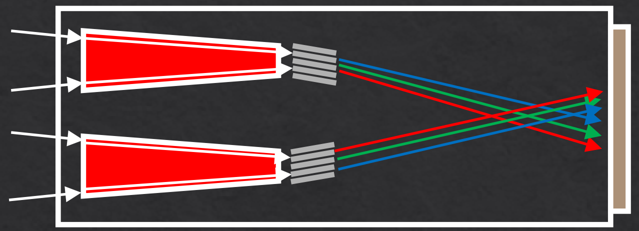
MBS Plates

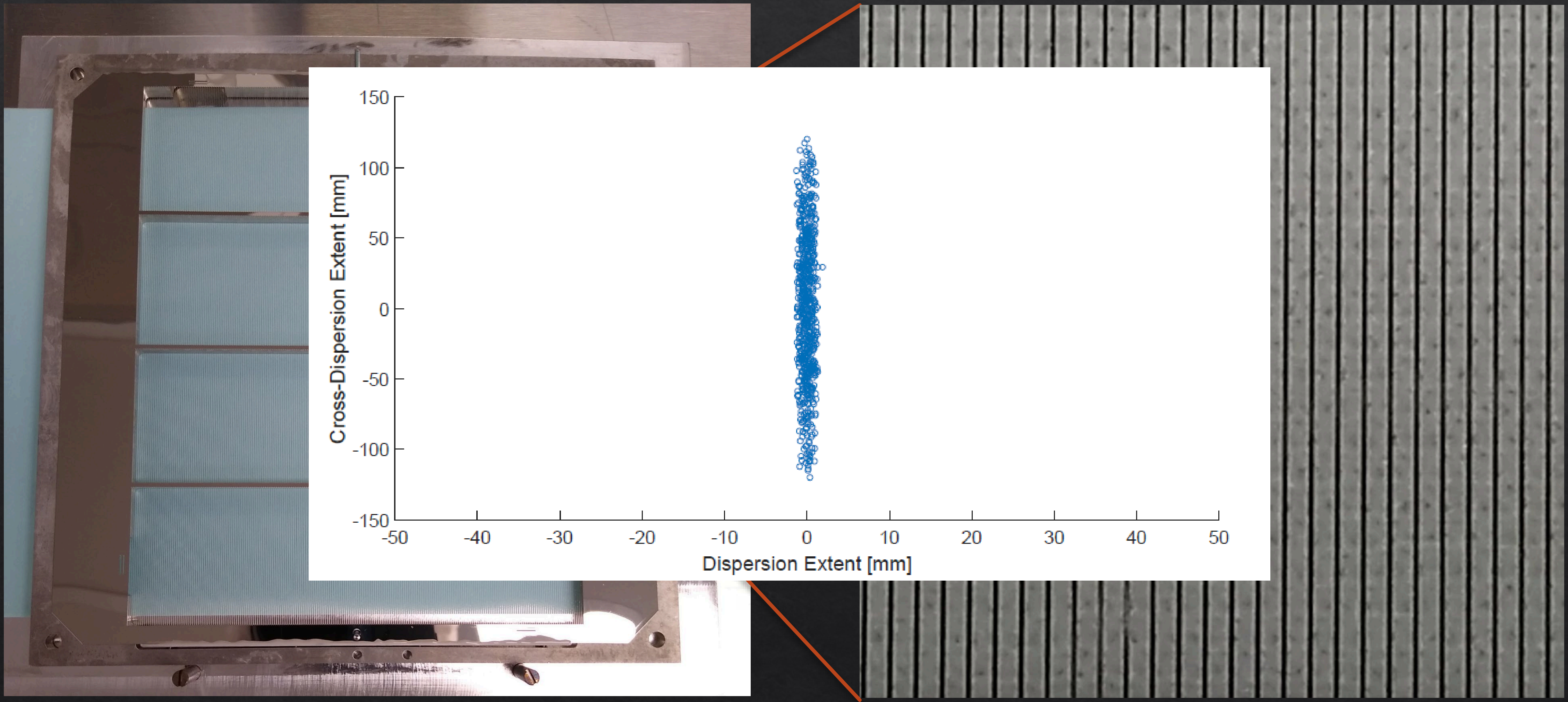




Slit width from 375 – 500 μm; 241 slits/plate; 45 plates

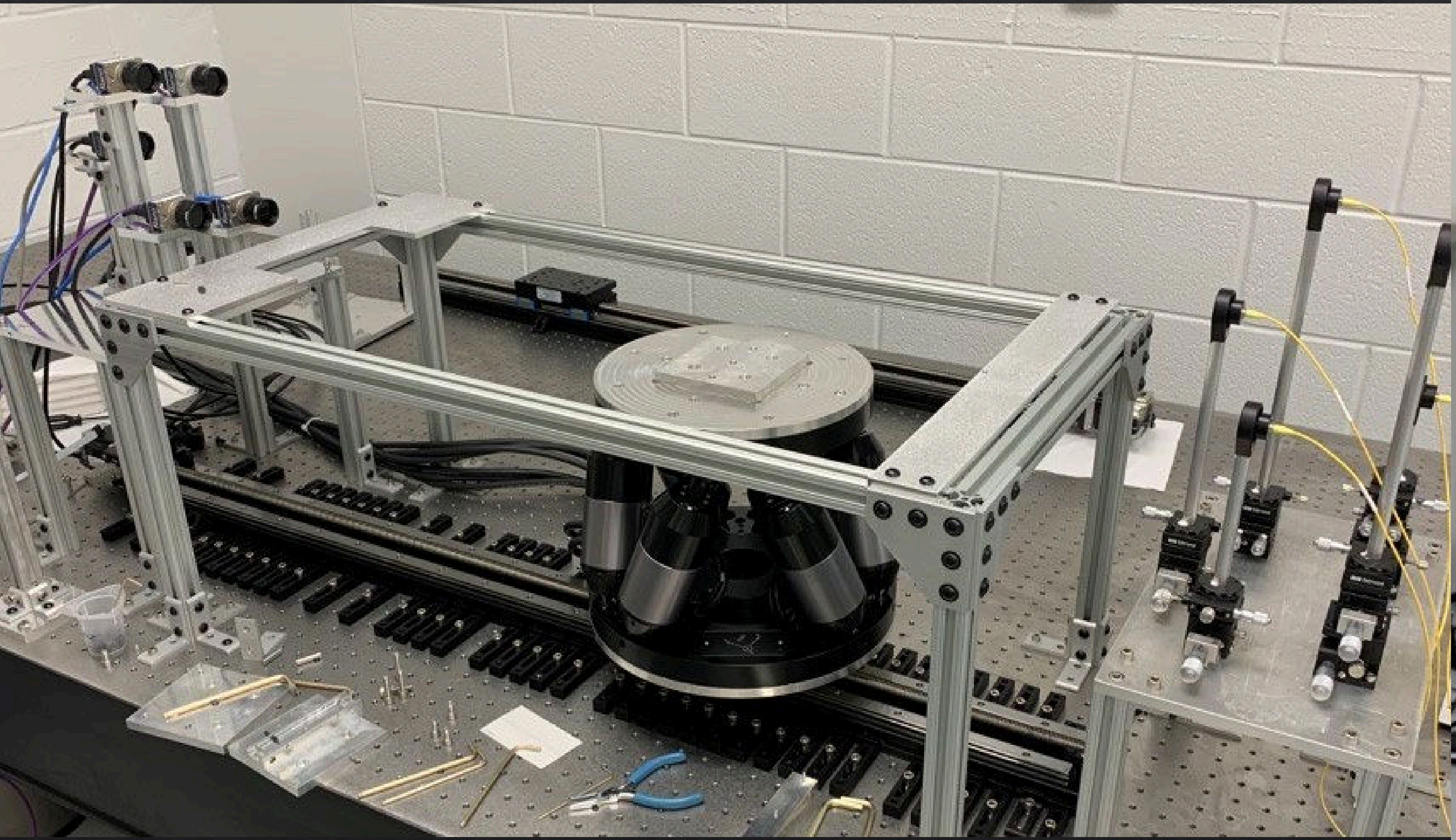
MBS Plates

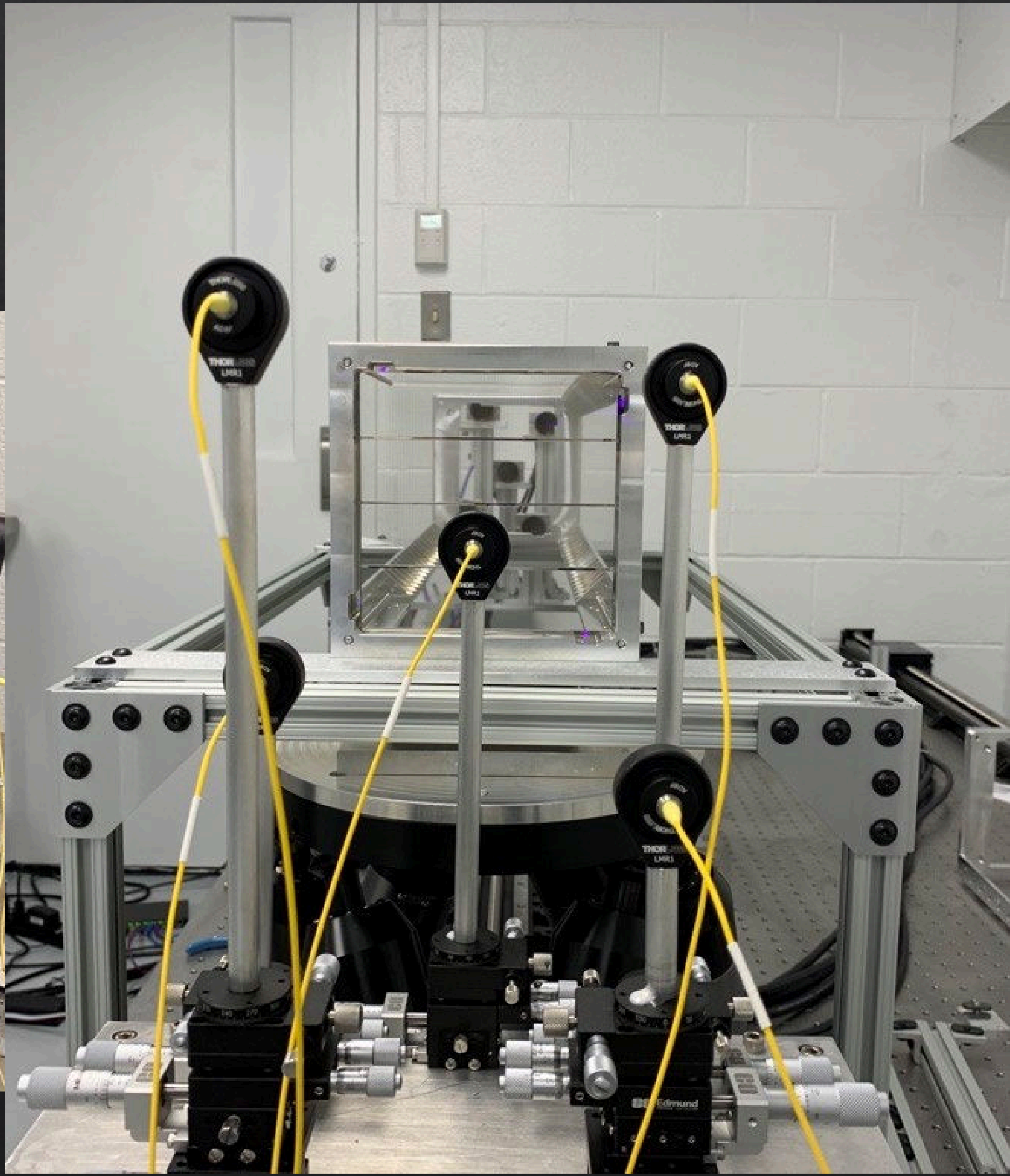




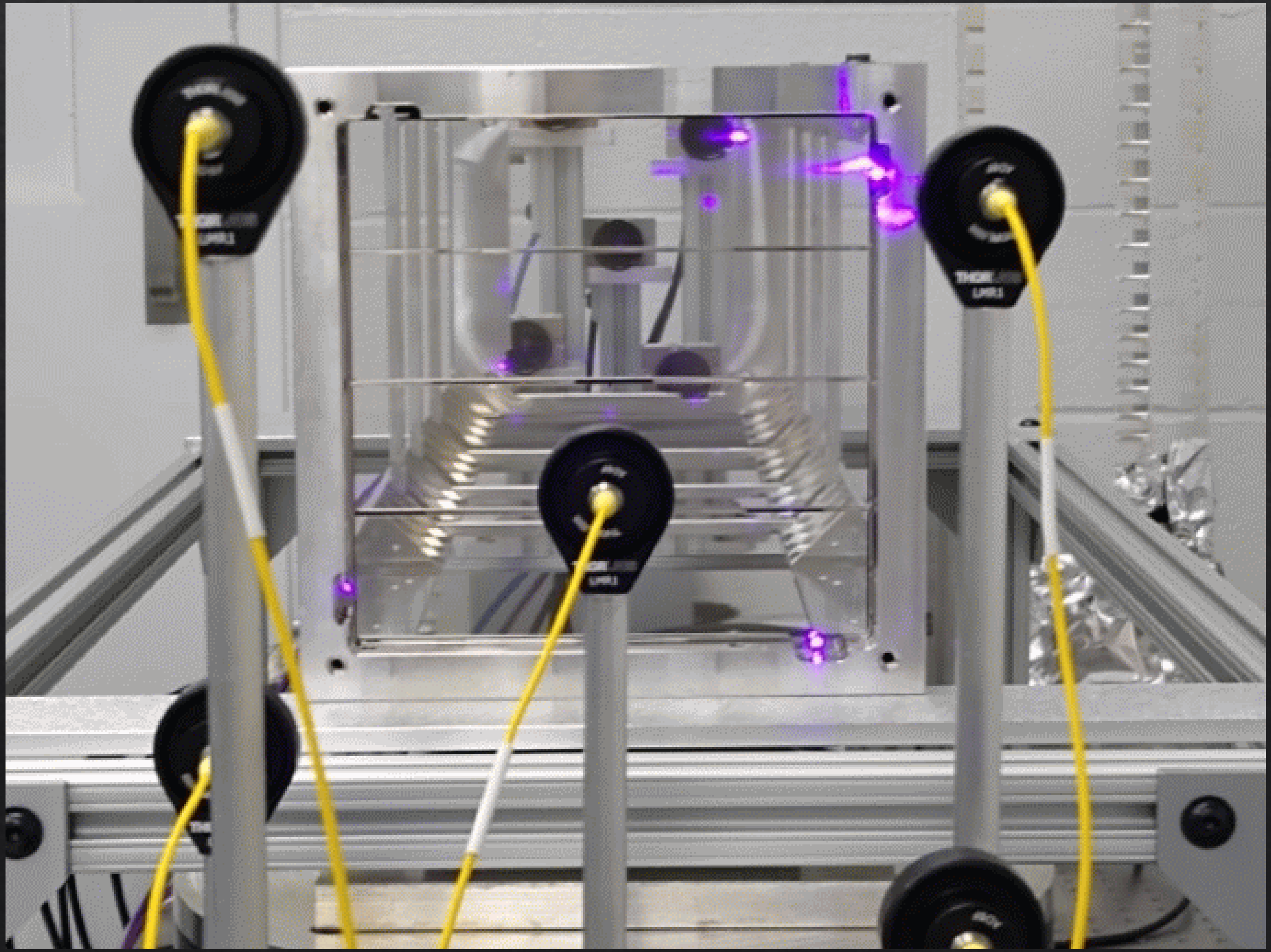
Slit width from 375 – 500 μm; 241 slits/plate; 45 plates

MBS alignment

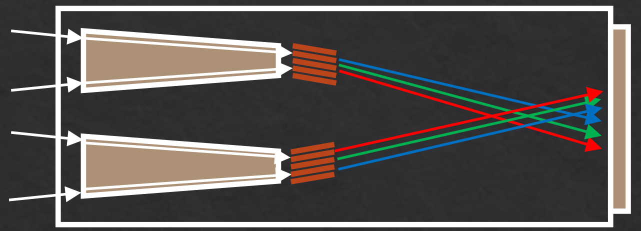




MBS alignment



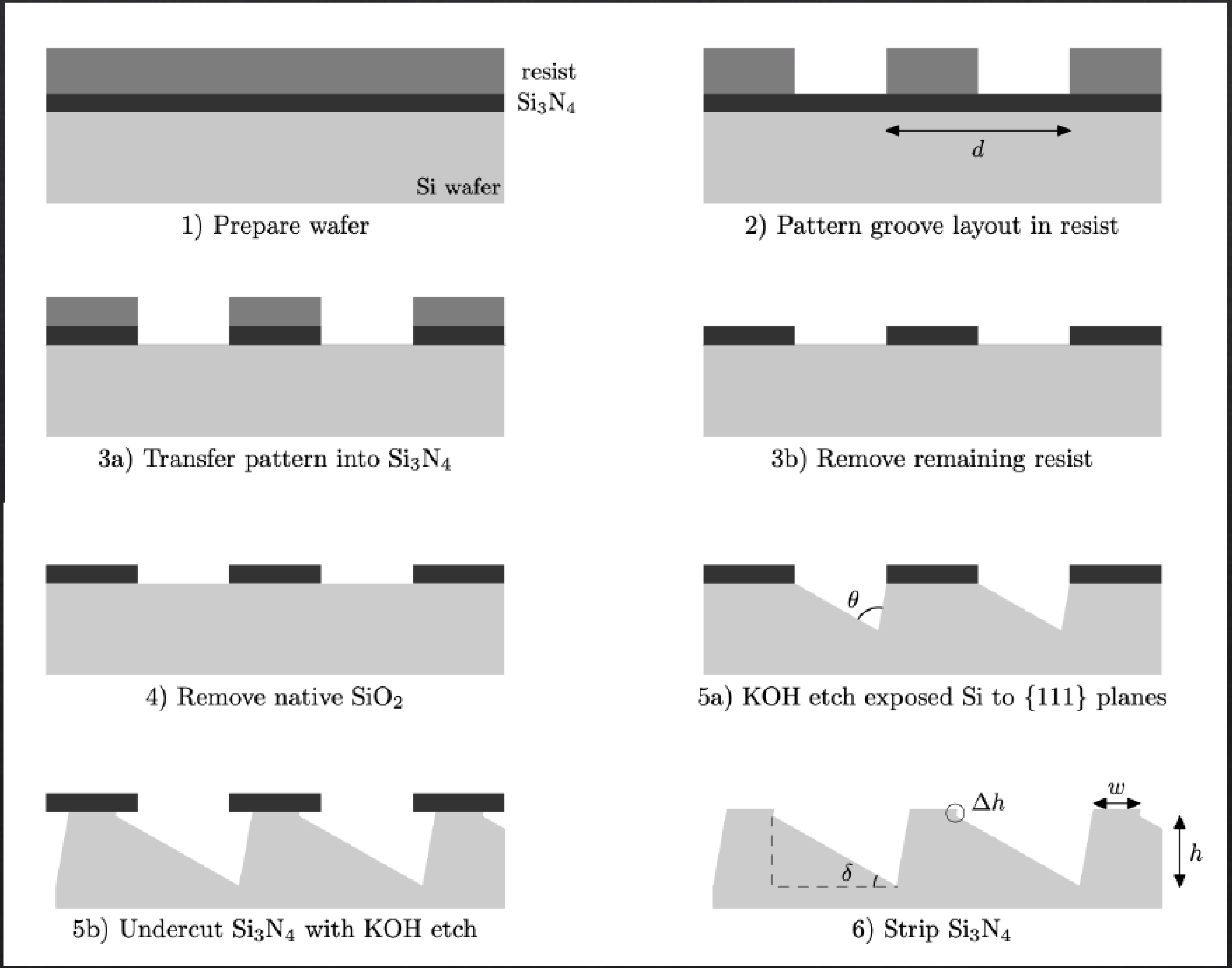
Blazed gratings – KOH etching



- Gratings provide wavelength-dependent dispersion to give spectral resolution
- Shape grating groove to have specific facet angle δ
- Preferentially diffracts light to specific order & wavelength combination:

$$n\lambda = 2d \sin\delta \sin\gamma$$

- tREXS $n\lambda \approx 88$ angstroms



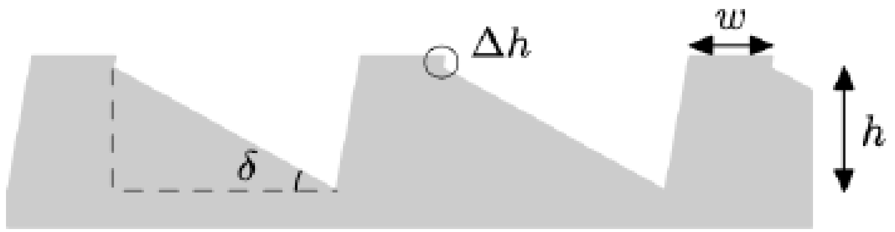
Miles et al. (2018)

Blazed gratings – KOH etching

5a) KOH etch exposed Si to {111} planes

Optimize electron-beam lithography (EBL) exposure, etch temperature, etch duration to produce ideal facets:

5b) Undercut Si_3N_4 with KOH etch



6) Strip Si_3N_4

Groove spacing ≈160 – 180 nm

Depth ≈70 – 90 nm

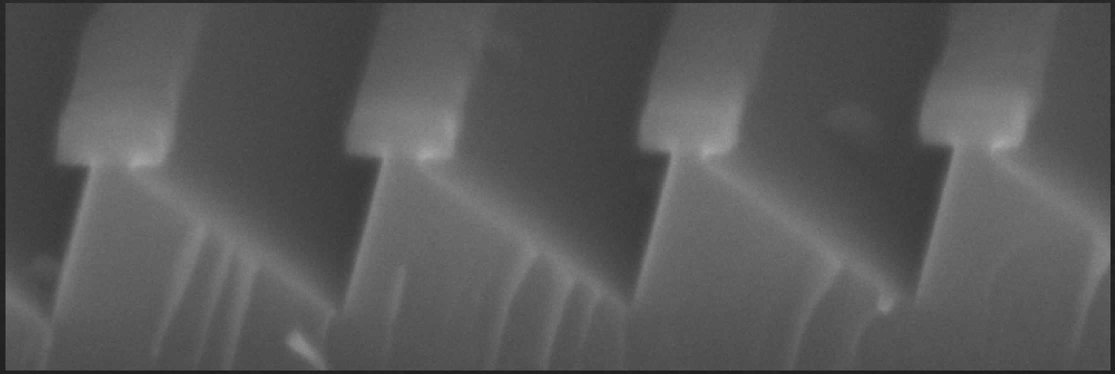
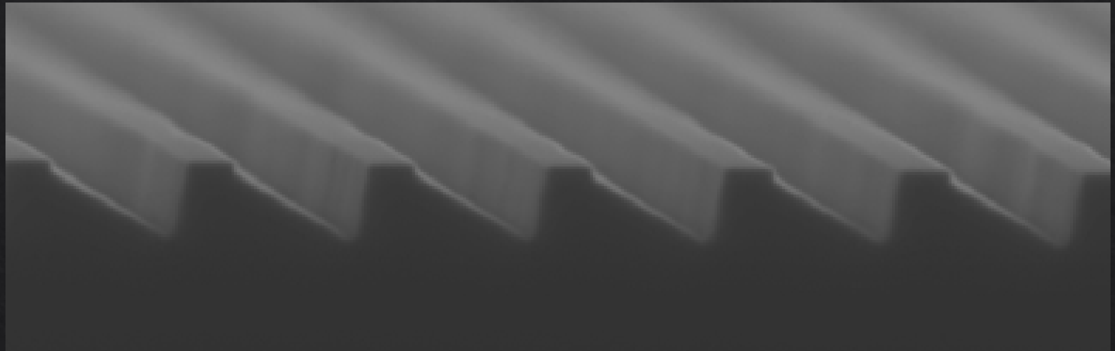


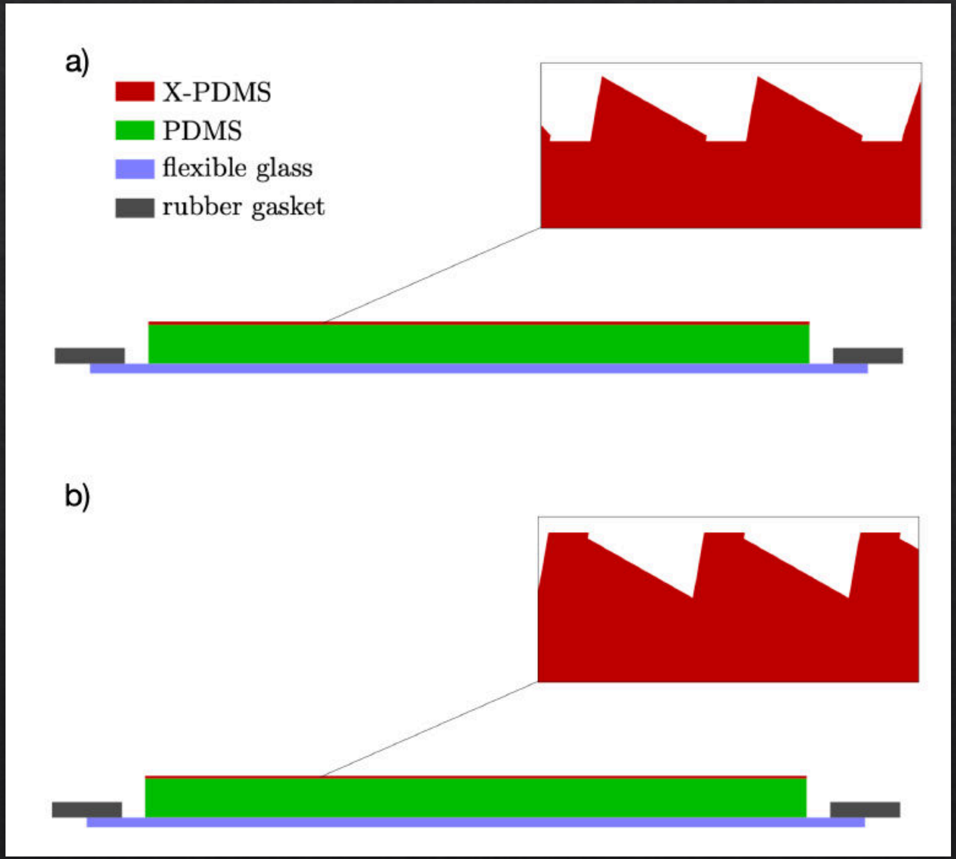
Image credit: Ross McCurdy



Miles et al. (2018)

Grating replication

- Substrate-conformal imprint lithography (SCIL) by Philips SCIL Innovations
- One imprint from master grating can yield hundreds of replicas
- Can *invert* the groove pattern to eliminate impact from groove plateaus
- tREXS: 100 replicas each from two unique masters



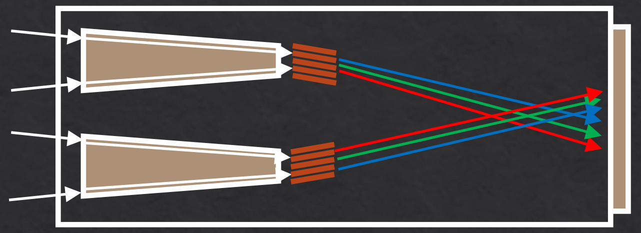
McCoy et al. (2020)

How are we doing? Diffraction efficiency

Grating	**Avg. Absolute Eff.**
Chandra (transmission)	$\lessapprox$10%[1]
XMM-Newton (reflection)	≈10 – 15%[2]
Lynx requirement	40%[3]
Arcus prototype	≈60%[4*]
WRXR rocket	≈65%[5]
tREXS rocket	≈50% ☹

*Up to 1.3 keV; insufficient access to higher energy

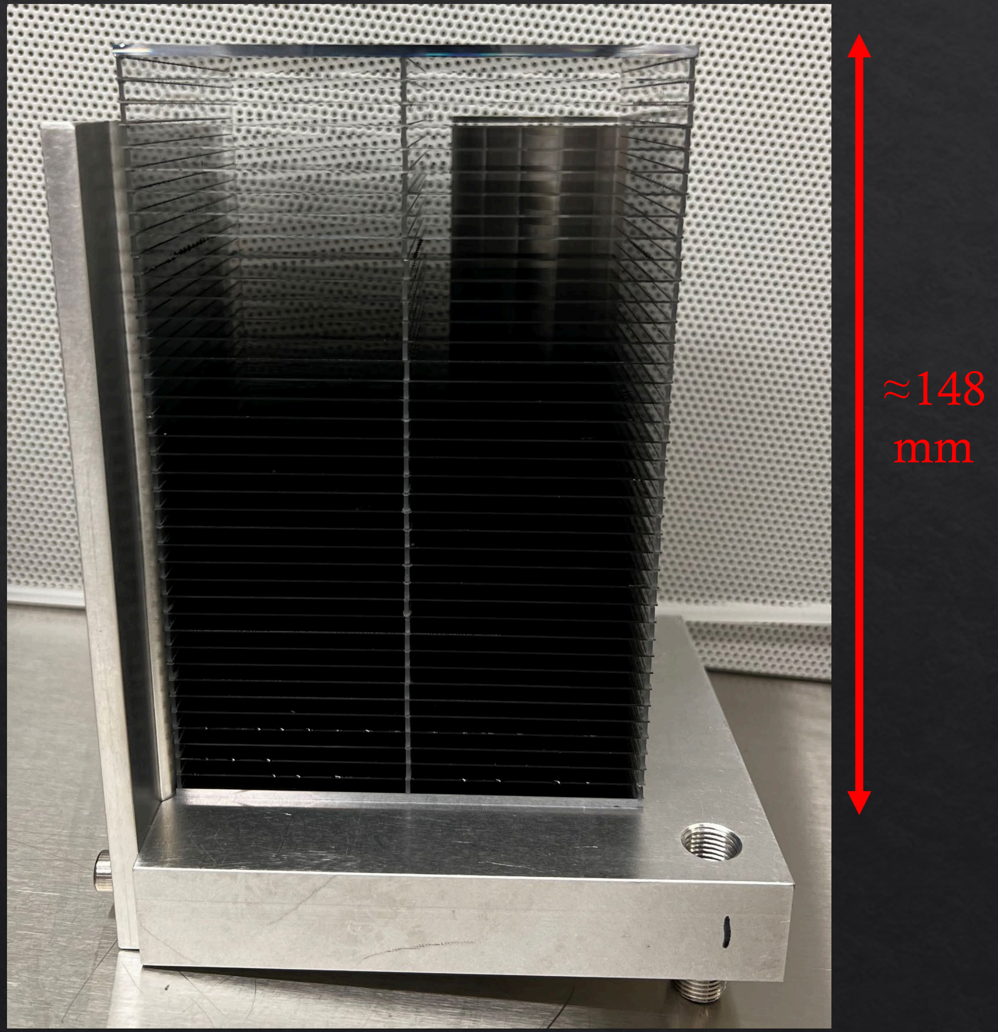
[1] Wargelin et al. (2004)
[2] den Herder et al. (2000)
[3] McEntaffer (2019)
[4] Miles et al. (2018)
[5] Miles et al. (2019)

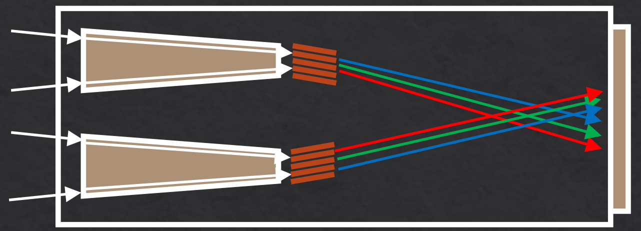


tREXS Reflection gratings

- Reflection gratings fabricated with electron-beam lithography
- Variable line space, average period of 181 nm
- Each replica is coated (Ni), diced, and aligned into stacks of 38 for the flight array

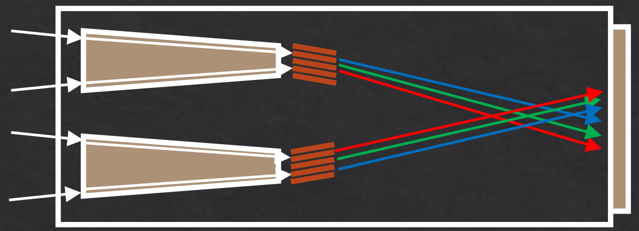
Image credits: Ross McCurdy





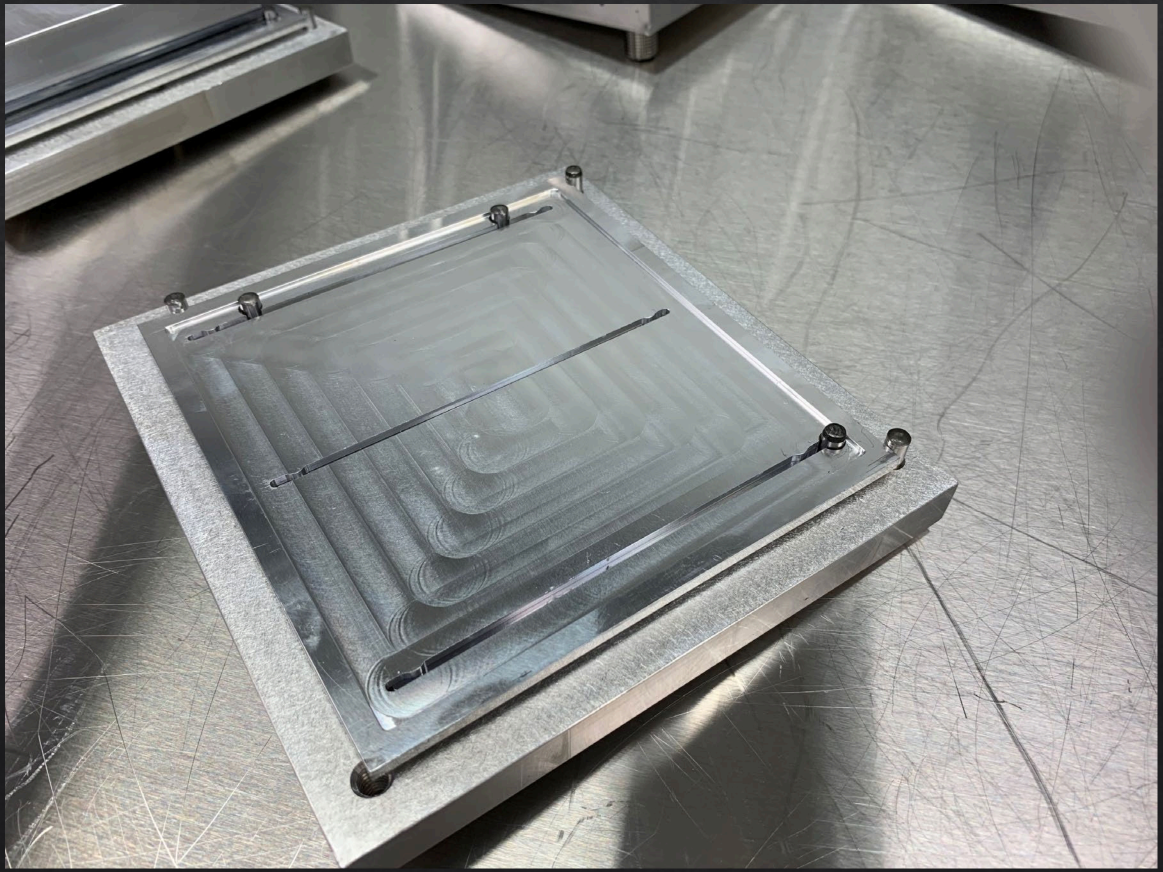
Grating alignment

1. Laser dice fused
silica spacers



Grating alignment

2. Bond 3 spacers
onto grating wafer



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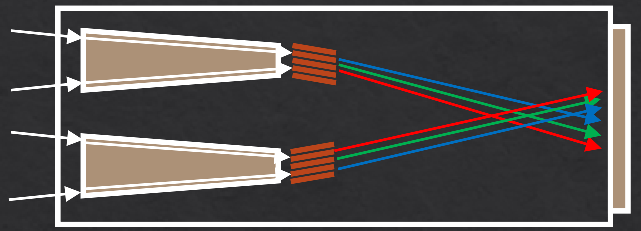

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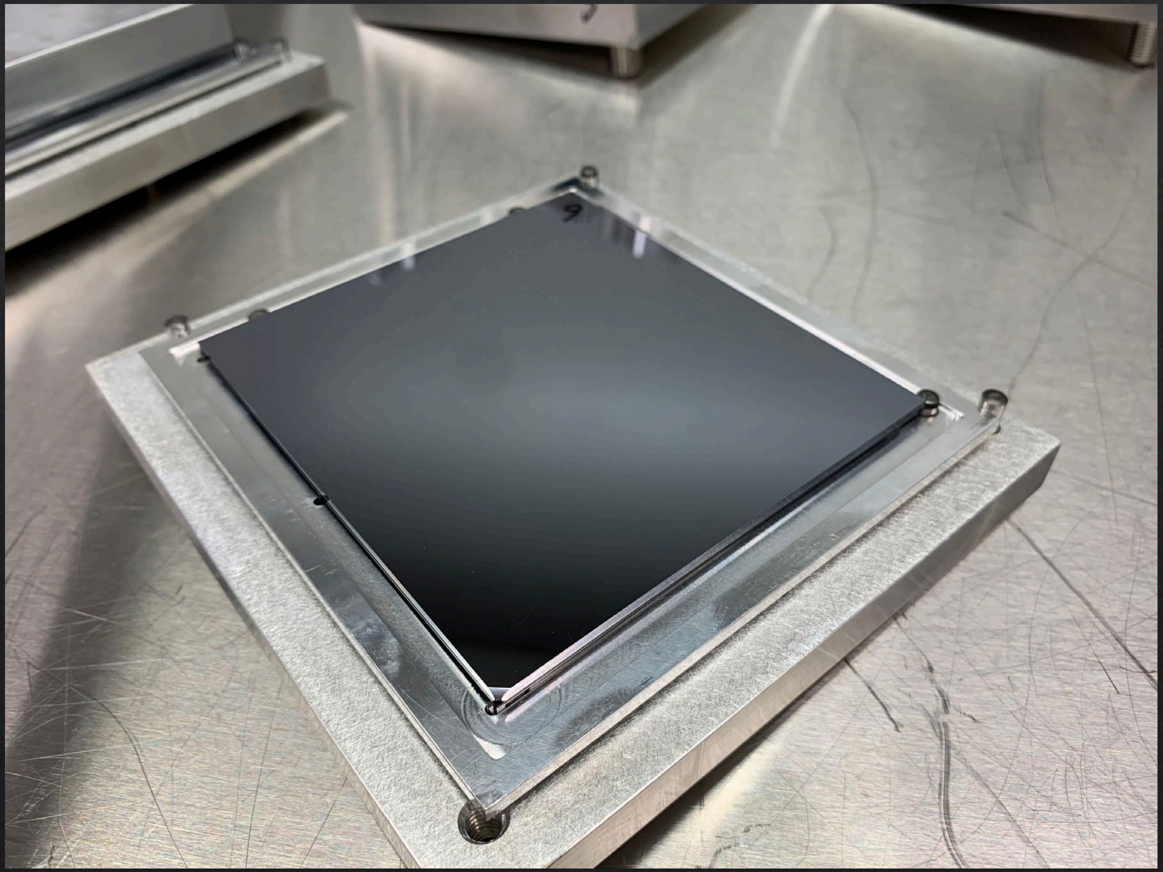

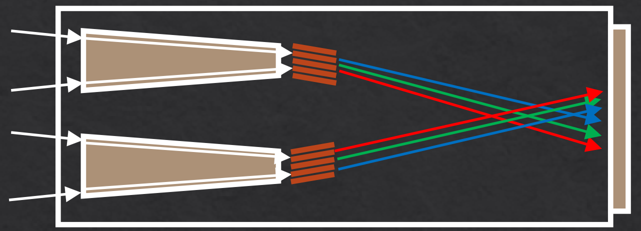

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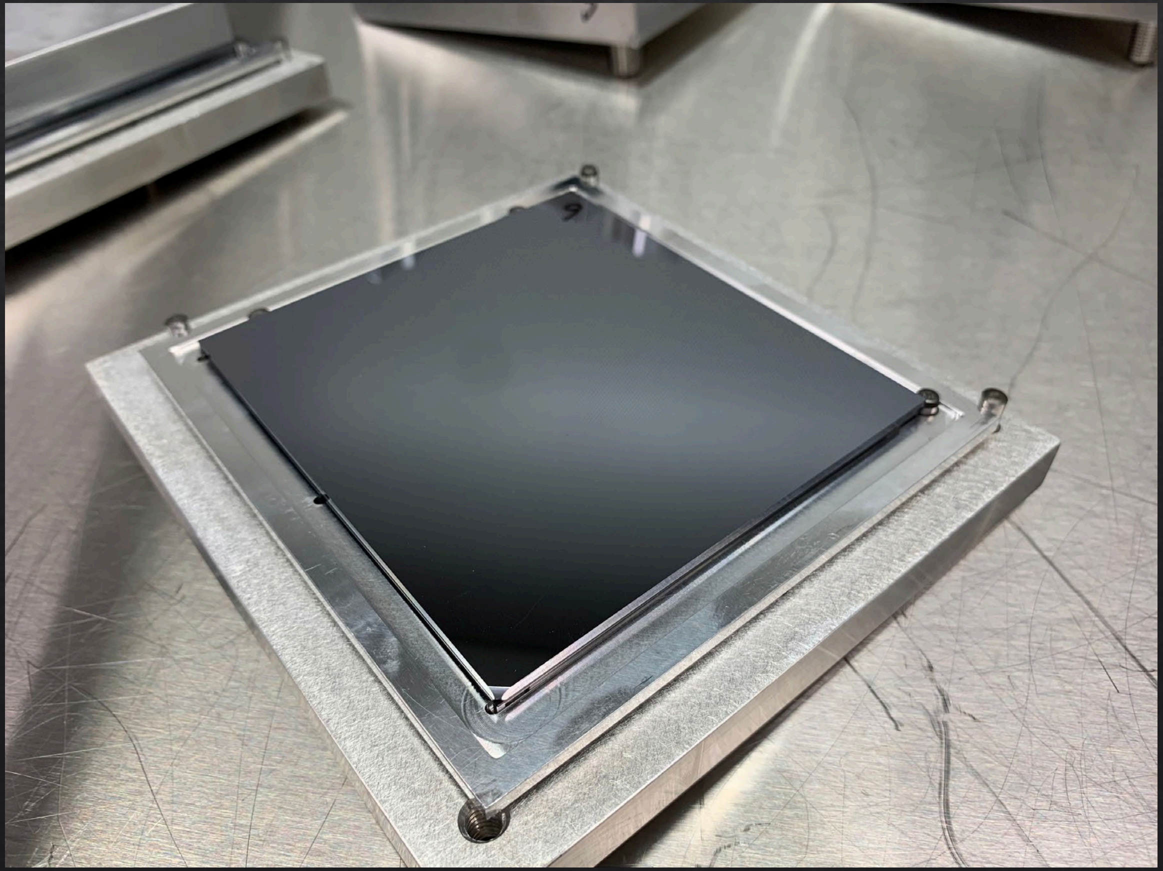
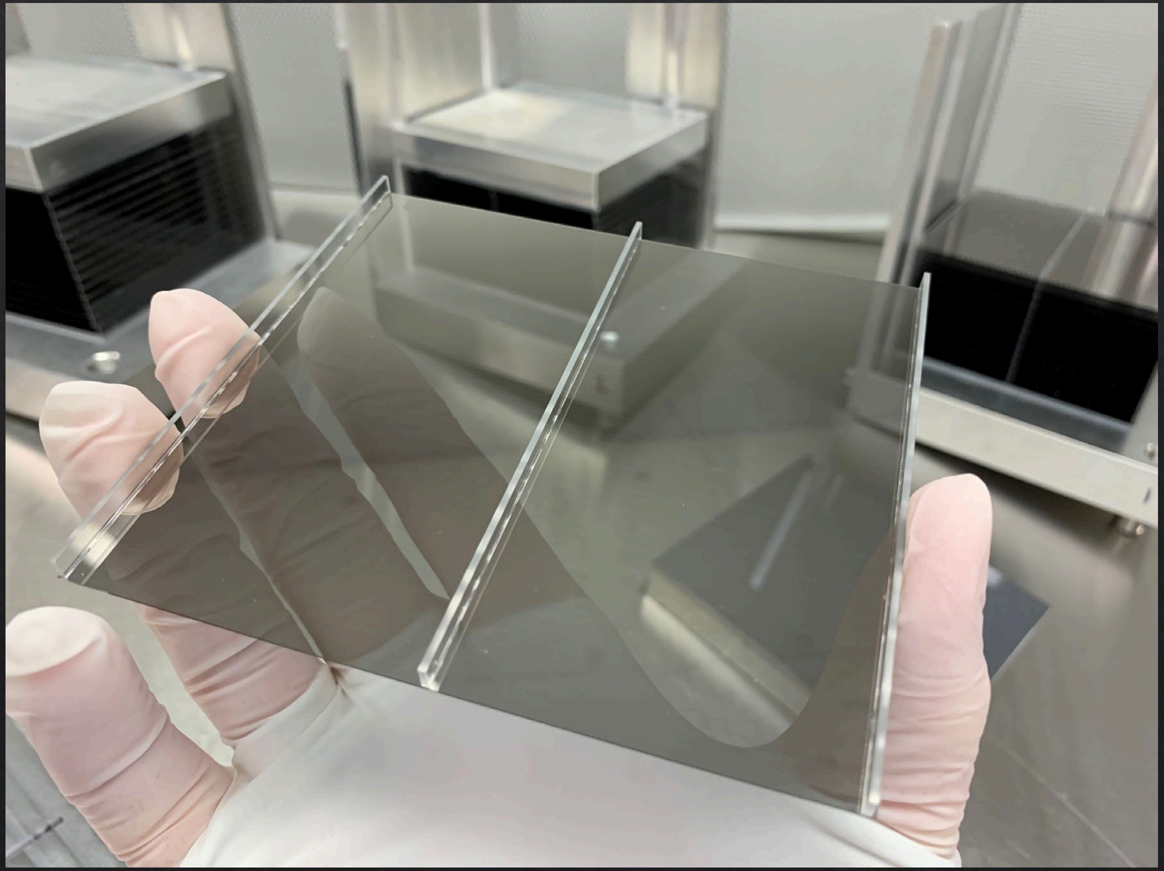
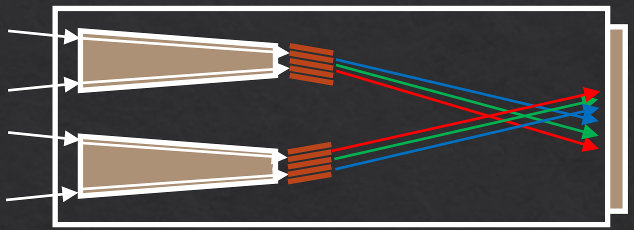
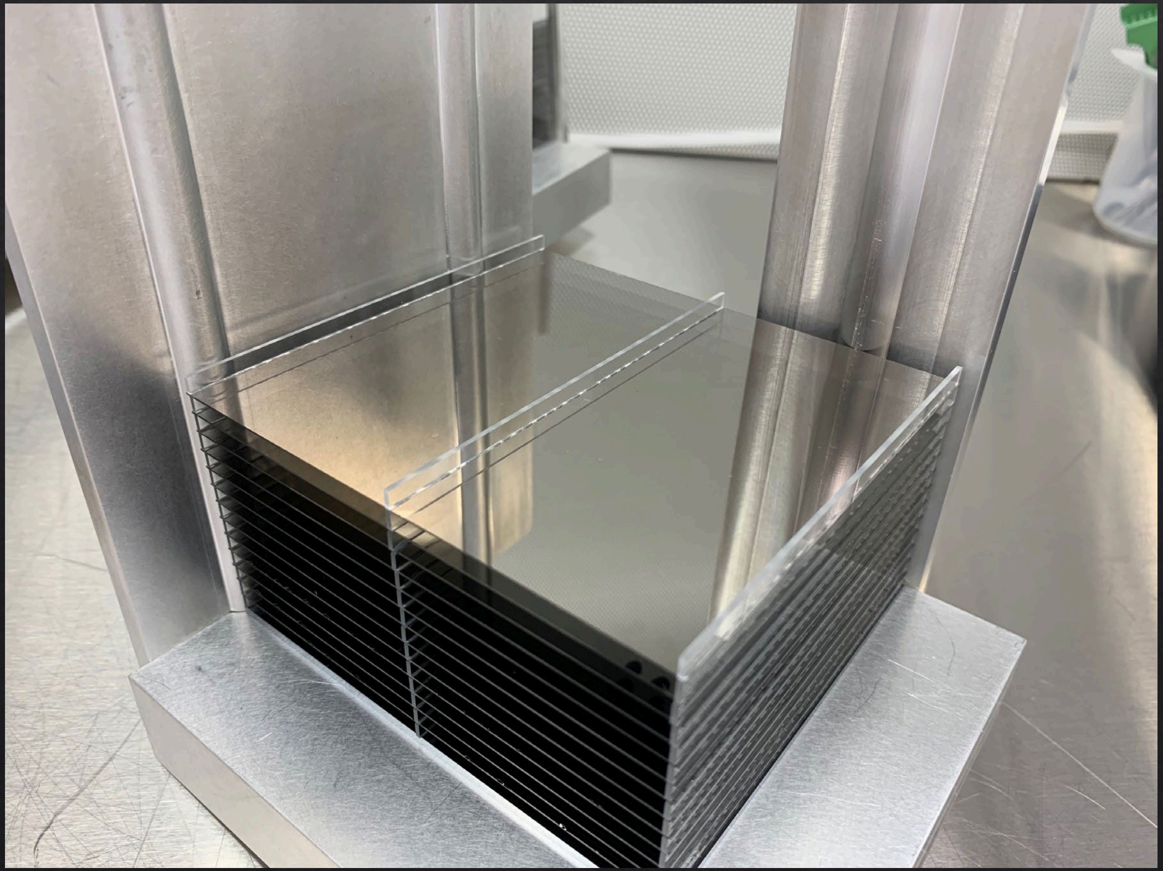


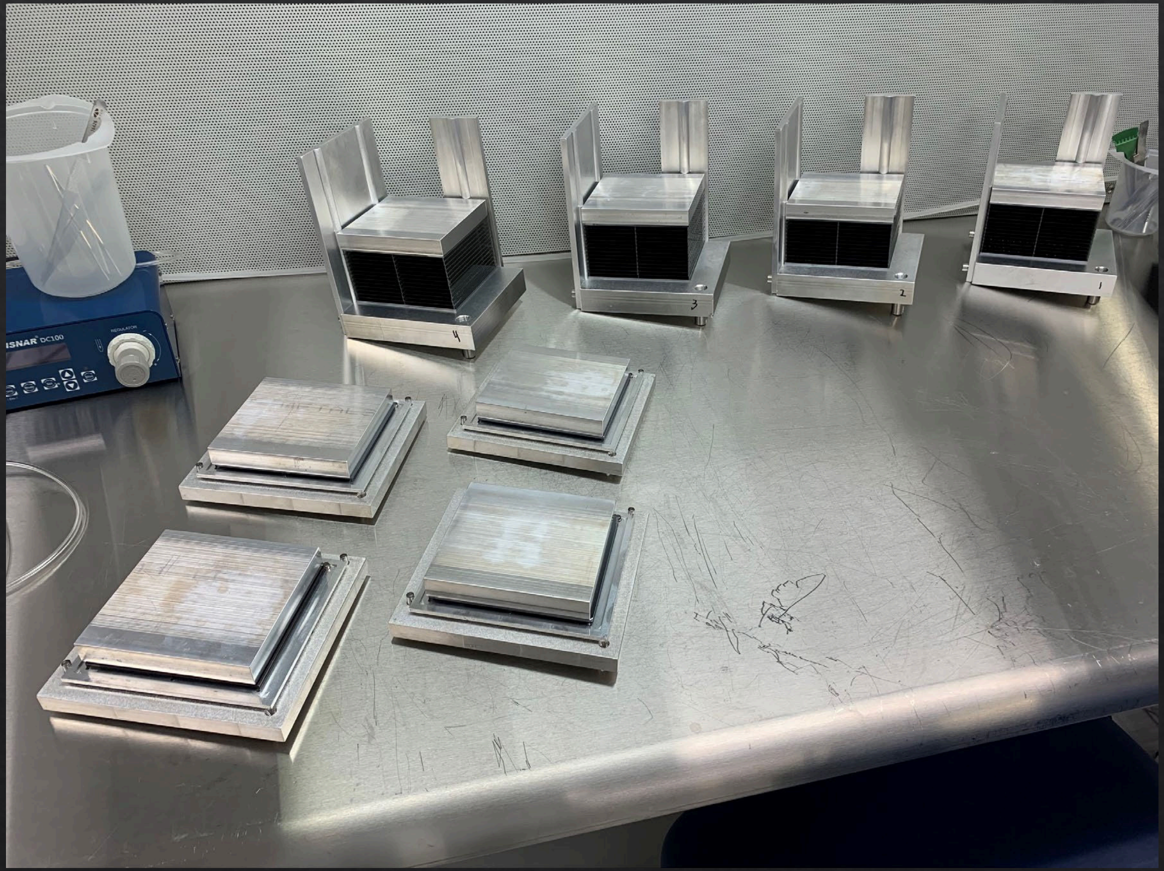


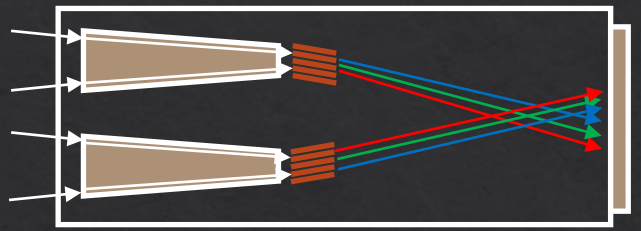


Grating alignment

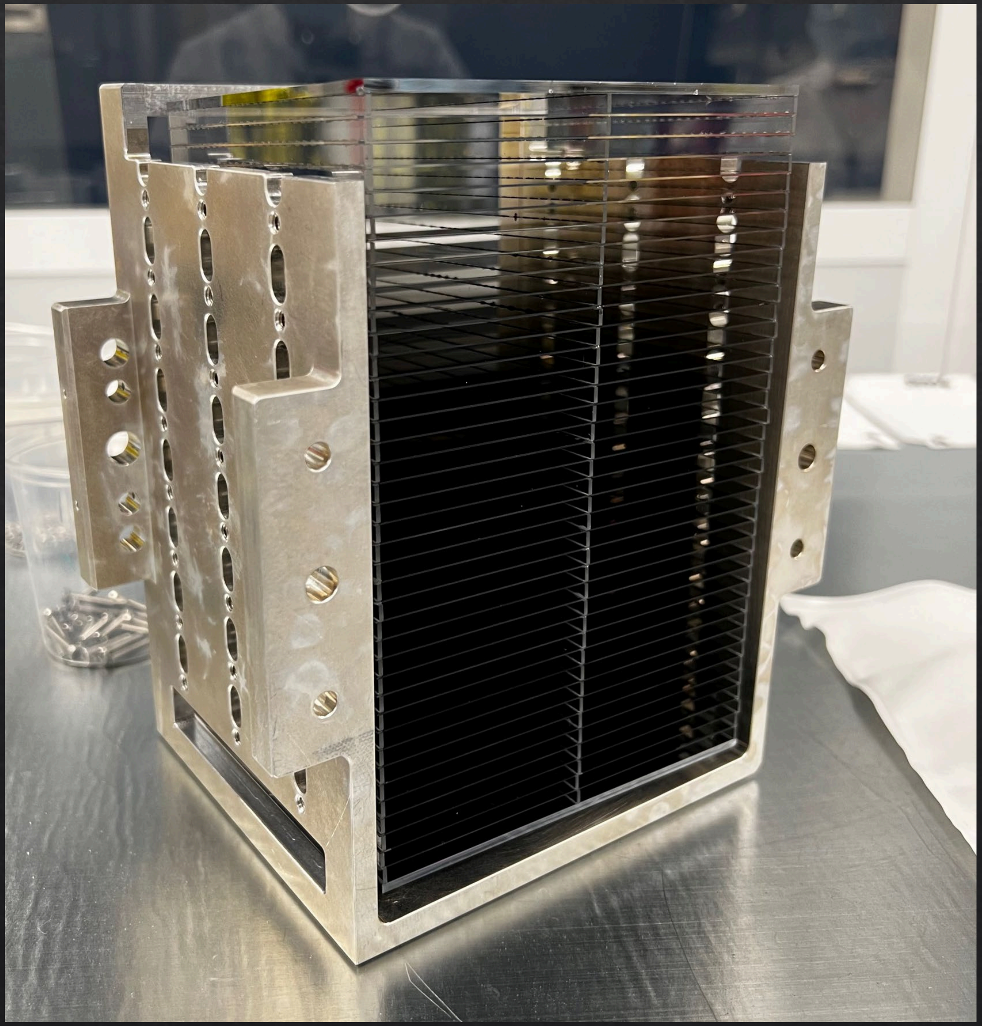
3. Bond grating wafer into grating stack



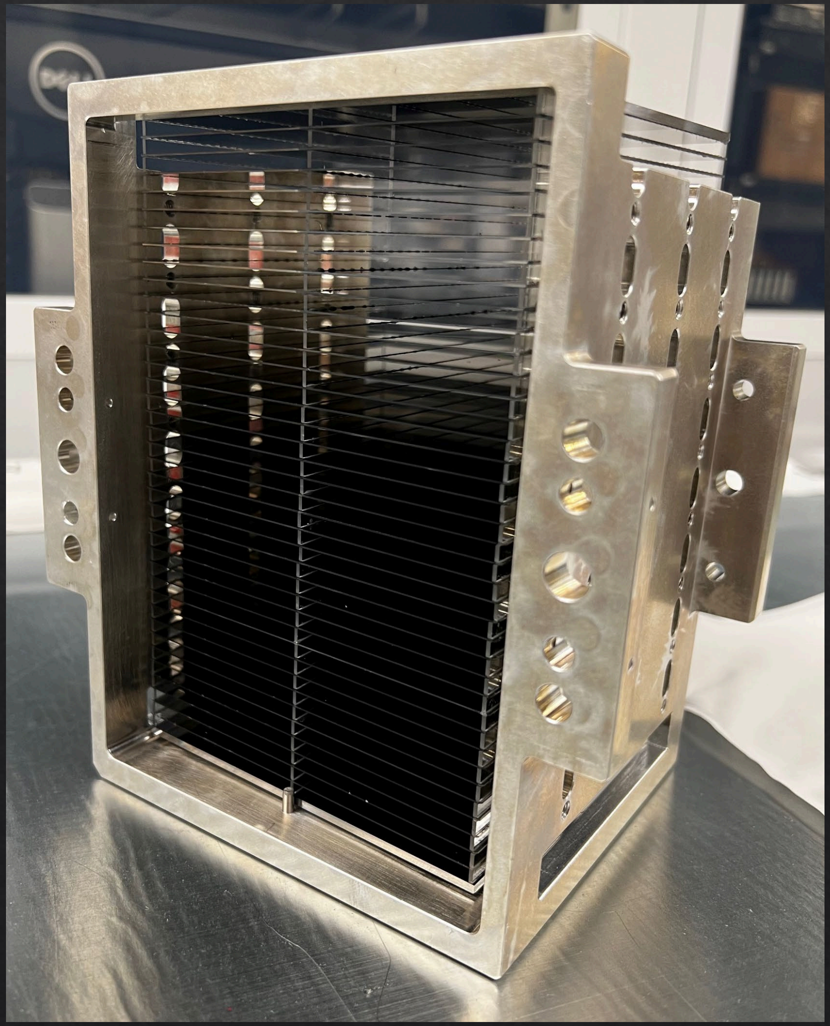




Grating alignment



4. Integrate stack into module



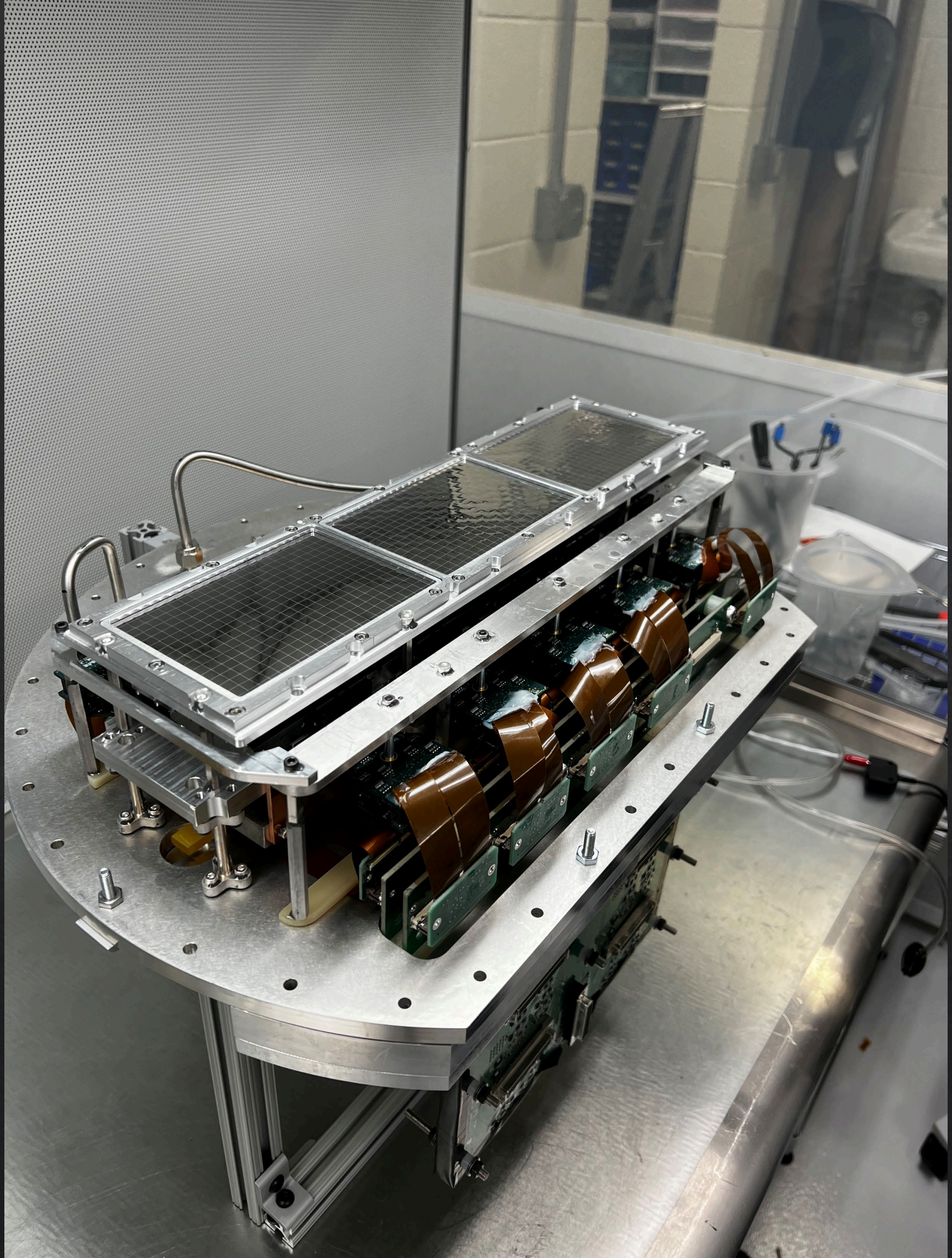
X-ray detectors

Require:

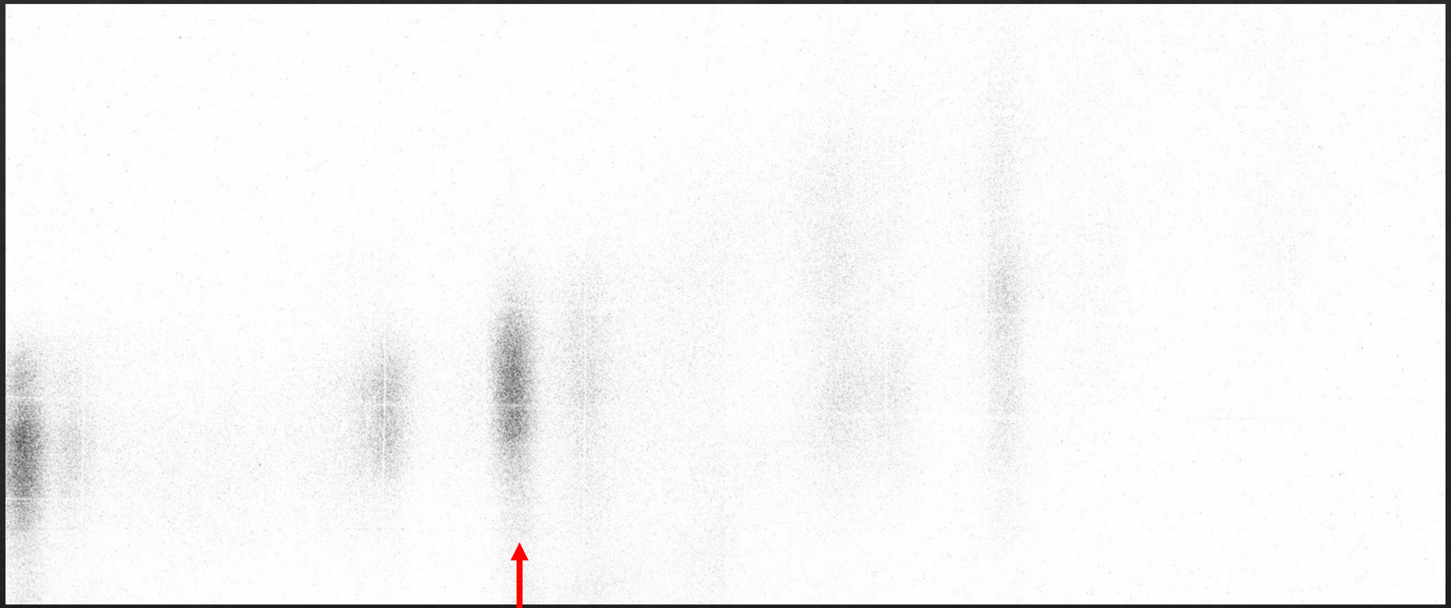
- Large format: dispersed spectral orders are >350 mm in cross-dispersion extent
- Low noise: low count rate (≈count/s), need to minimize instrument background
- $\Delta E < 140$ eV across bandpass

Flight sensor:

- Teledyne/e2v CIS 113 CMOS
- ≈31 mm x 74 mm image area
- ≈3 e^- read noise, will be operated (LN2) at ≈190K
- Custom PSU-designed camera package

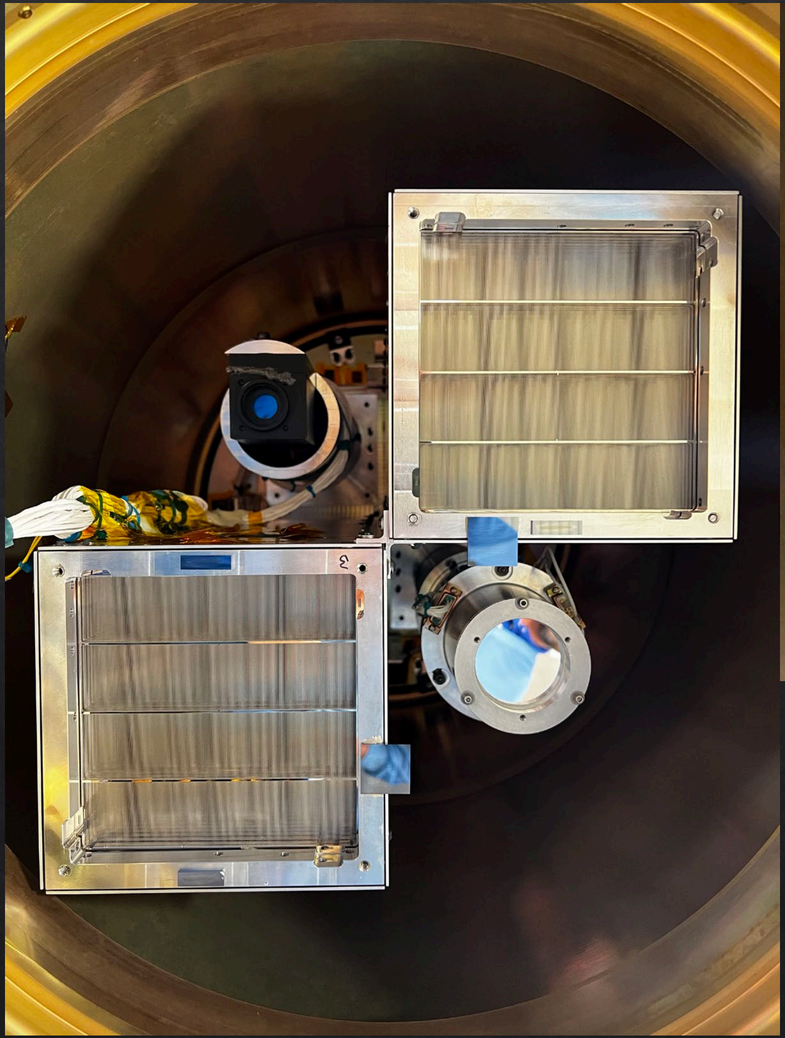


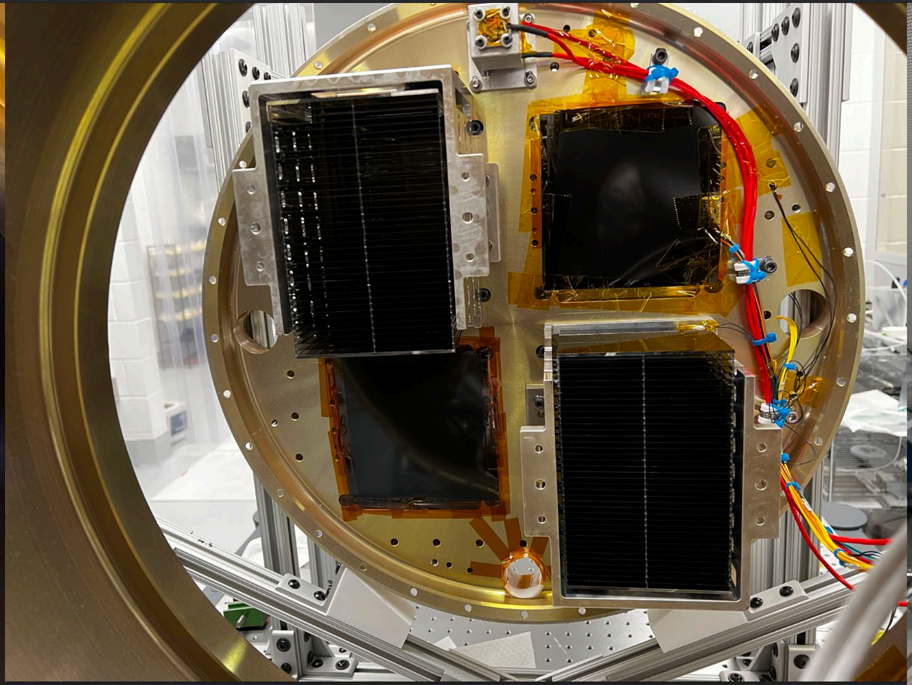
Calibration spectrum on one detector – Cr target



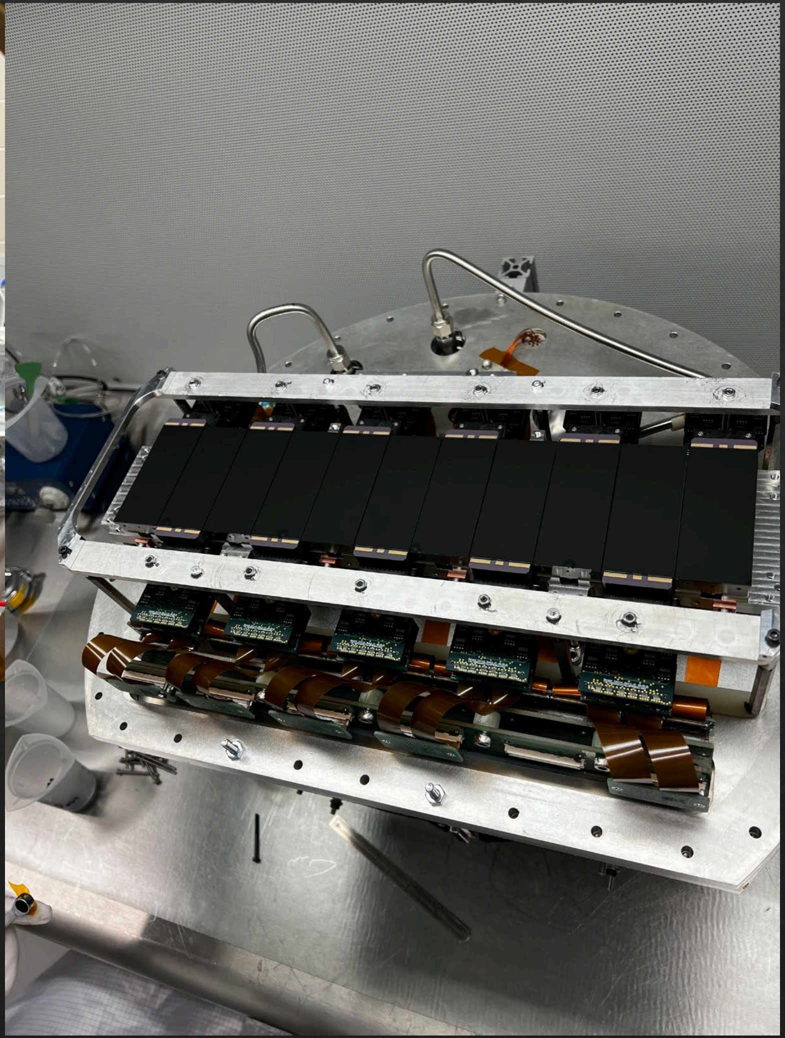
O-K 4th order
~1.4-mm FWHM

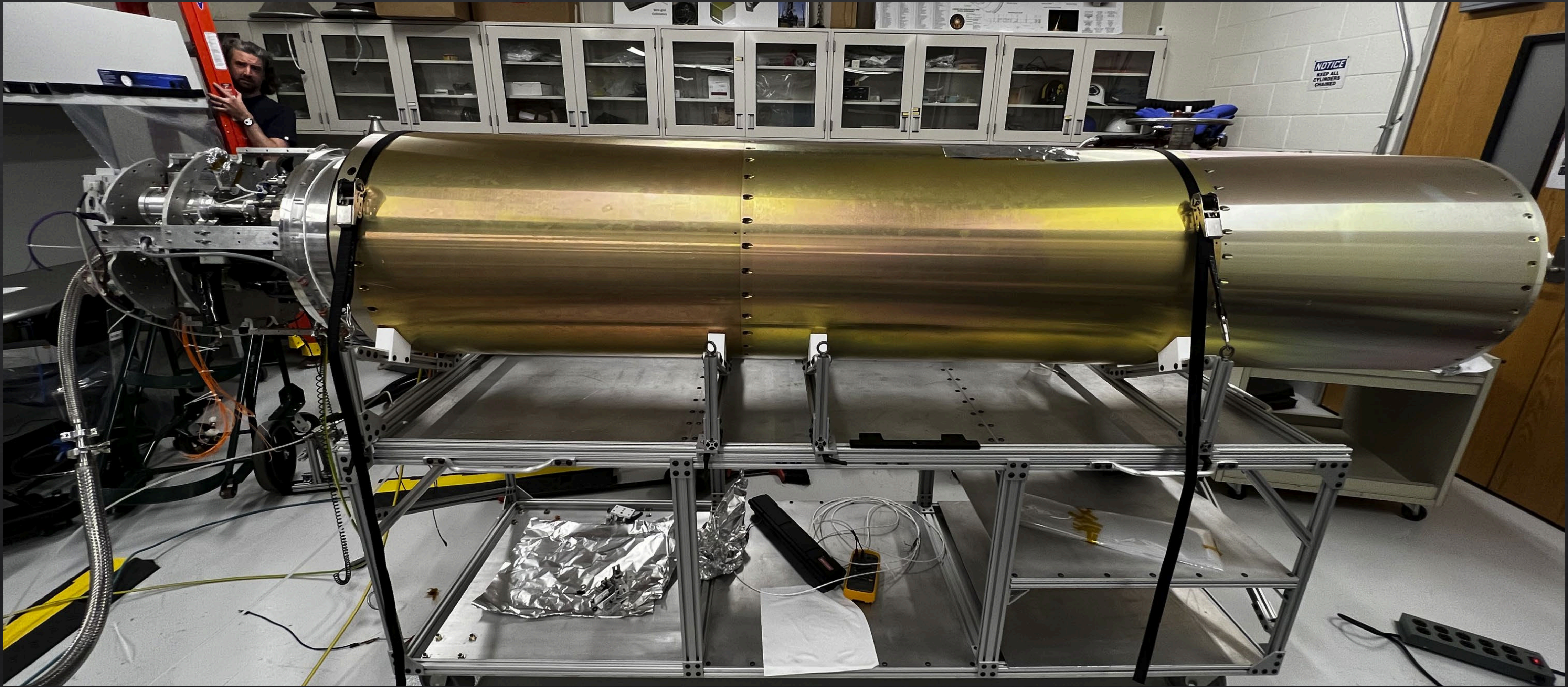
Instrument build





Left: Aft end Mechanical Beam Shapers
Middle: Diffraction gratings, foreward end of optics bulkhead.
Right: Focal plane and readout electronics.




NOTICE
KEEP ALL CYLINDERS CHAINED

Metric	Current tREXS	Full tREXS	MBS-based SmallSat variant
Channels	2	4	90
Optic collecting area, per channel	175 cm^2	175 cm^2	27 cm^2
Optic grasp, per channel	63 cm^2 deg^2	Same	~2.5 cm^2 deg^2
Instrument grasp	~1.8 cm^2 deg^2	~4.2 cm^2 deg^2	~3.4 cm^2 deg^2
FOV	~10.5 deg^2	Same	~7 deg^2
LSF quality	~2.4’	~2.8’	~1’
Focal length	2010 mm	Same	~940 mm
Spectral resolution	~50-80 (~1.3Å)	~40-70 (~1.5Å)	~100 (~0.9Å)
FP coverage	~250 cm^2	Same	?
Grating efficiency (avg)	~45%	~65%	~65%
Spectrograph dimensions	Conical, ~550-mm diameter, 3000-m length	Same	Cubic, ~1450 mm x 800 mm x 800 mm

Path to satellite:

- Redesign and fabricate new MBS plates – fabrication approach stays the same
  - Shorter FL, smaller slits, faster convergence
- New grating design – fabrication approach stays the same
  - Faster groove convergence
- Optimize alignment/focal-plane layout

Backup Slides

tREXS

- Specifications:
  - ≈10 sq. deg. FOV
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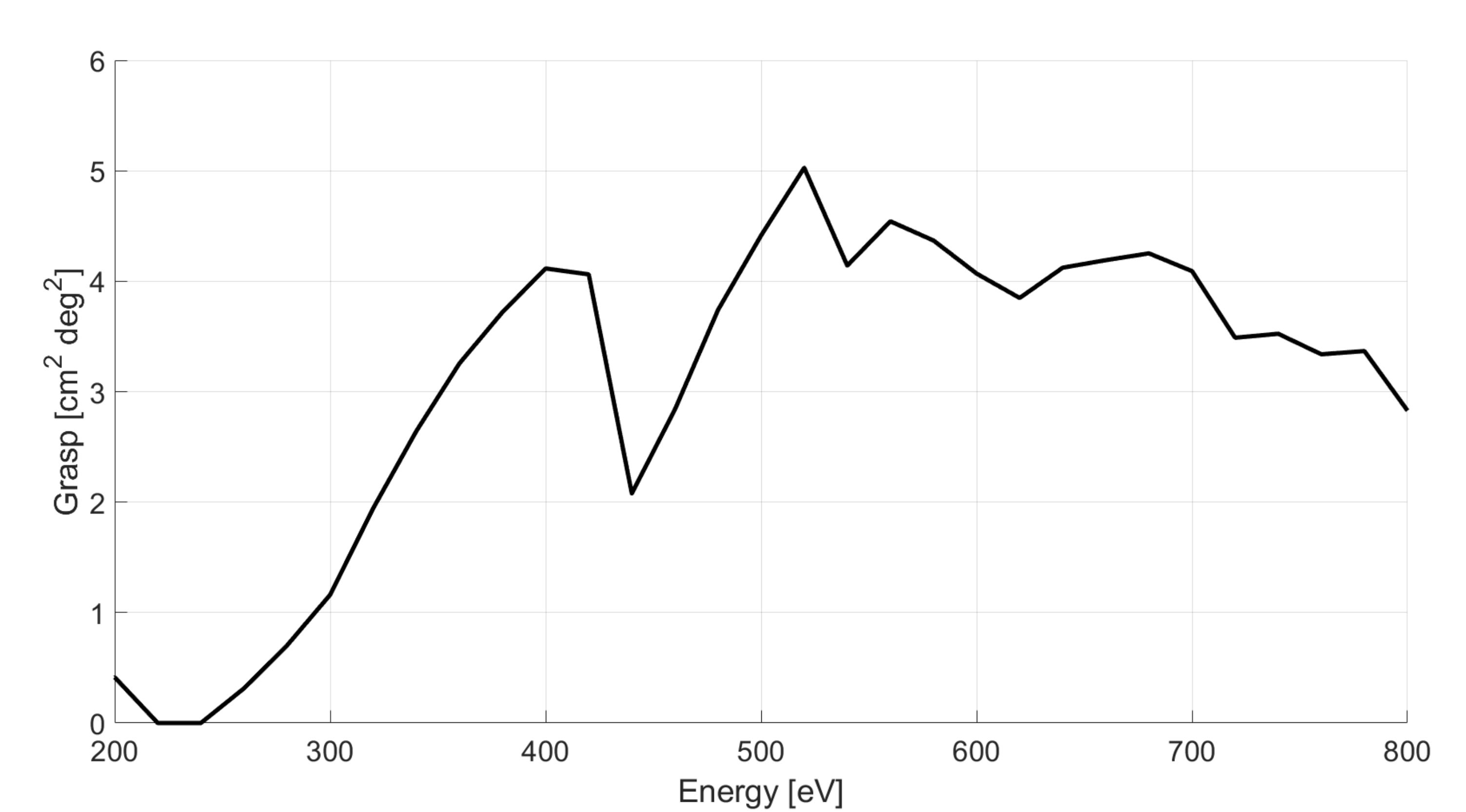
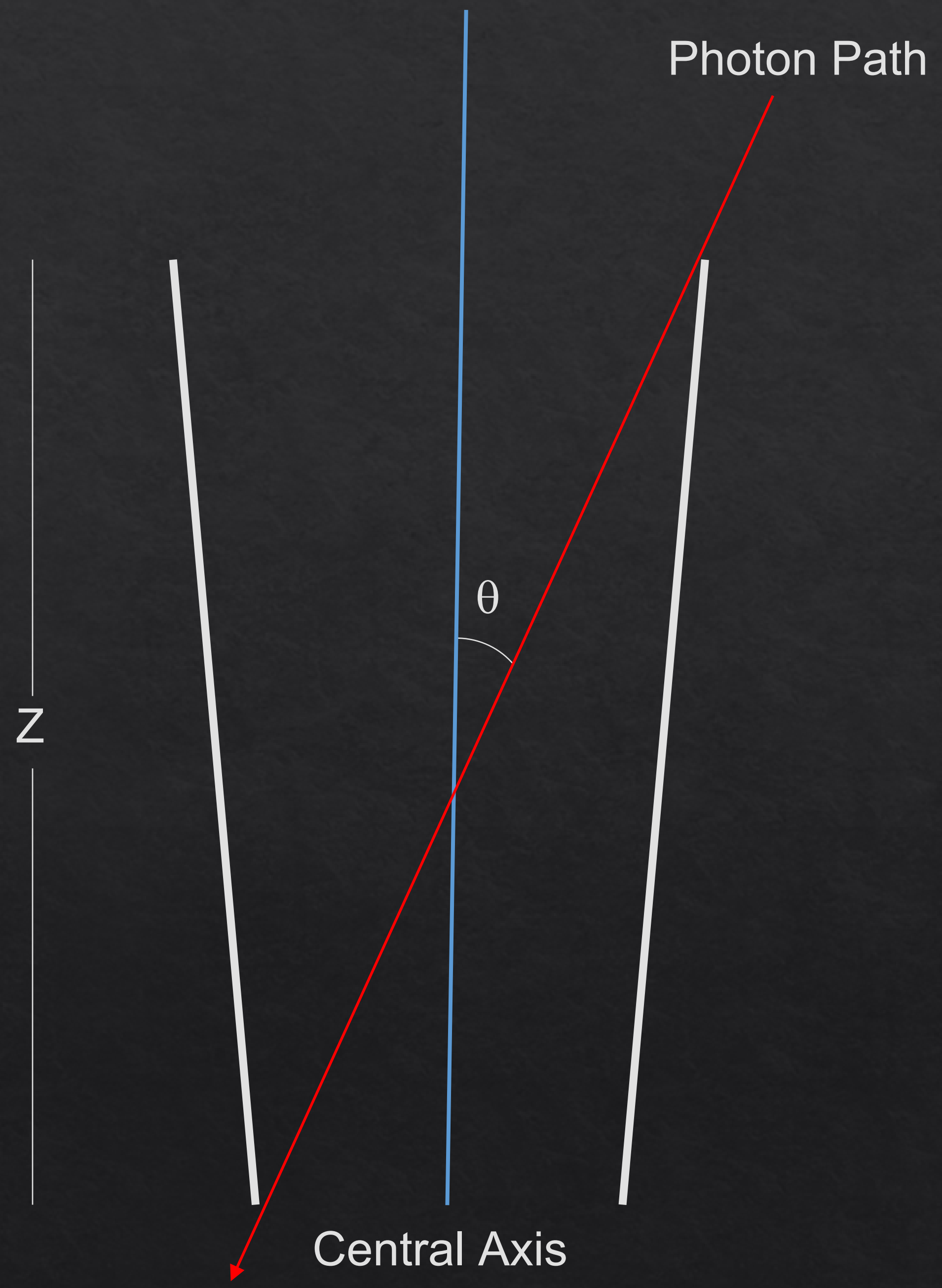
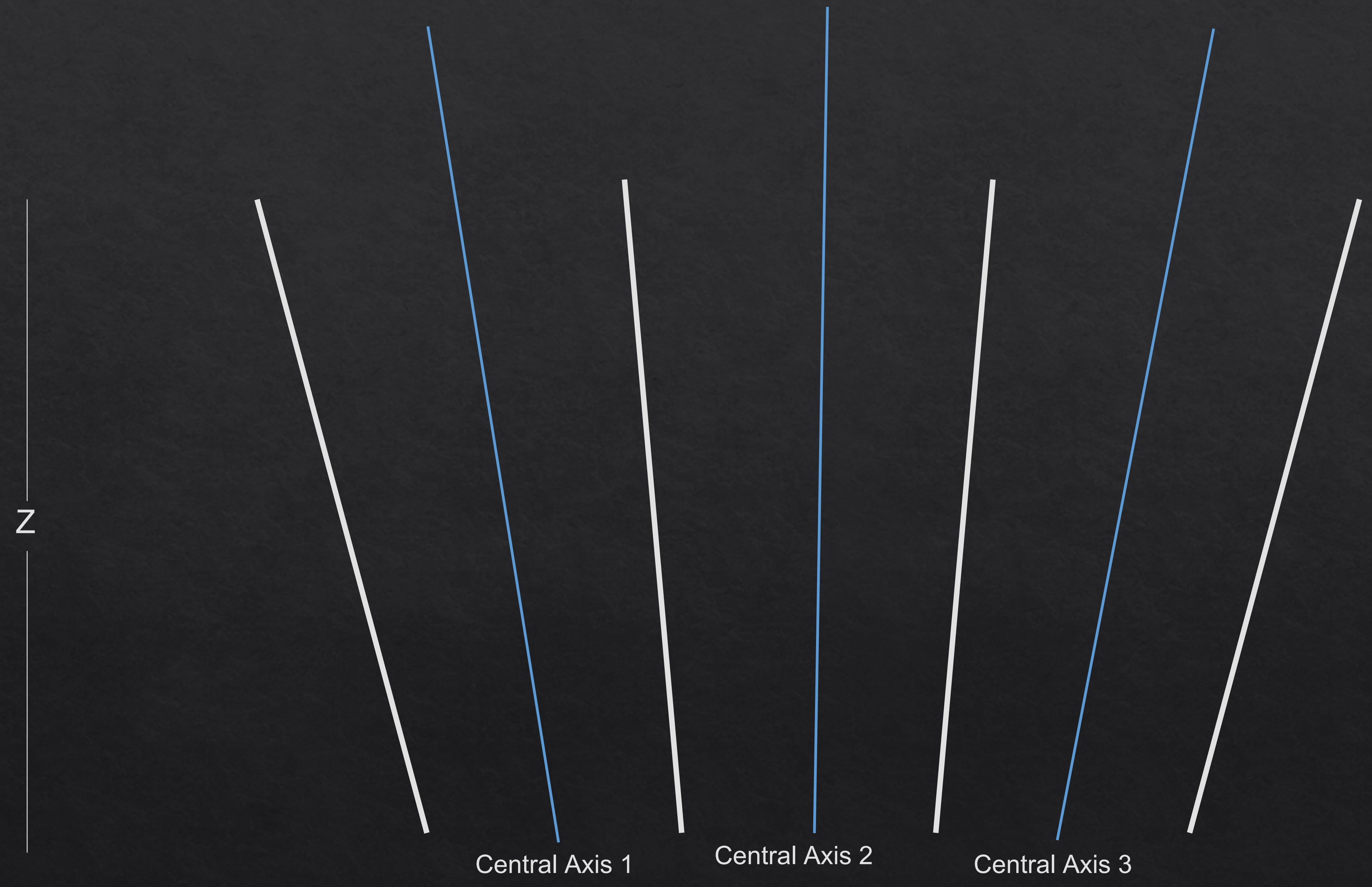


Mechanical beam-shapers (MBS)

- Aperture channel that converges over a distance Z
- Acceptance angles from $\pm\theta$
  - Range of angles that can propagate through entire slit channel with some non-zero probability
- Aperture: 0.5 mm → 0.375 mm
- Z = 700 mm
- $\theta \approx 2.15$ arcminutes





Point at which all channels converge is the focal length; 2.01 m in tREXS

$N_{chan} = 241$

FOV = 3.1 deg.

Component	Parameter	Tolerance ($\pm 1\sigma$)	Driver
MBS Module	slit apertures	15 μm	throughput
	wire apertures	12 μm	throughput
	frame flatness	15 μm peak-to-valley	throughput
	plate-to-plate x	15 μm	throughput
	plate-to-plate y	250 μm	throughput
	plate-to-plate z	500 μm	throughput
	plate-to-plate *pitch*	5 arcminutes	throughput
	plate-to-plate *yaw*	30 arcminutes	throughput
	plate-to-plate *roll*	30 arcseconds	throughput
Gratings	wafer flatness	20 μm peak-to-valley	resolving power
	edge roughness	5 μm rms	throughput
	grating-to-grating x	1 mm	throughput
	grating-to-grating y	250 μm	throughput
	grating-to-grating z	250 μm	resolving power
	grating-to-grating *pitch*	1 arcminute	throughput
	grating-to-grating *yaw*	1 arcminute	throughput
	grating-to-grating *roll*	30 arcseconds	resolving power
Instrument	MBS-to-MBS x	100 μm	resolving power
	MBS-to-MBS z	500 μm	resolving power
	MBS-to-MBS *pitch*	30 arcminutes	resolving power
	MBS-to-MBS *yaw*	15 arcseconds	resolving power
	MBS-to-MBS *roll*	1 arcminute	resolving power
	MBS-to-gratings x	1 mm	throughput
	MBS-to-gratings y	500 μm	throughput
	MBS-to-gratings z	425 μm	resolving power
	MBS-to-gratings *pitch*	5 arcminutes	throughput
	MBS-to-gratings *yaw*	5 arcminutes	throughput
	MBS-to-gratings *roll*	1 arcminute	resolving power
	optics-to-focal plane x	2 mm	throughput
	optics-to-focal plane z	1 mm	resolving power
	optics-to-focal plane *pitch*	30 arcminutes	resolving power
	optics-to-focal plane *yaw*	20 arcminutes	resolving power
	optics-to-focal plane *roll*	20 arcminutes	resolving power