Generation of arbitrary bunch shapes using a multileaf collimator and emittance exchange

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Motivation

- Transformer ratio, $\mathcal{R}$, defines the maximum energy that can be transferred from driver to witness: $\Delta E_w = \mathcal{R}\,\Delta E_d$
  - <2 for symmetric beams but shaped beams can exceed
- Pulse shaping options: laser pulse stacking, wakefield structures, doglegs, emittance exchange

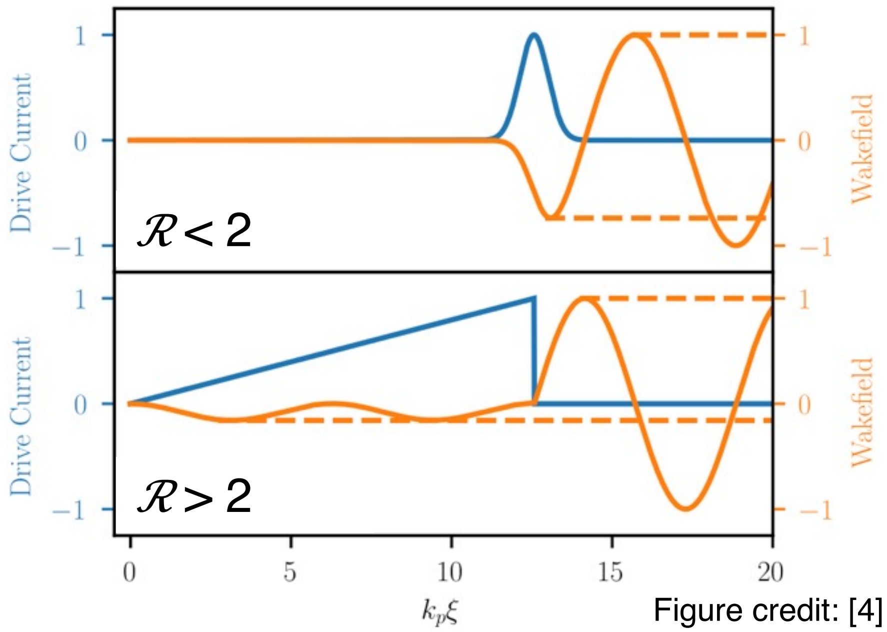
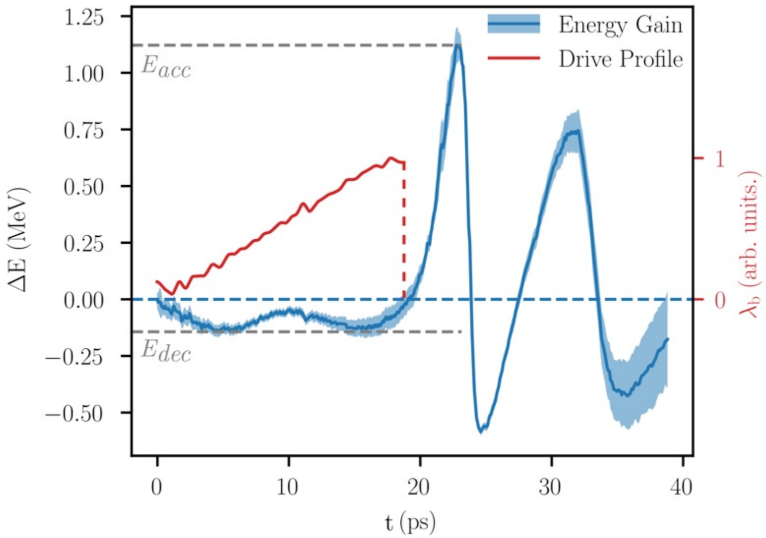


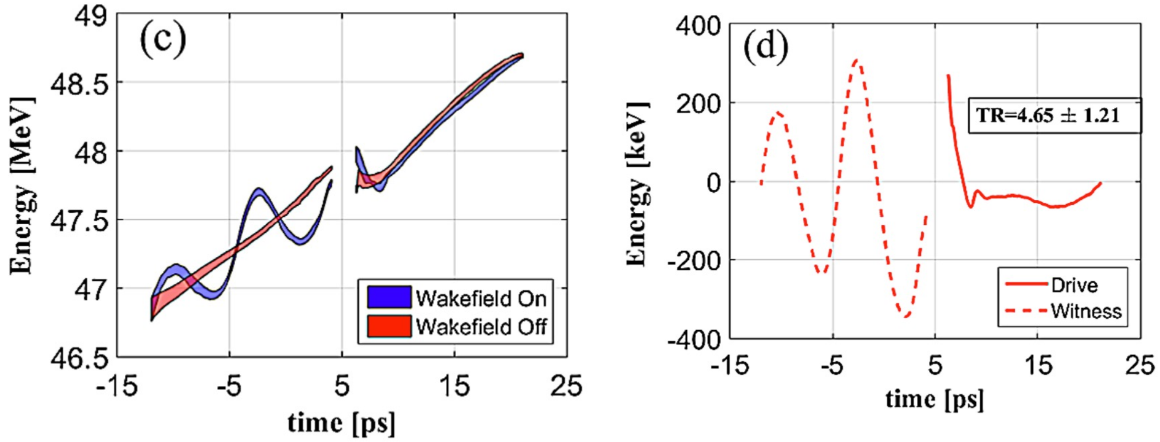
Figure credit: [4]

$\mathcal{R} = 7.8$ in plasma wakefield



Roussel, R., et al. *PRL* 124 (2020): 044802.

$\mathcal{R} = 4.8$ in dielectric wakefield

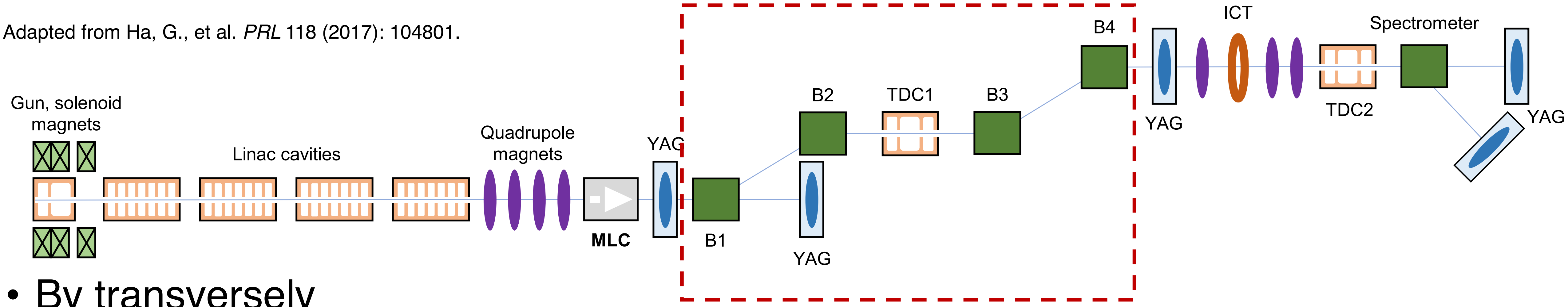


Gao, Q., et al. *PRL* 120 (2018): 114801.

See also: Loisch, G., et al. *PRL* 121 (2018): 064801.

Emittance exchange for advanced accelerators

Adapted from Ha, G., et al. *PRL* 118 (2017): 104801.



- By transversely masking the beam before the EEX beamline, the final current profile is controlled
- Shaping drive and witness bunches with this approach has yielded record-breaking transformer ratios

$$\underbrace{\begin{pmatrix} 1 & \frac{L}{2} & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \frac{\xi}{2} \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Dogleg}} \underbrace{\begin{pmatrix} 1 & Lc & \frac{Lc\,\kappa}{2} & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \frac{Lc\,\kappa}{2} & \frac{Lc\,\kappa^2}{4} & 1 \end{pmatrix}}_{\text{Deflecting cavity}} \underbrace{\begin{pmatrix} 1 & \frac{L}{2} & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \frac{\xi}{2} \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Dogleg}} = \underbrace{\begin{pmatrix} 0 & 0 & -\frac{L}{2\,\eta} & \eta - \frac{L\,\xi}{4\,\eta} \\ 0 & 0 & -\frac{1}{\eta} & -\frac{\xi}{2\,\eta} \\ -\frac{\xi}{2\,\eta} & \eta - \frac{L\,\xi}{4\,\eta} & 0 & 0 \\ -\frac{1}{\eta} & -\frac{L}{2\,\eta} & 0 & 0 \end{pmatrix}}_{\text{EEX}}$$

Multileaf collimator masking

- Replace the laser cut tungsten masks in EEX beamline with a multileaf collimator (MLC)
- MLCs are commonly employed to shape radiotherapy beams
- Real-time, nearly arbitrary drive and witness beam shaping
- Highly synergistic with machine learning
- Extension of UCLA/AWA collaboration to study exotic shaped beams for HTR PWFA

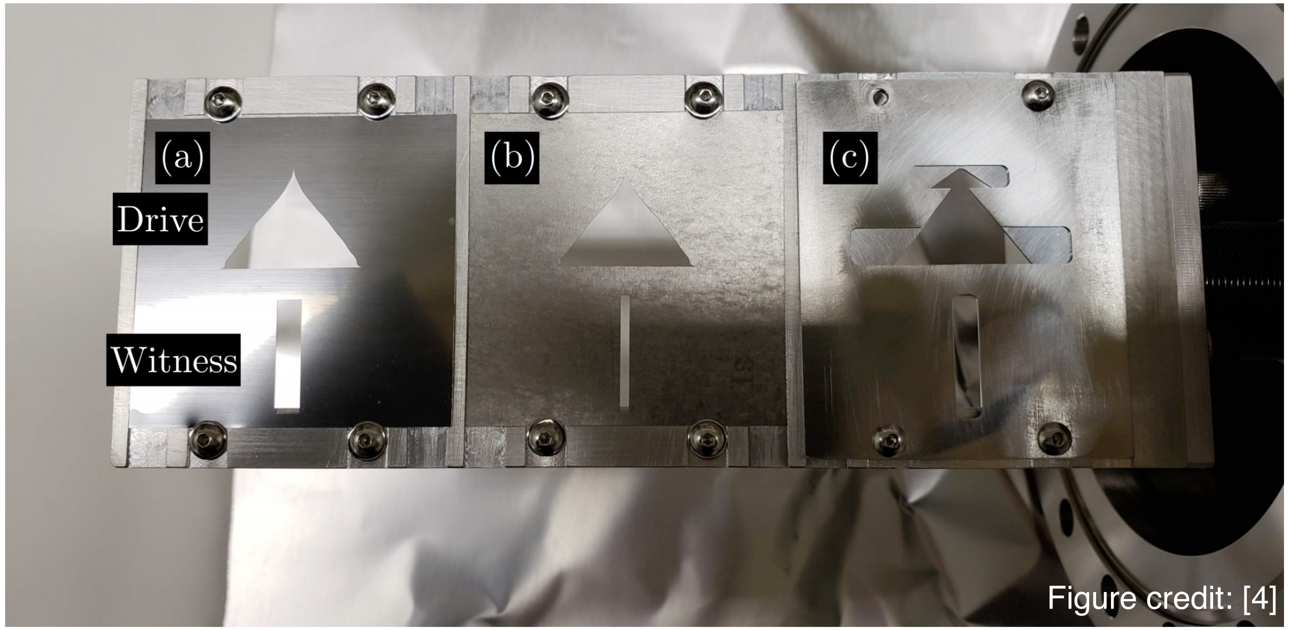


Figure credit: [4]

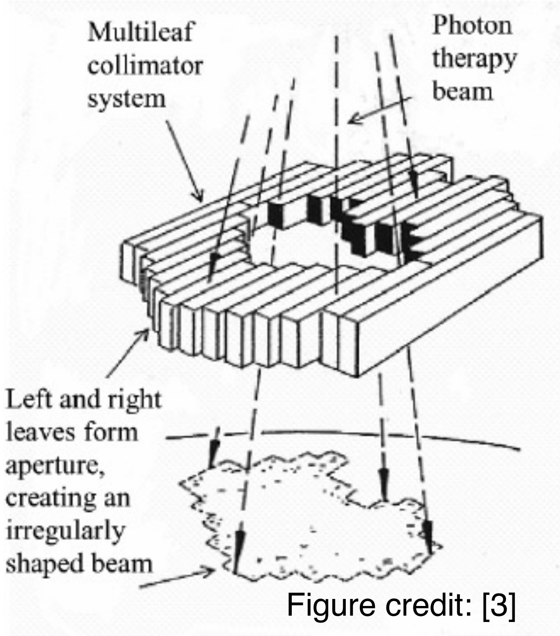


Figure credit: [3]

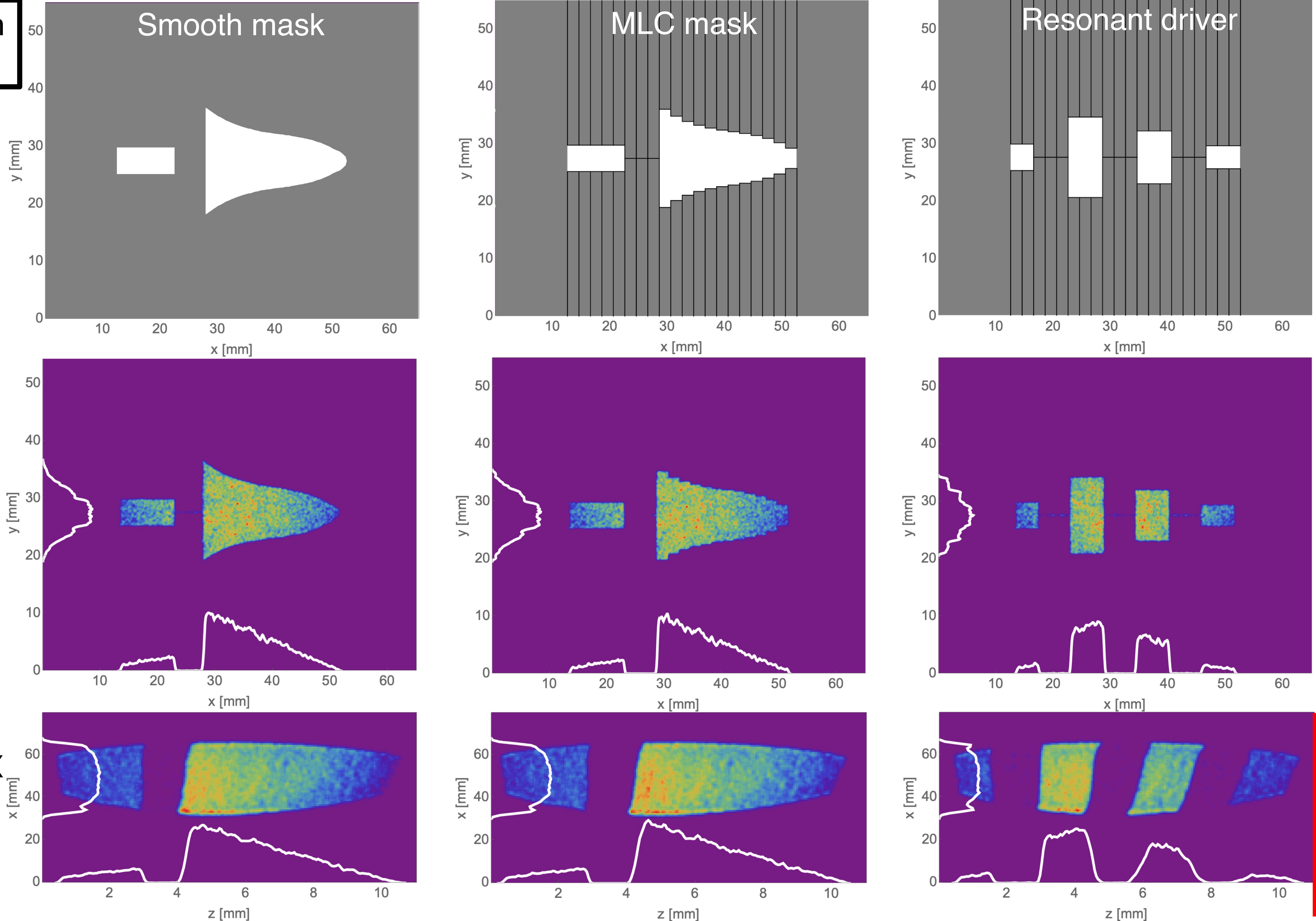

Figure credit: [3]

Simulation results

Mask

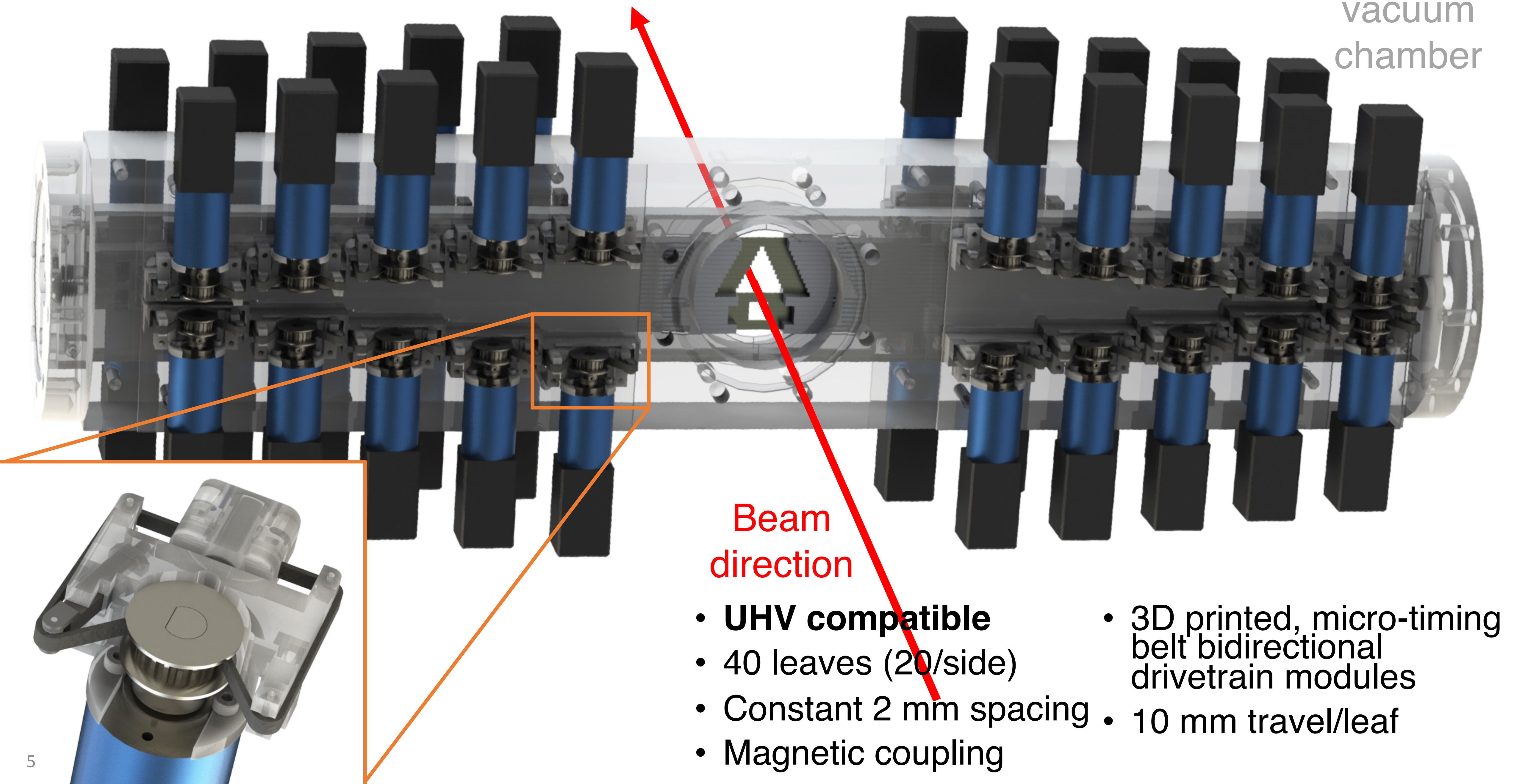
Mask shadow

Post-EEX current profile



40 leaf MLC functionally equivalent to existing AWA masks

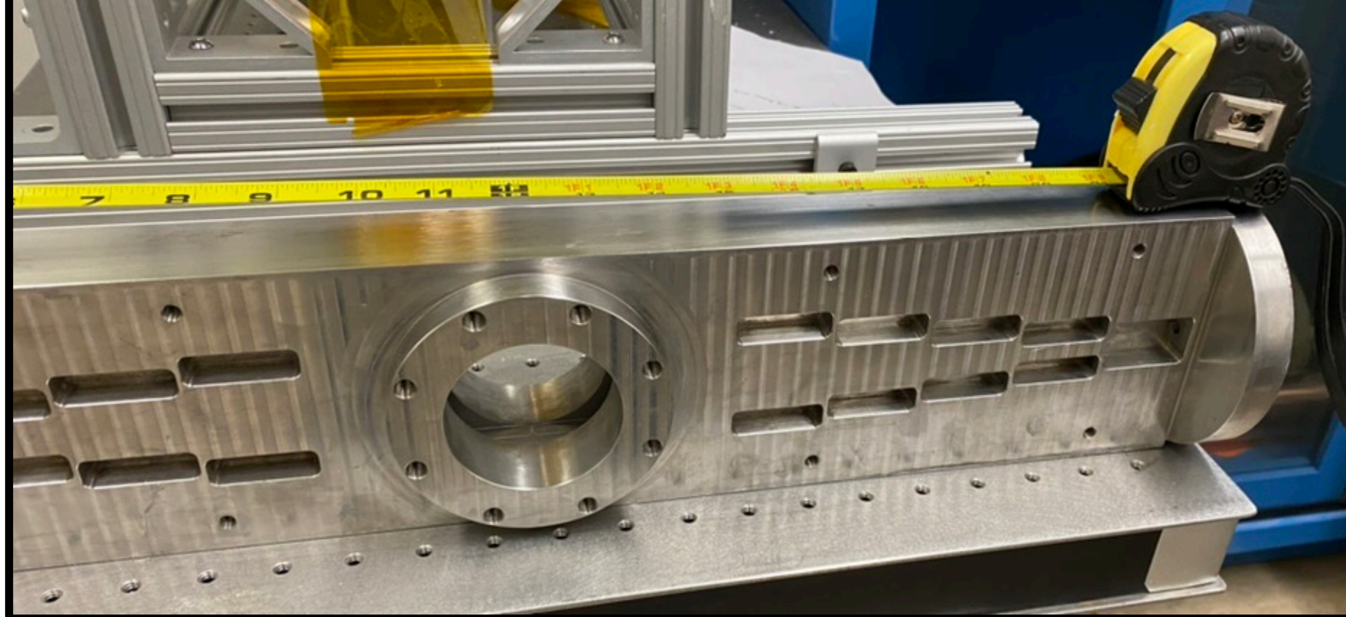
Design (rotated to fit on slide)

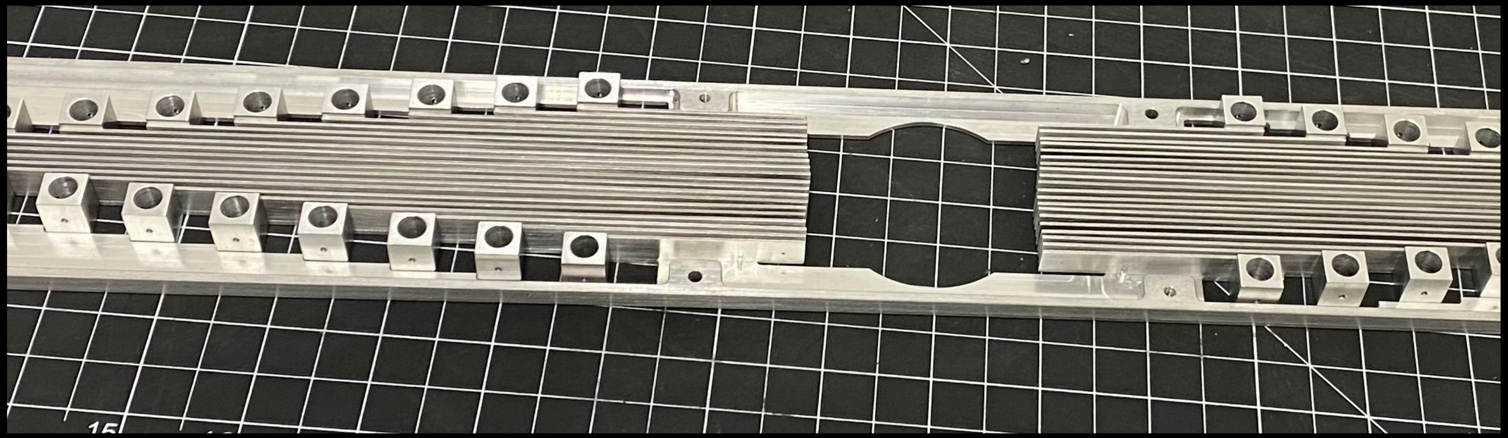


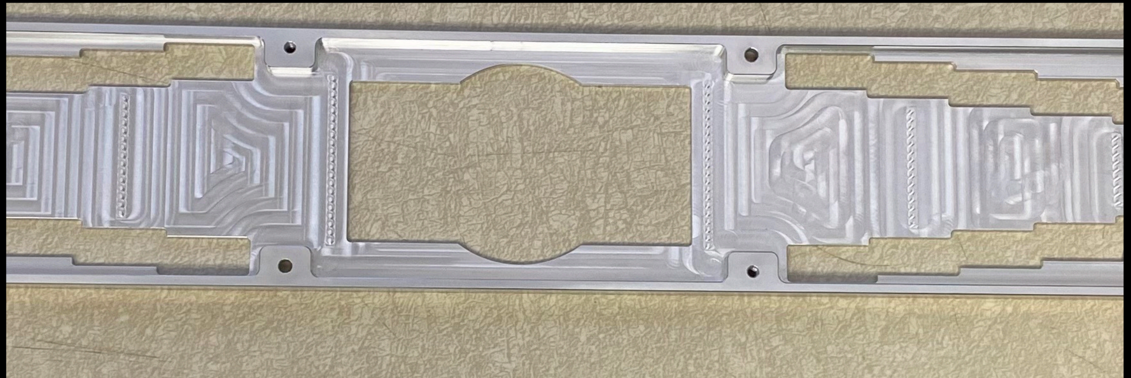
- **UHV compatible**
- 40 leaves (20/side)
- Constant 2 mm spacing
- Magnetic coupling
- 3D printed, micro-timing belt bidirectional drivetrain modules
- 10 mm travel/leaf

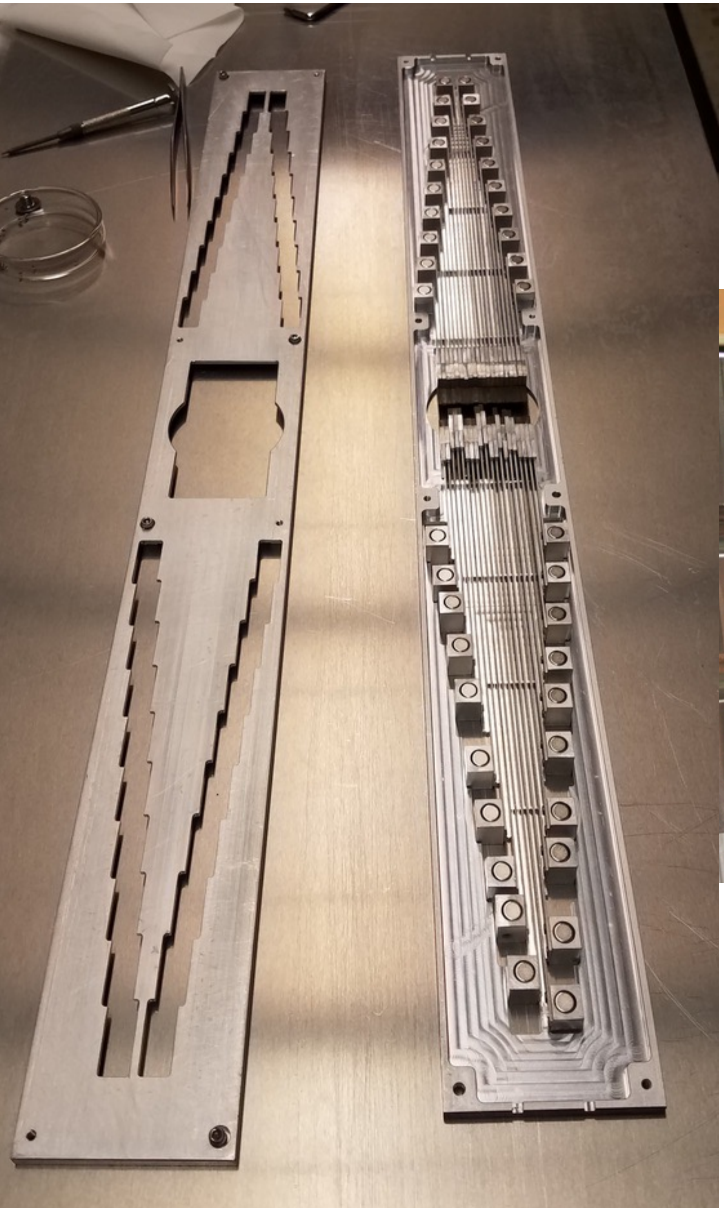
Fabrication

- Almost 2000 individual parts
  - 3D printed as much as possible
- Chamber required high aspect ratio wire EDM for central slot
- Tungsten tips used multi-axis wire EDM for tapered press fit

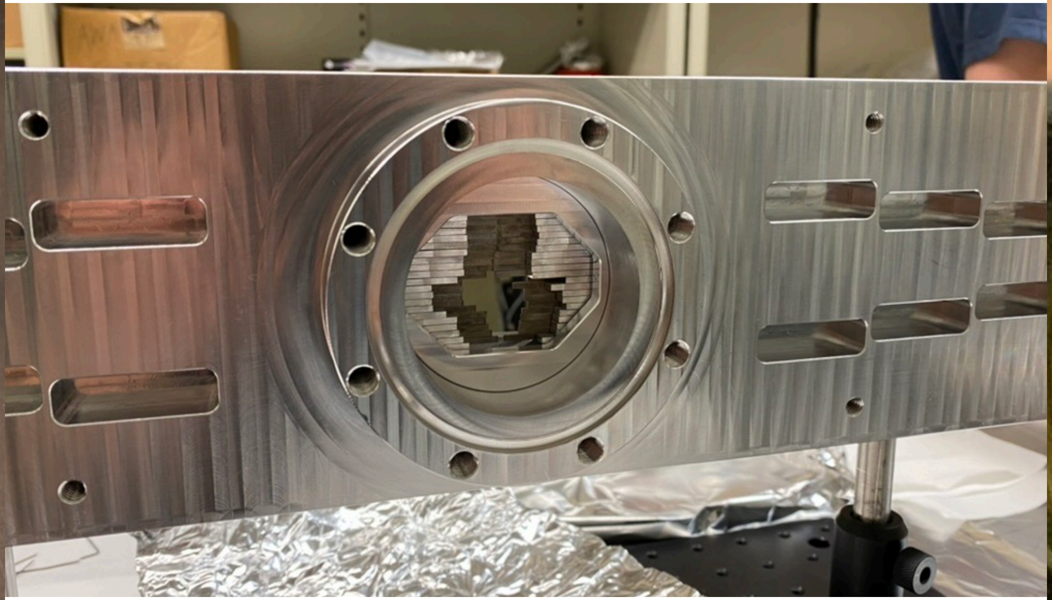




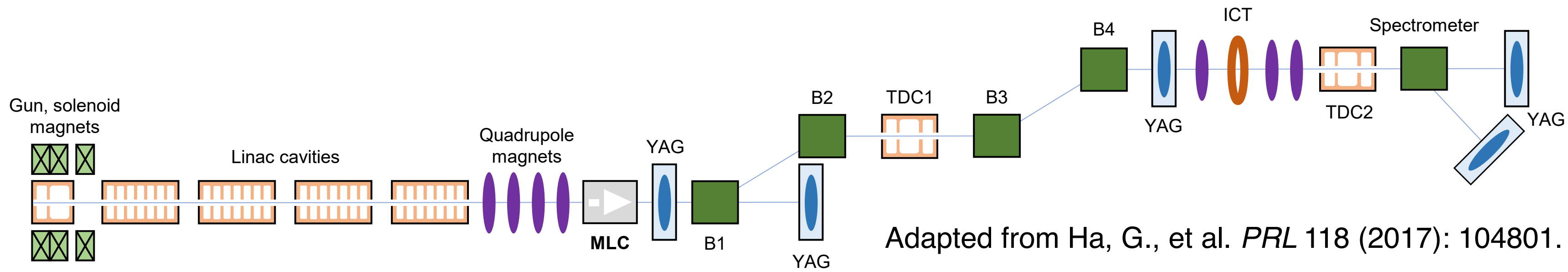




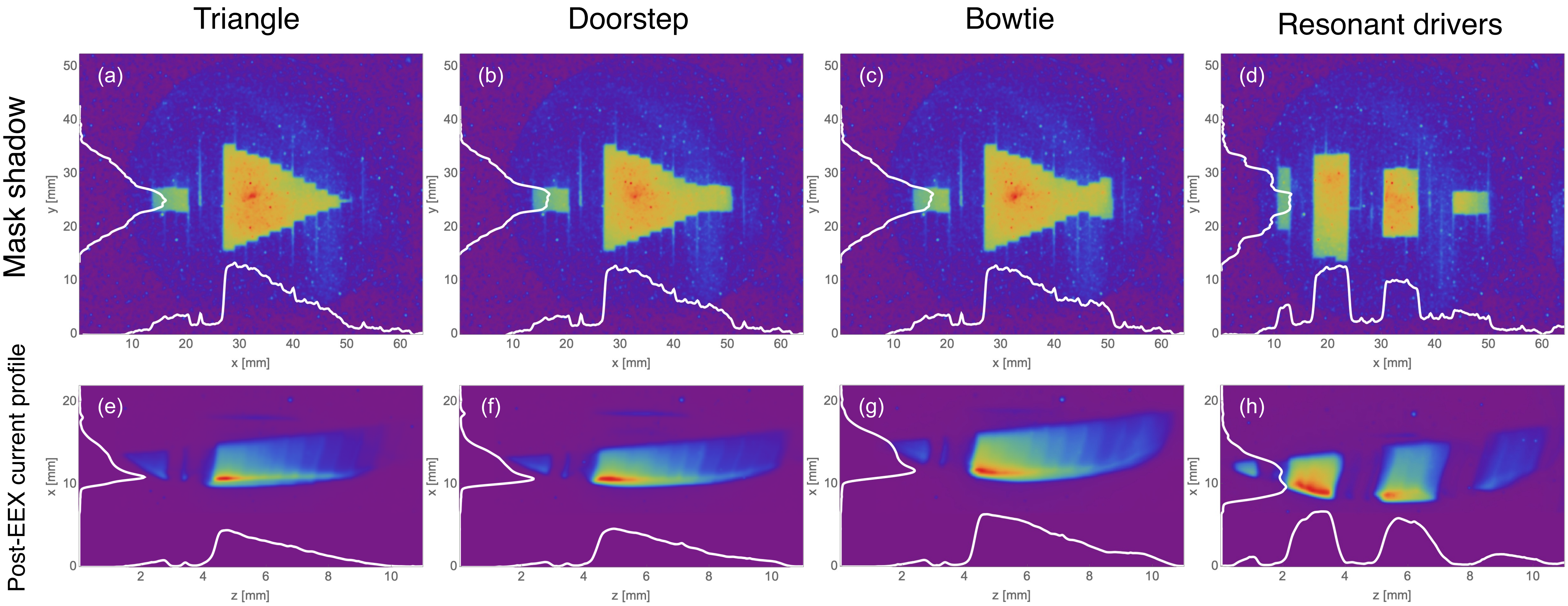
Reassembly and installation

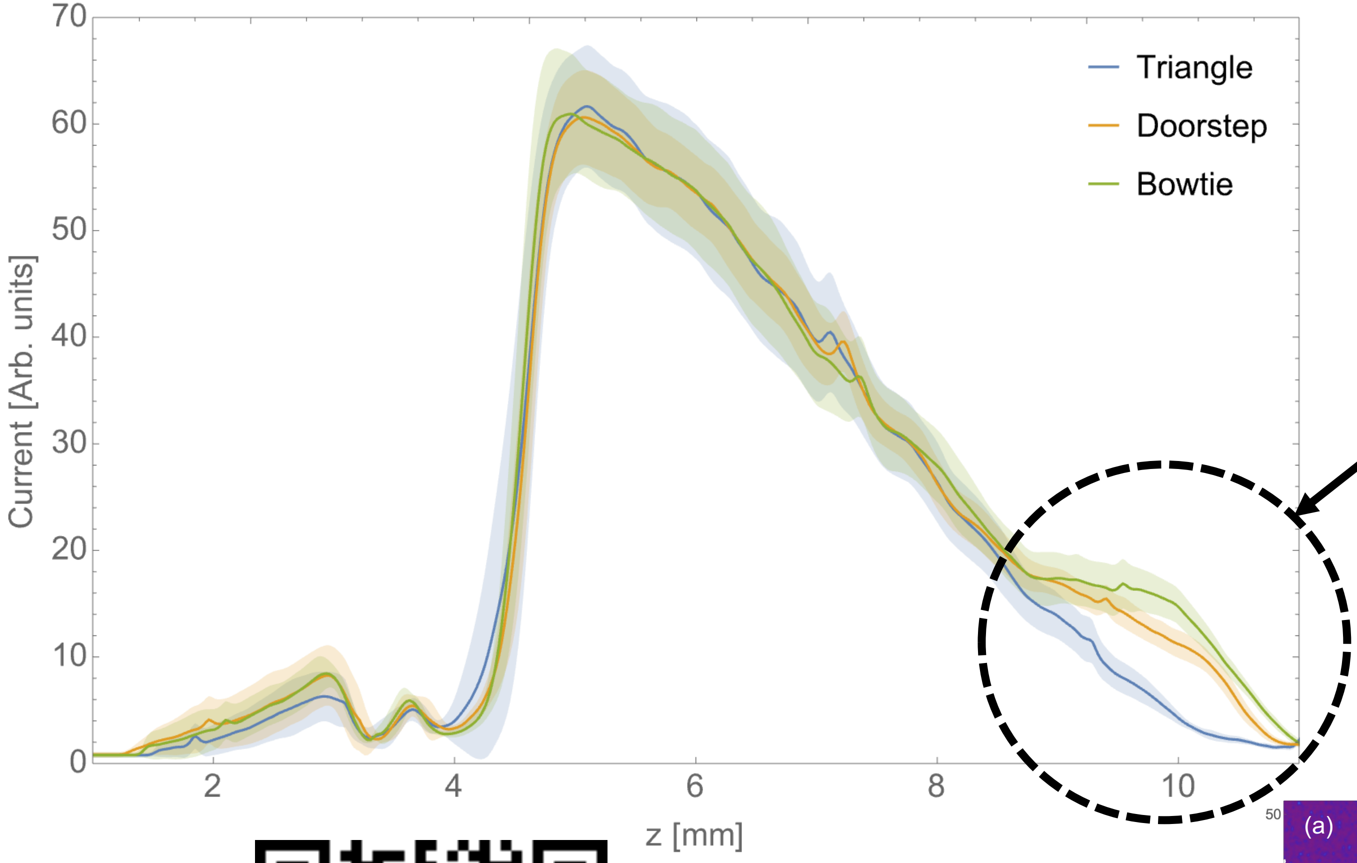


Experimental results

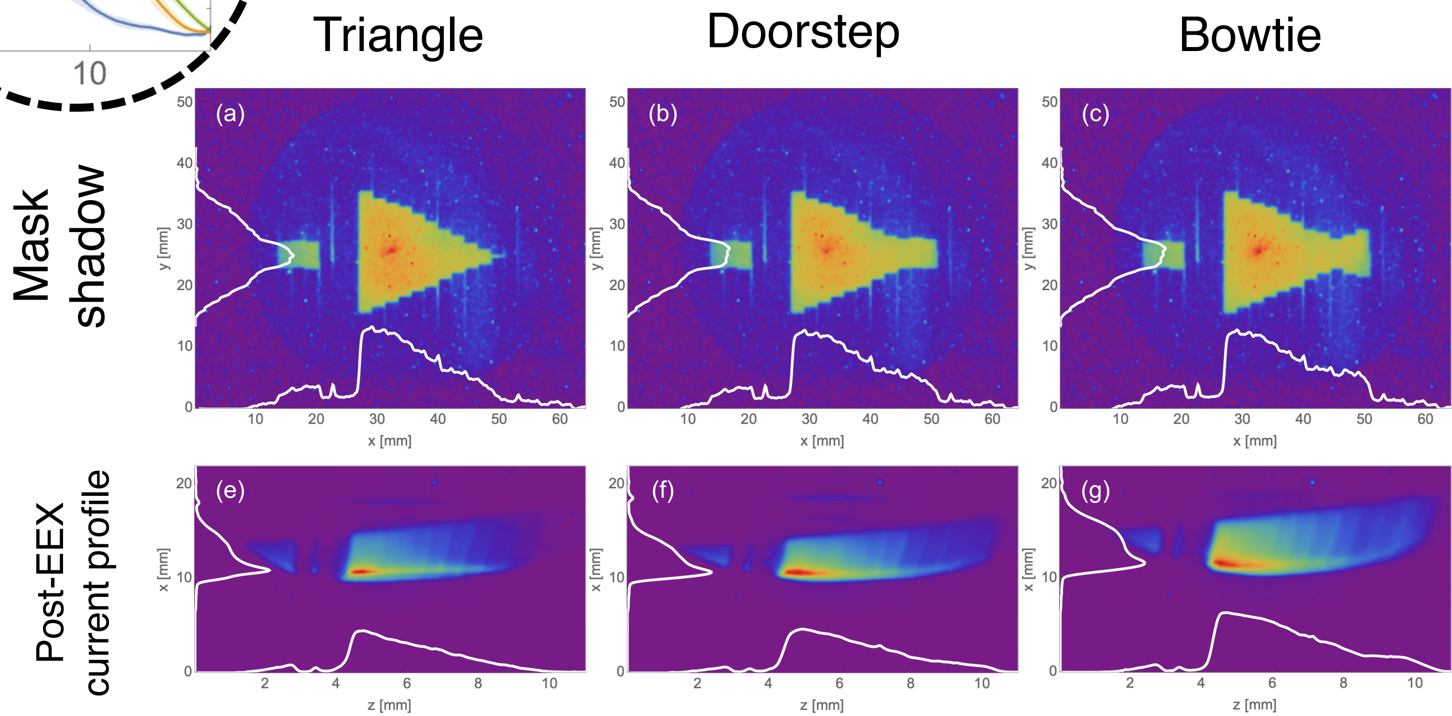


Adapted from Ha, G., et al. *PRL* 118 (2017): 104801.





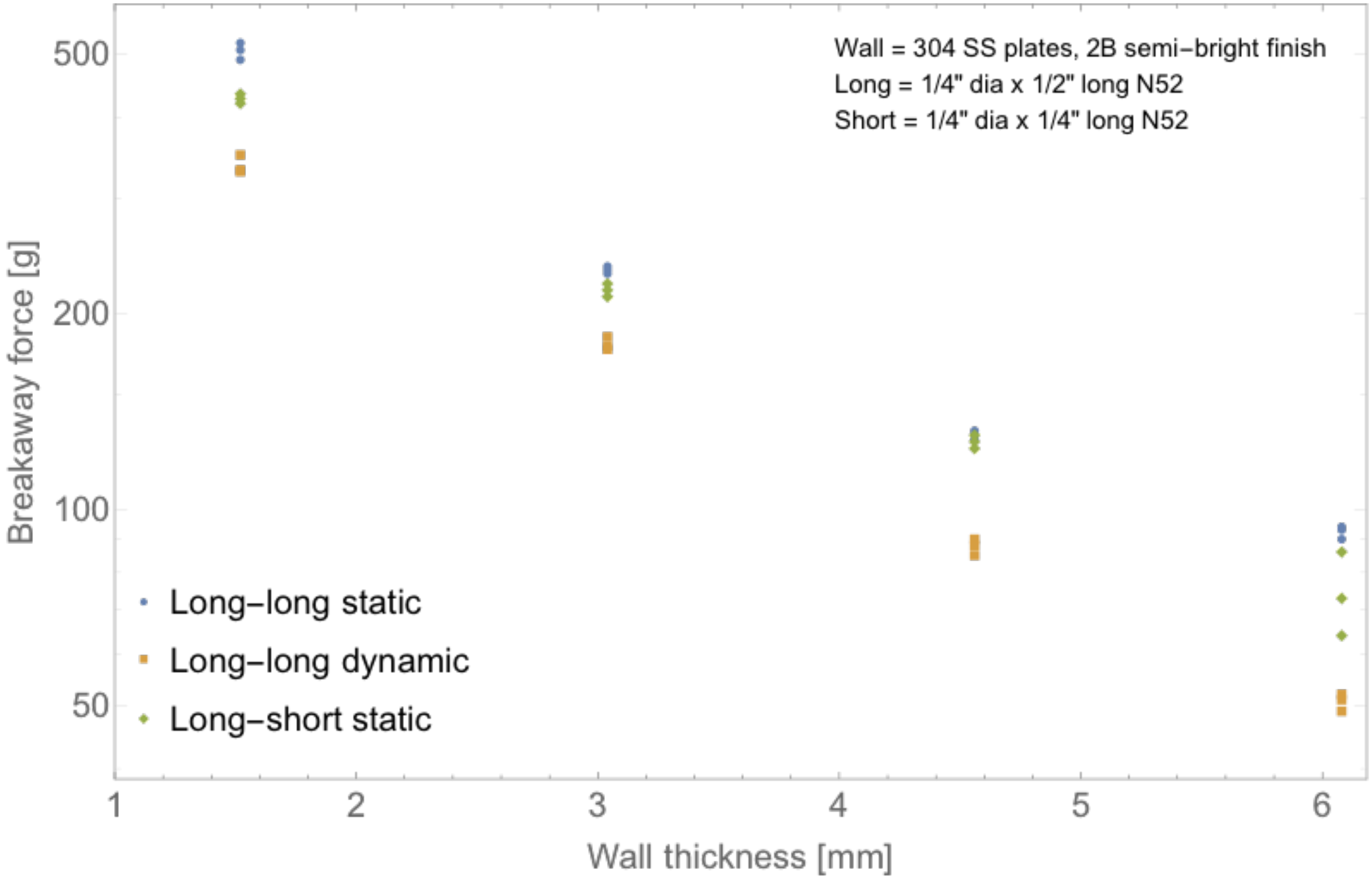
Beam shaping detail



Majernik, N., et al. "Beam shaping using an ultrahigh vacuum multileaf collimator and emittance exchange beamline." *Physical Review Accelerators and Beams* 26.2 (2023): 022801.

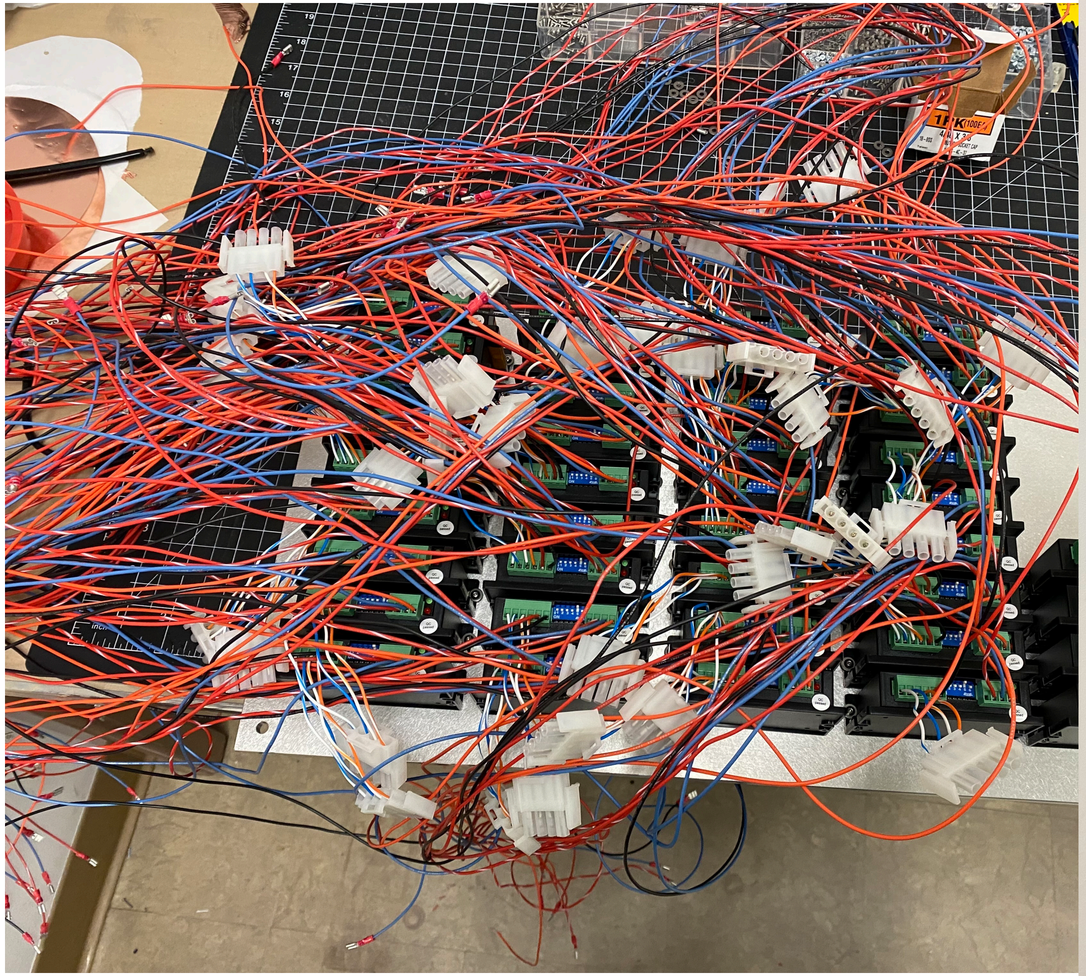
Initial friction test

- Need to ensure that the magnetic coupling is sufficient
  - Tradeoff between coupling strength and compactness
  - Breakaway force must exceed leaf+carrier weight, all friction sources, and some safety margin
  - Friction expected to be dominated by magnet-chamber interface due to substantial normal force
- Characterized breakaway force as function of vacuum chamber thickness for ¼” diameter magnets (consistent with 2 mm leaf spacing design)



Spaghetti and software

- 40 individual stepper controllers
- Arduino Mega controls these
- Arduino controlled over serial by laptop
  - Presently no automated feedback
- Designed with challenging EMI environment in mind
  - Double shielded, 4 twisted conductor cables connect to each stepper
  - Wires run in EMF shielded sheathes, grounded to Faraday cage electronics box



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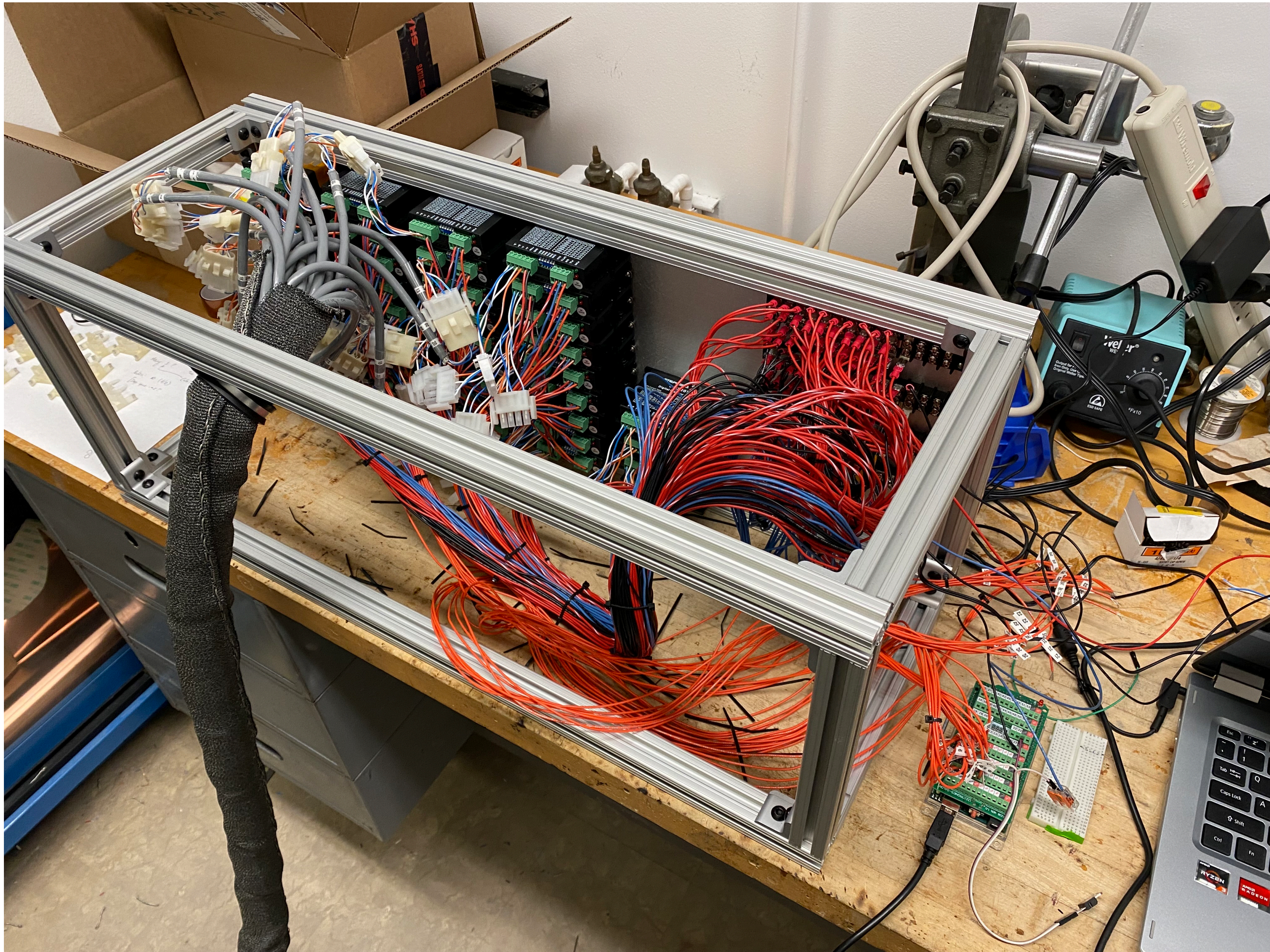
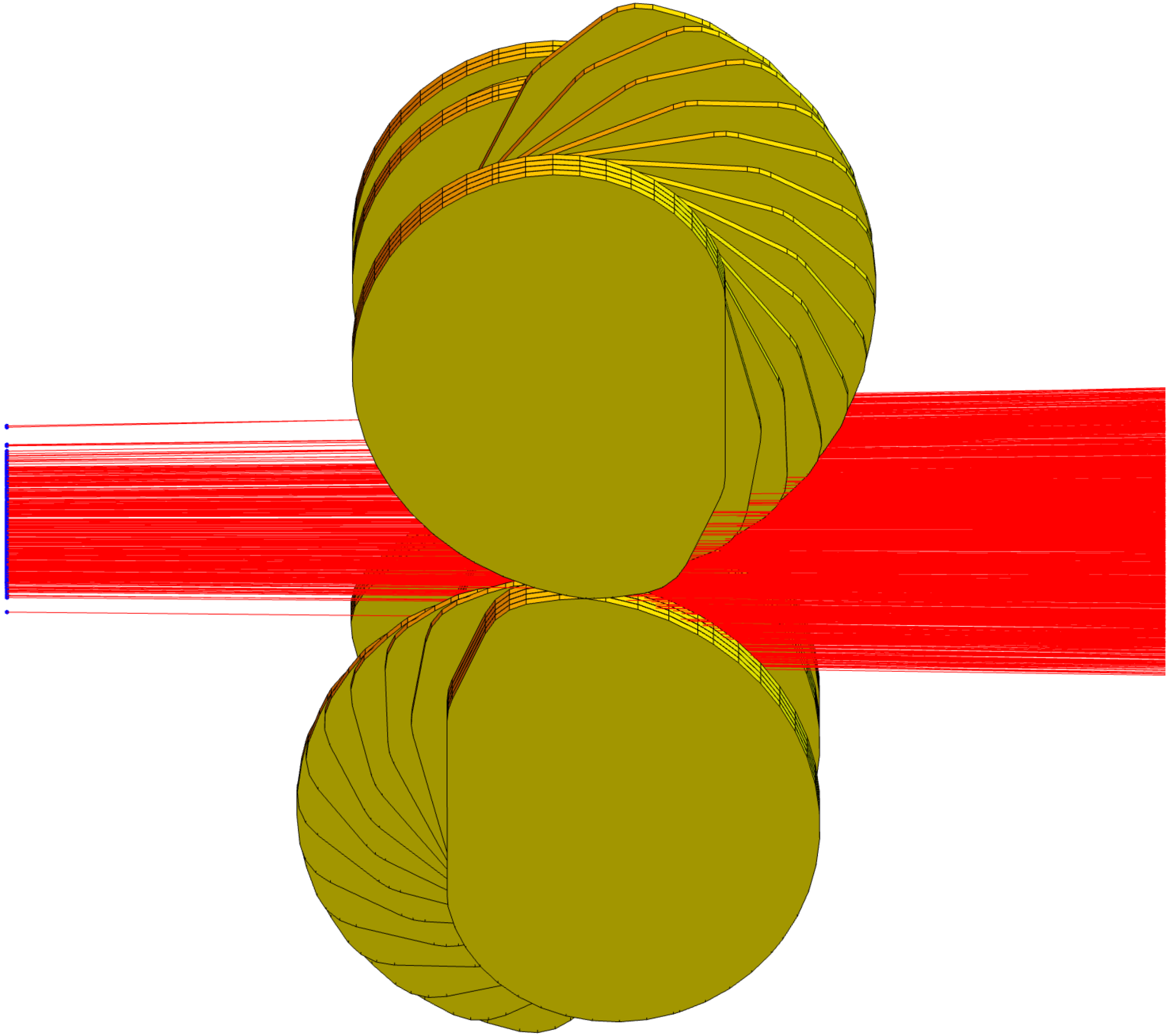
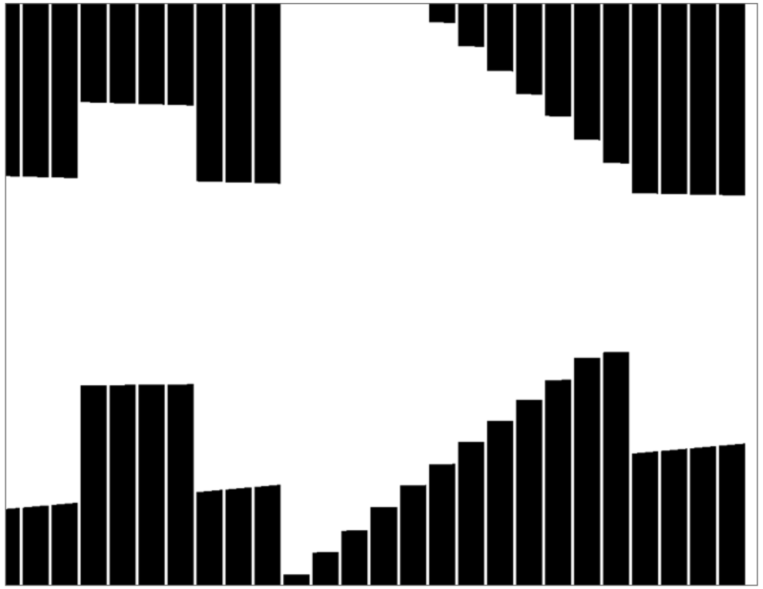
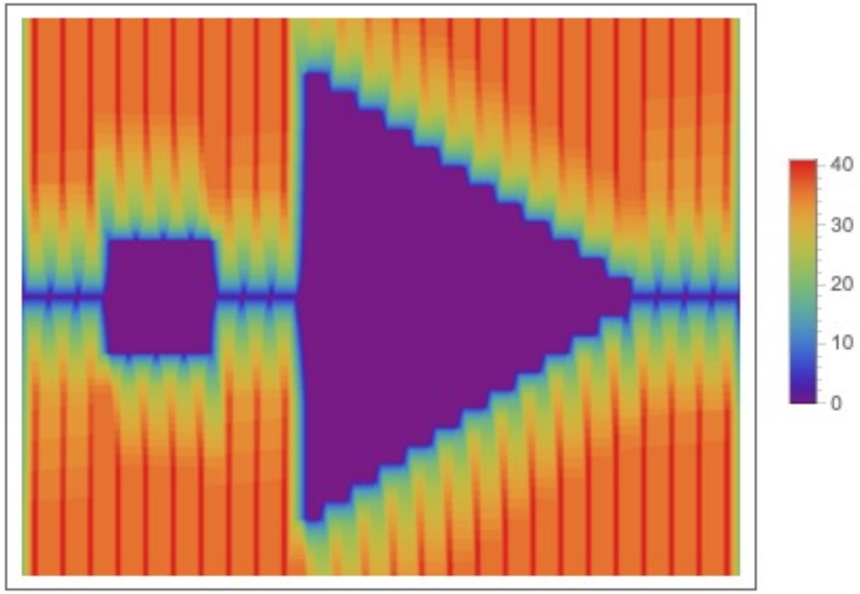
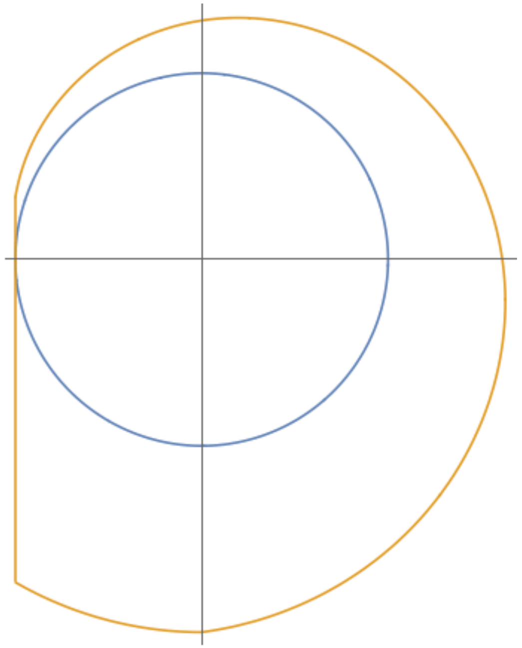


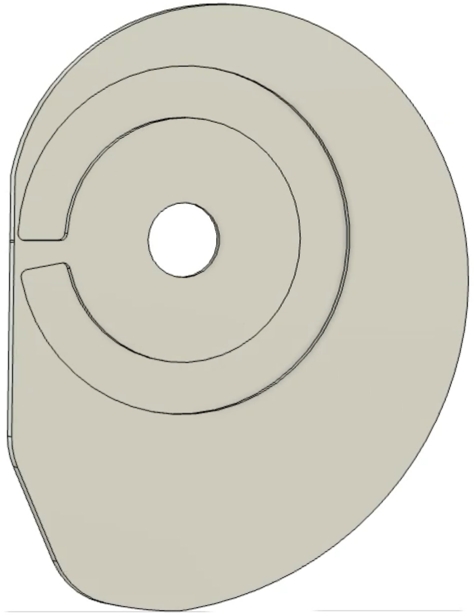
Rotor MLC concept







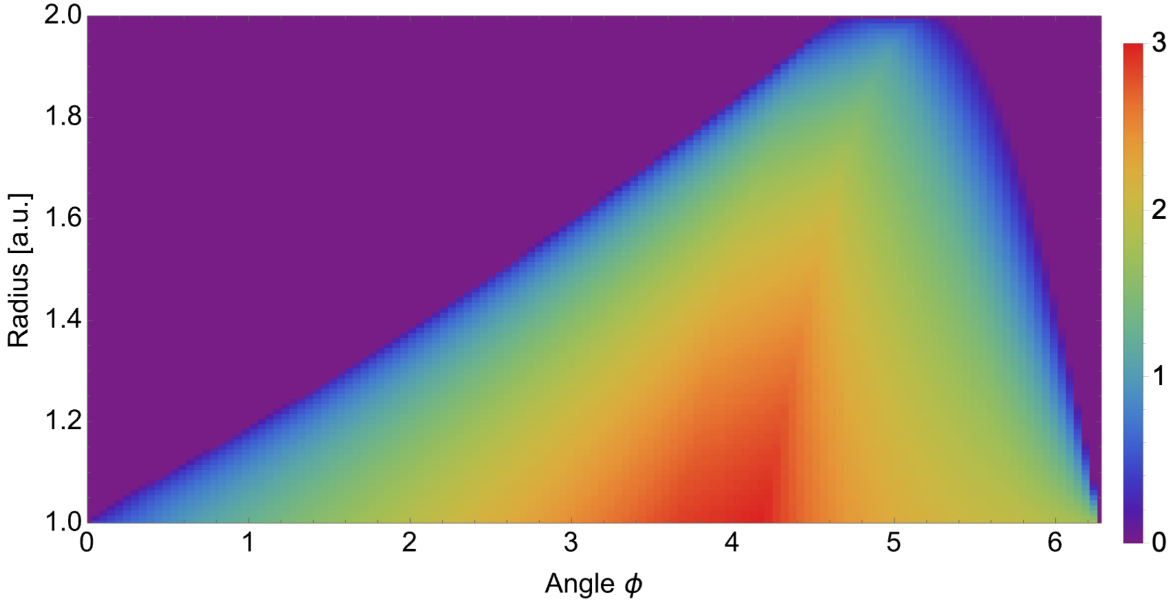


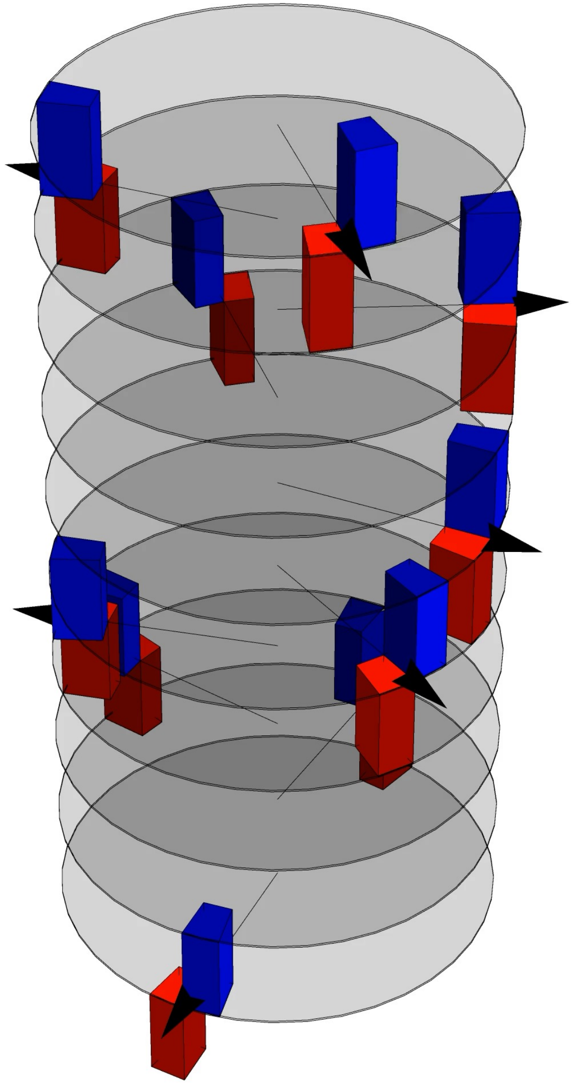


Rotor MLC actuation

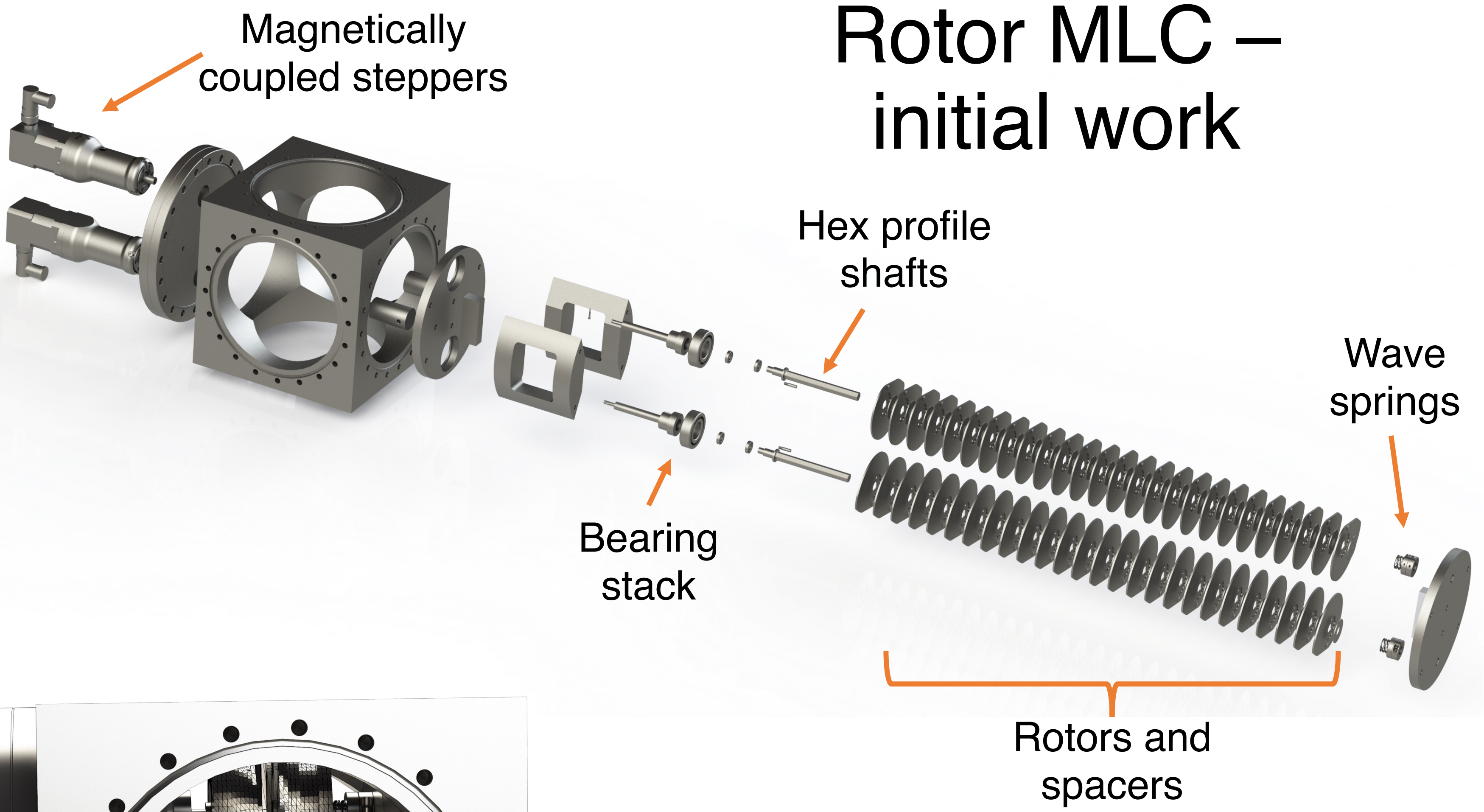
- Padlock inspired mechanism
- 20x fewer trans-chamber couplings
- Scales to larger aperture
  - Always installed on beamline

Provisional patent

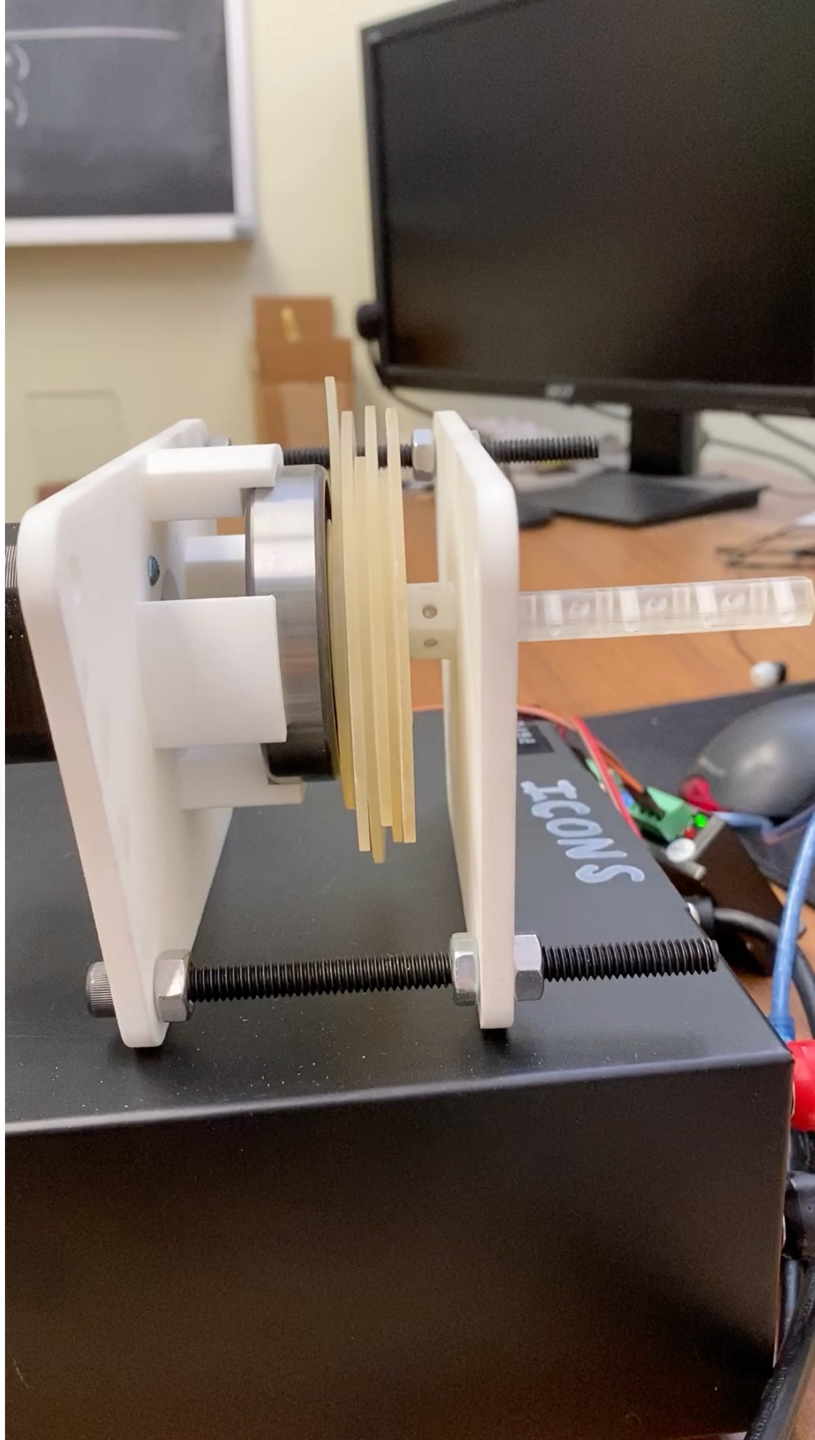




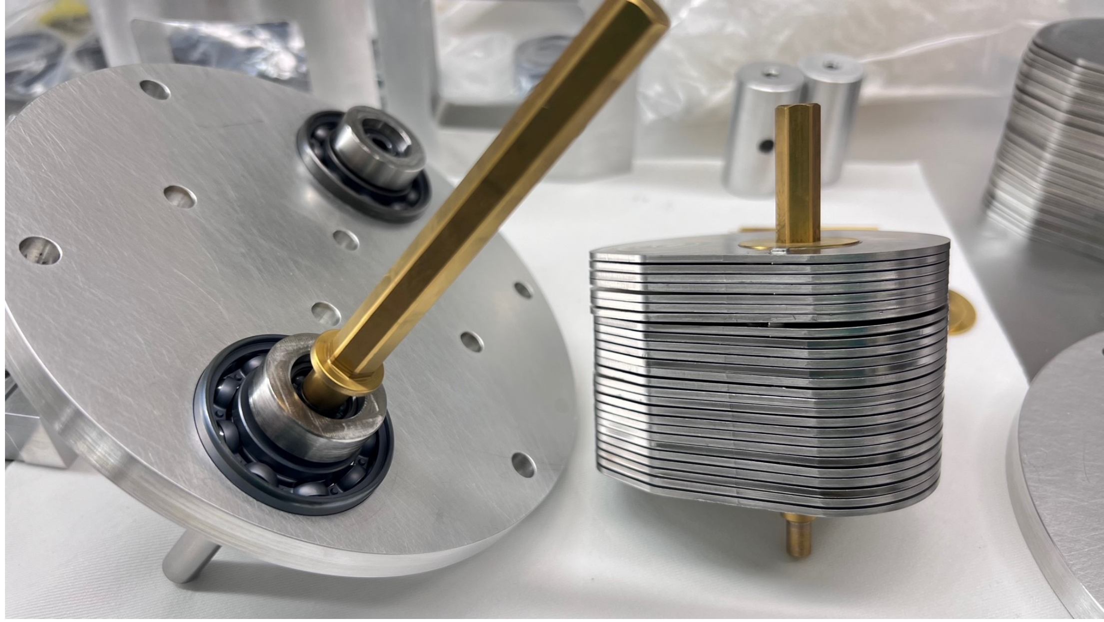
Rotor MLC – initial work

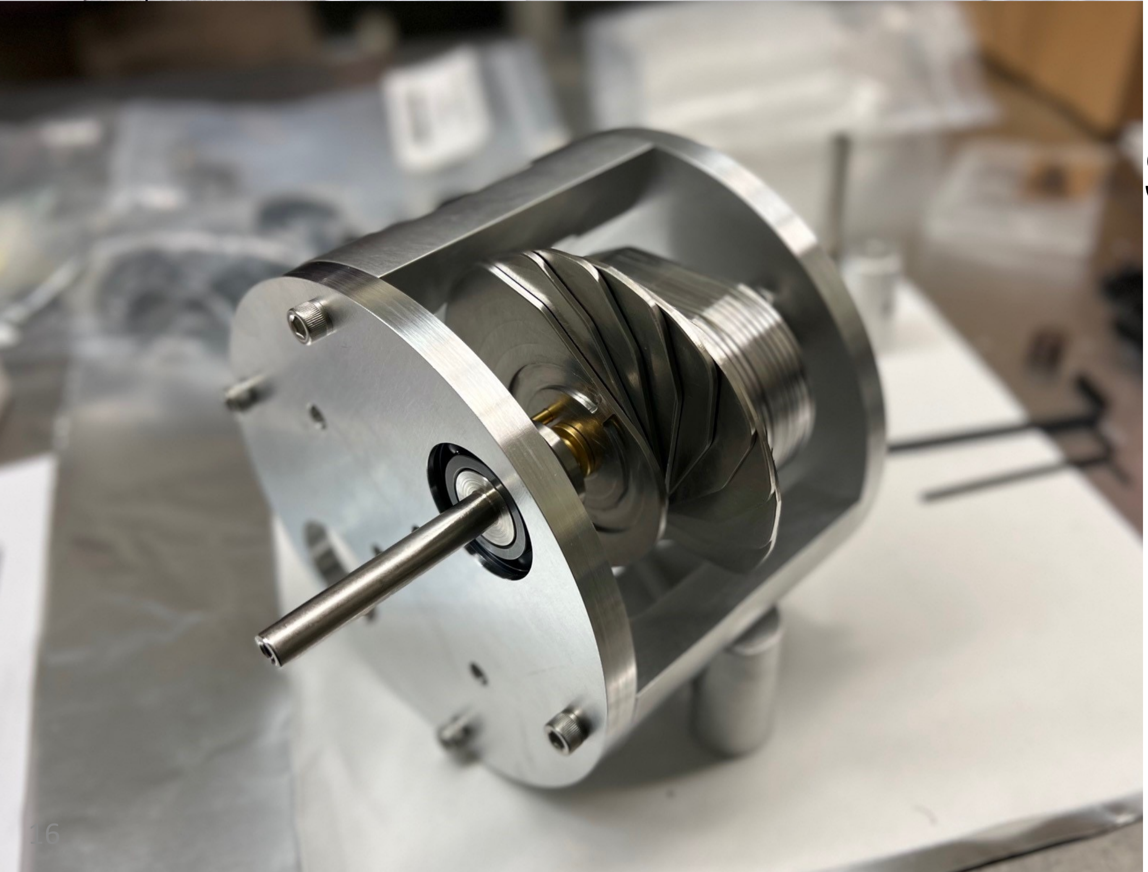


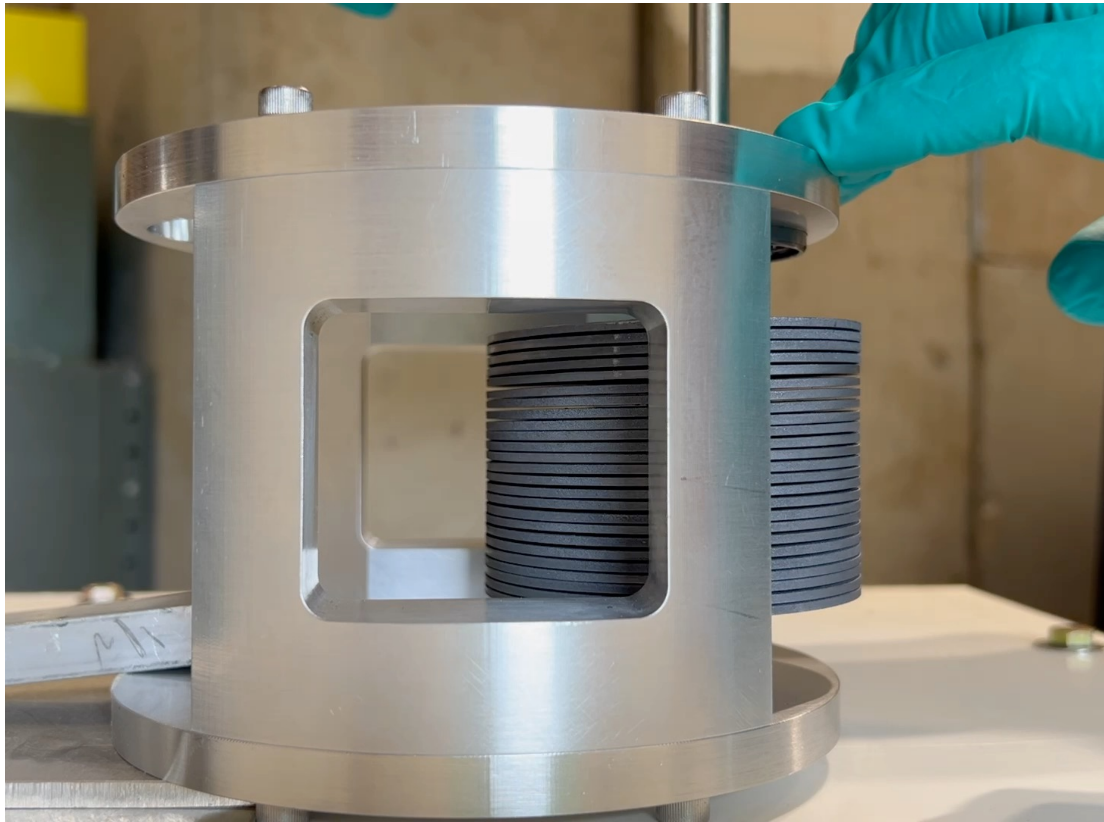
- 3D printed prototype demonstrated
- Engineering design complete



Rotor MLC – status

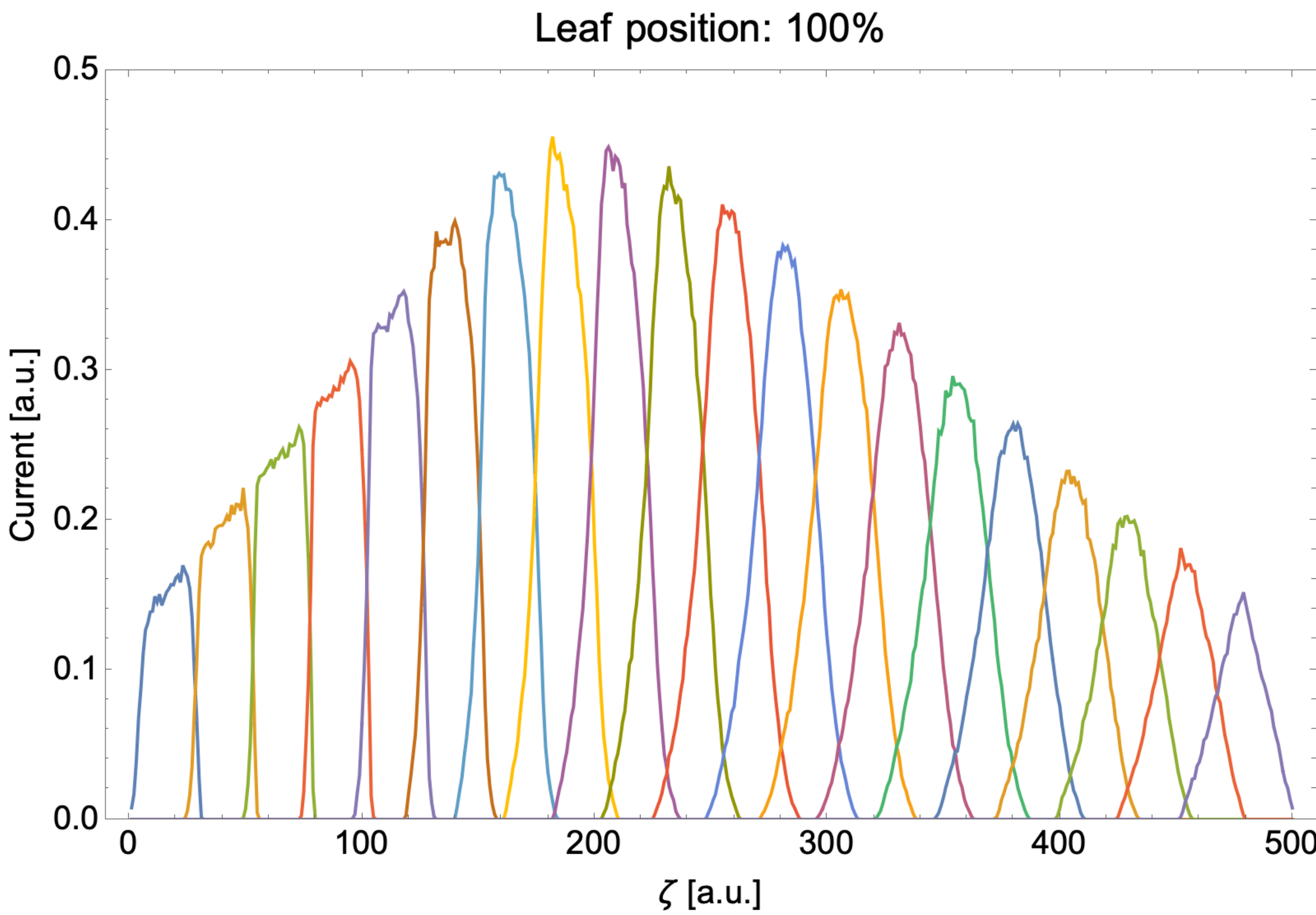






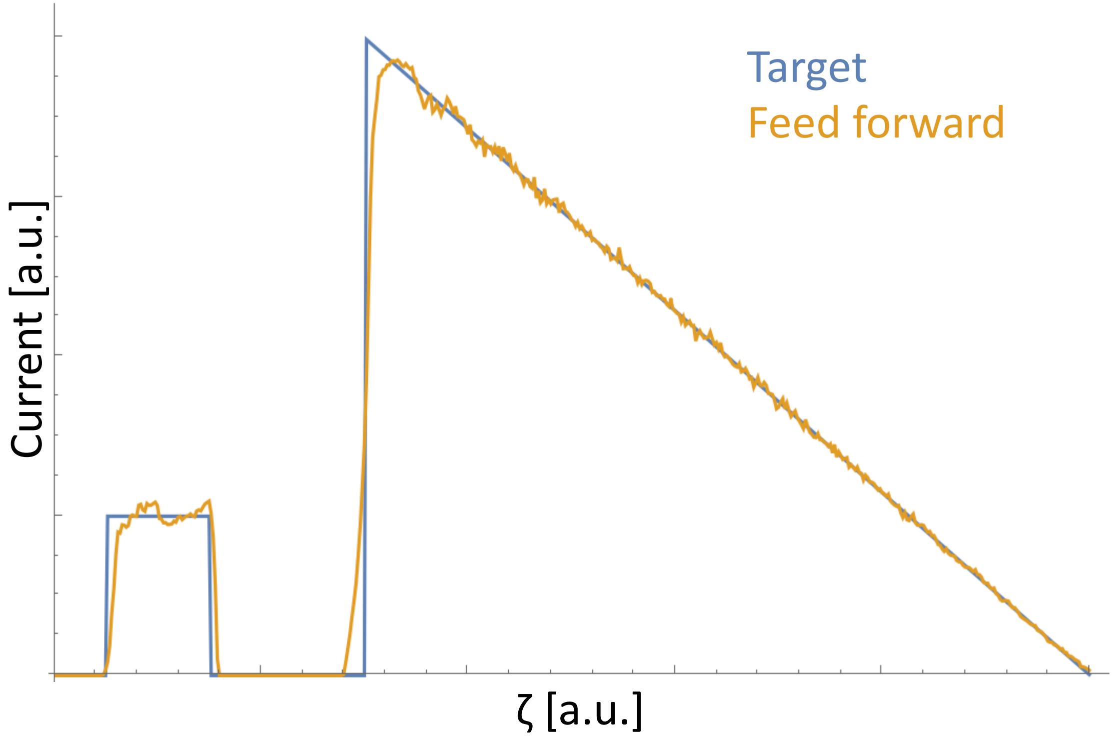
Feed forward control – initial guess

- **Goal**: Set leaves to produce user-defined current profile
- **Input space**: n leaf positions
- **Output space**: Current in k bins
- Each leaf, i, at a position x_i, maps to a contribution in this output space, $\overrightarrow{f_i}(x_i)$
- Since we're neglecting collective effects, sum all $\overrightarrow{f_i}$ to find the resulting current profile as a point in output space
- Optimize $\vec{x}$
- Additional considerations:
  - Increasing x_i gives monotonic response, but not in a straight line
  - Determining response functions:
    - Simulations
    - Experimentally via interpolation

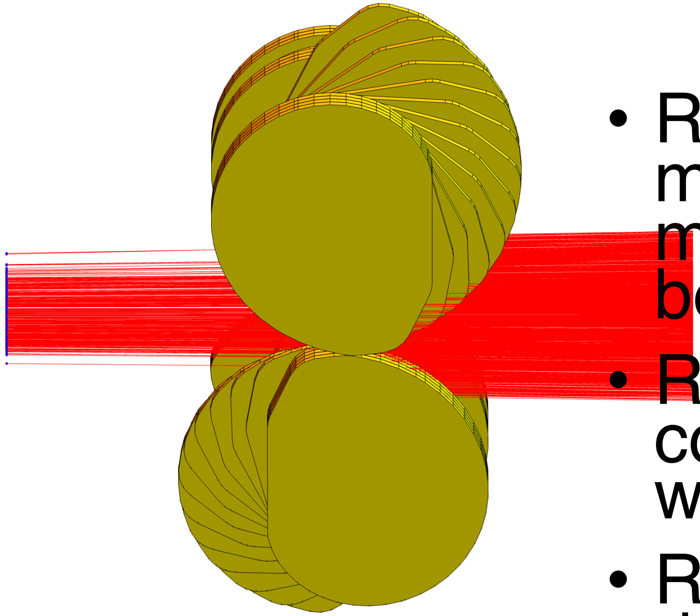


Feed forward control – refinement

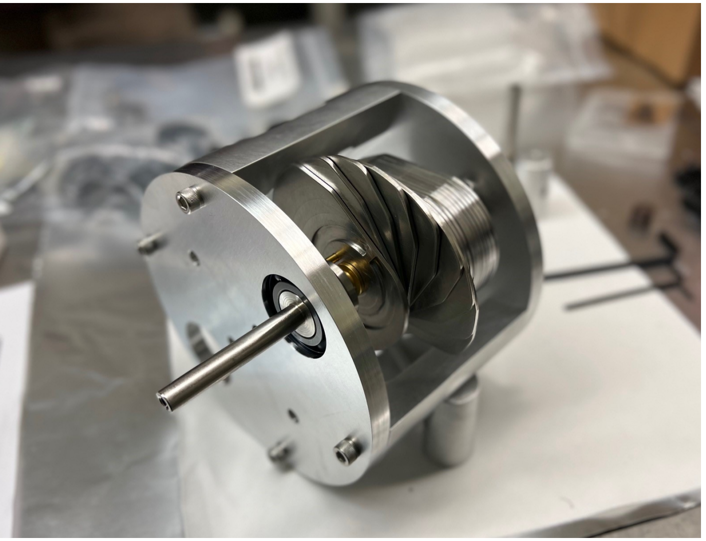
- Perturb each leaf about nominal position
  - Now assume linear response
  - Collective effects should be ~constant under this perturbation
- Perform optimization with these new response functions
  - Rinse and repeat as needed
- Users don't need to care about the rotor profiles, if there are 3D effects, etc.
  - **Just specify what you want and let the control system create it**

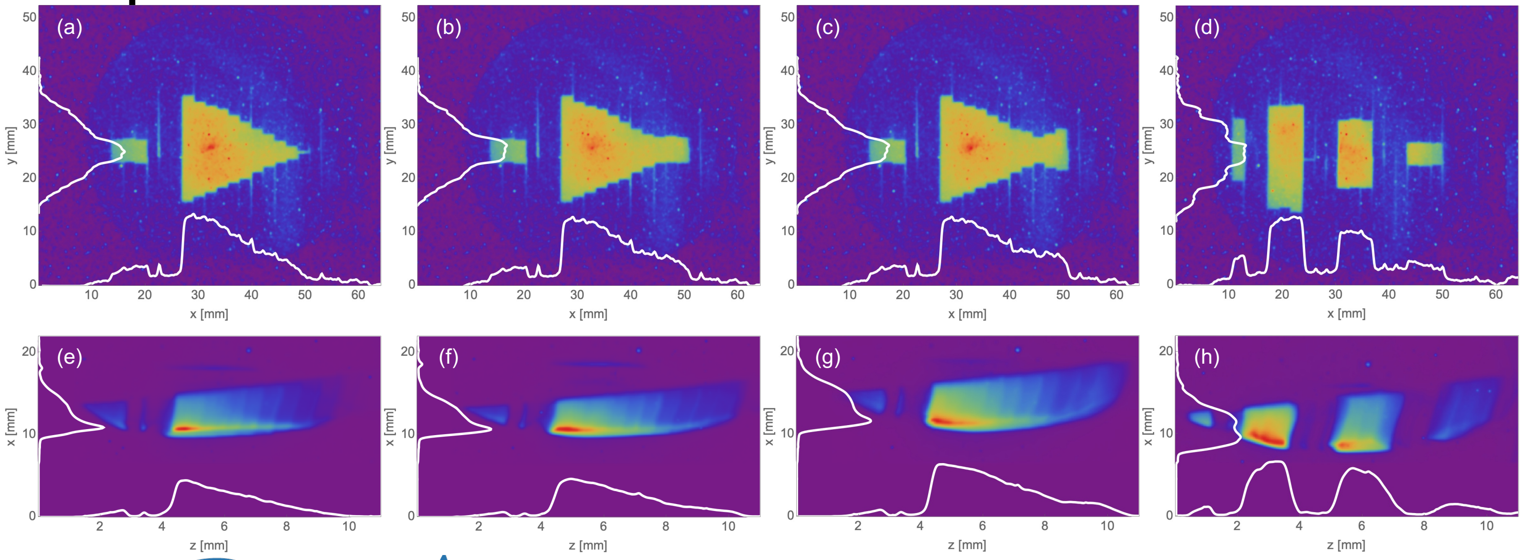


Summary



- Replaced laser cut tungsten masks with UHV-compatible multileaf collimator in EEX beamline
- Real-time, nearly arbitrary control over drive and witness bunch shaping
- Rotor-based MLC in development
- Feed-forward control demonstrated on simulated data; ready to deploy experimentally
- Future
  - Always-available AWA user capability: profile-on-demand
  - ML optimization of high transformer ratio





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