Beam shaping using an ultra-high vacuum multileaf collimator and emittance exchange beamline

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Motivation

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

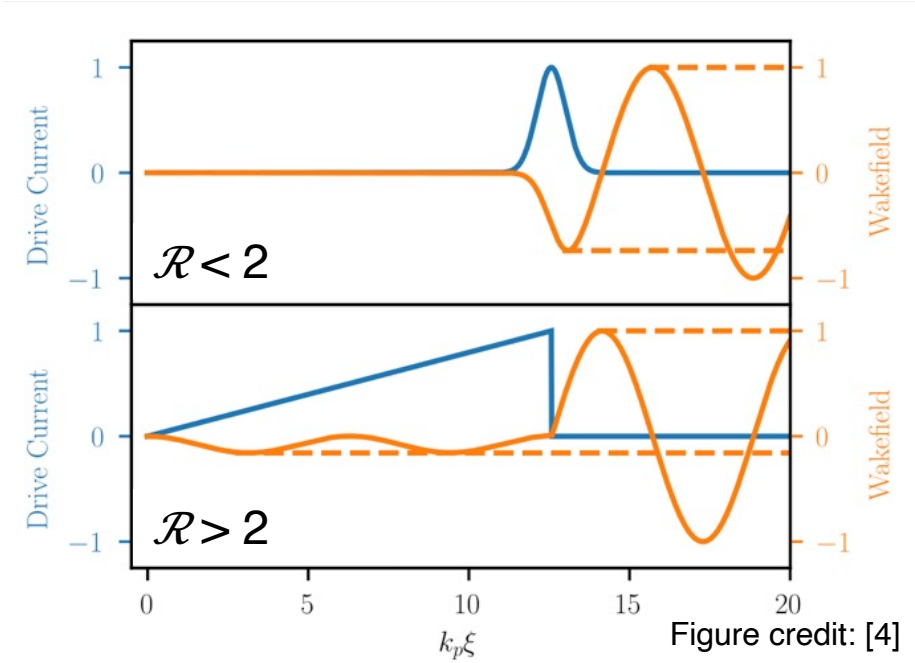
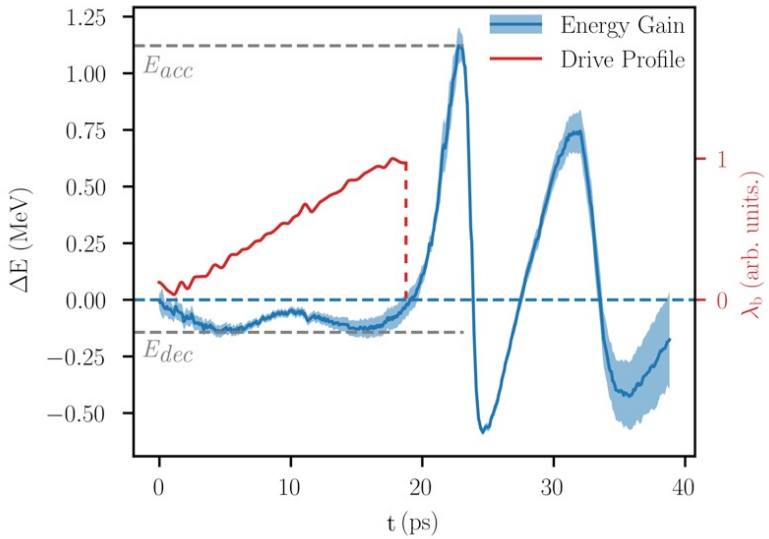


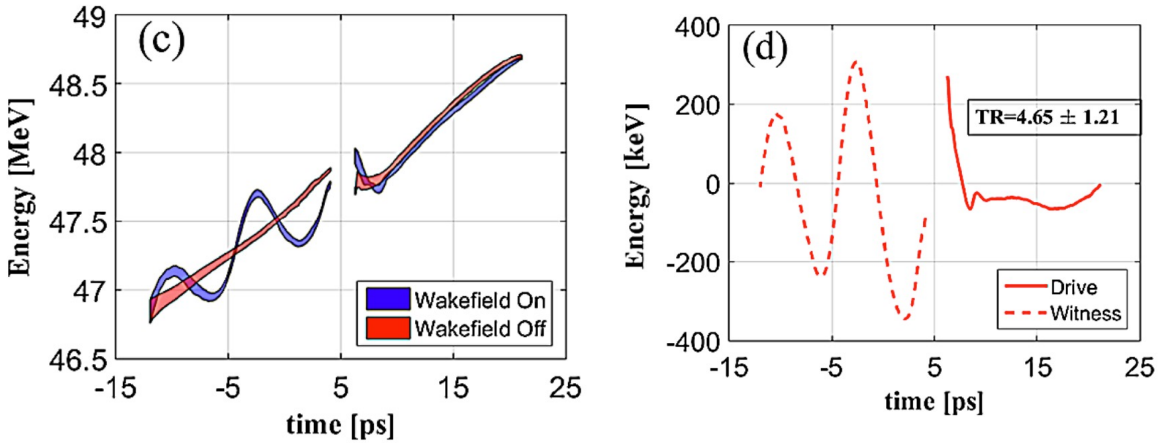
Figure credit: [4]

$\mathcal{R} = 7.8$ in PWFA



Roussel, R., et al. *PRL* 124.4 (2020): 044802.

$\mathcal{R} = 4.8$ in DWA



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Emittance exchange for advanced PWFA

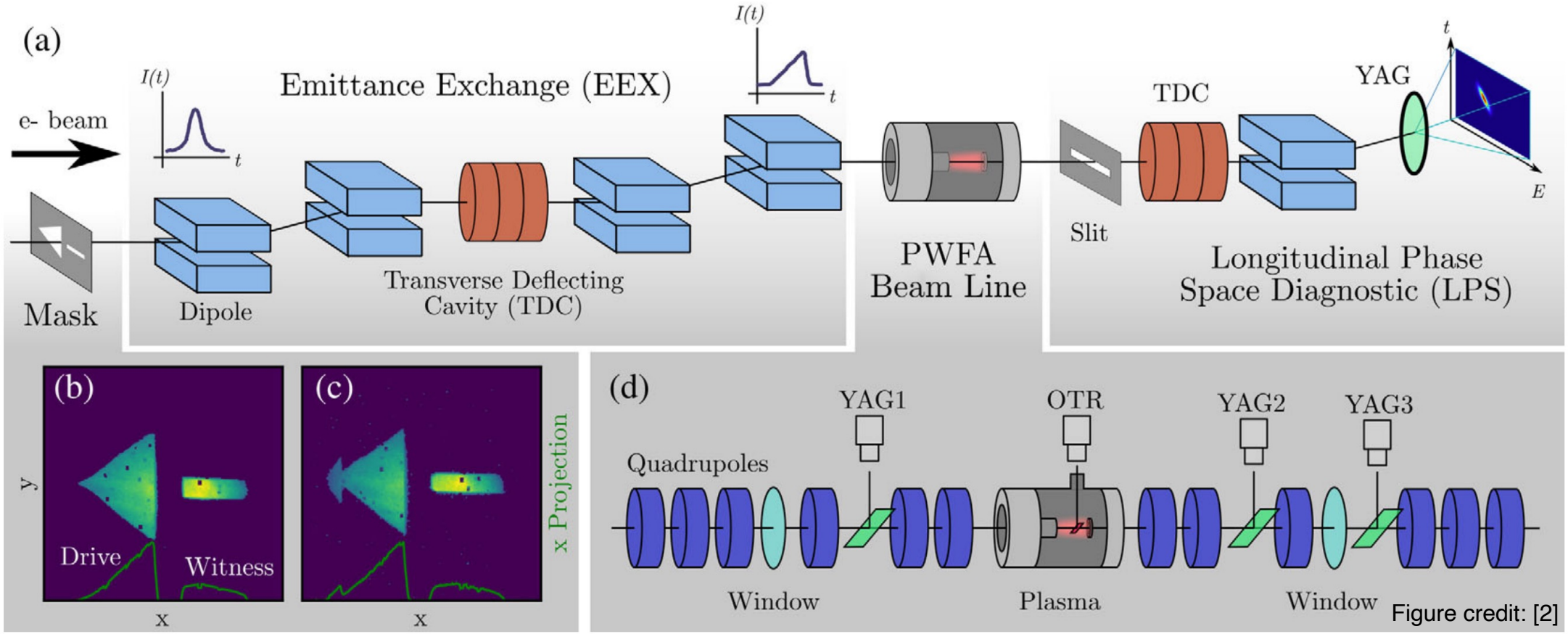

Figure credit: [2]

- 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 [2]

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

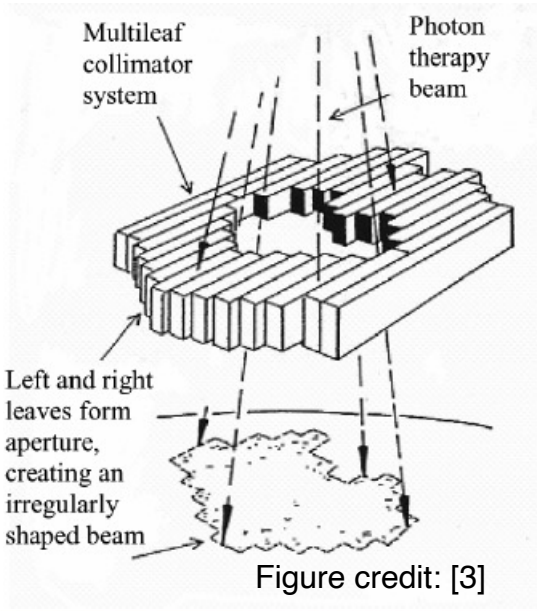

Figure credit: [3]


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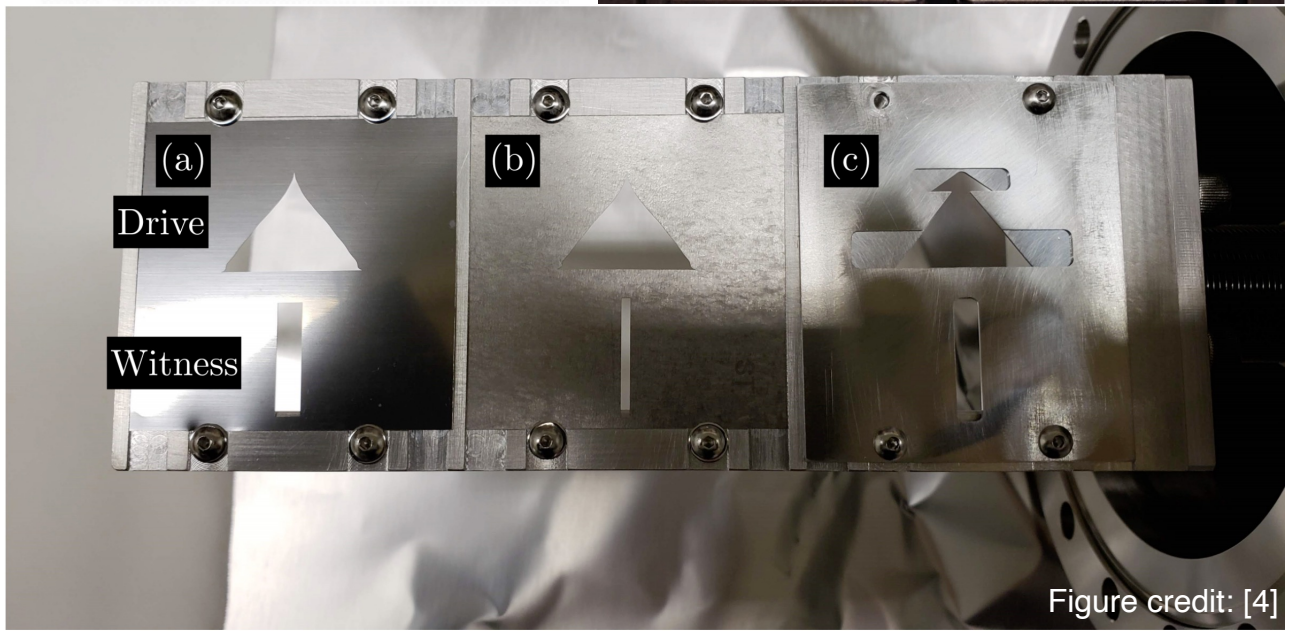


Figure credit: [4]

Simulation

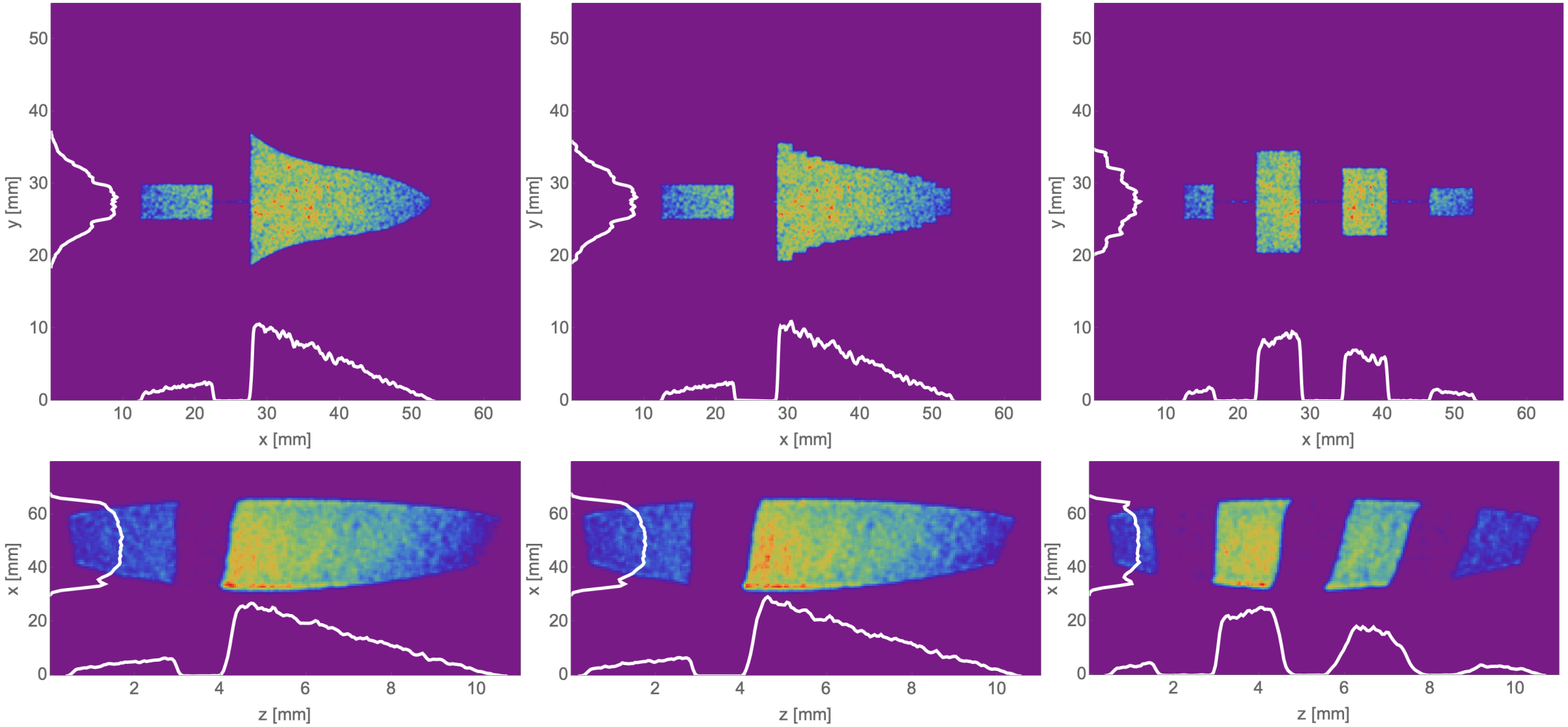
Smooth mask

MLC mask

Resonant driver

Mask shadow

Post-EEX current profile

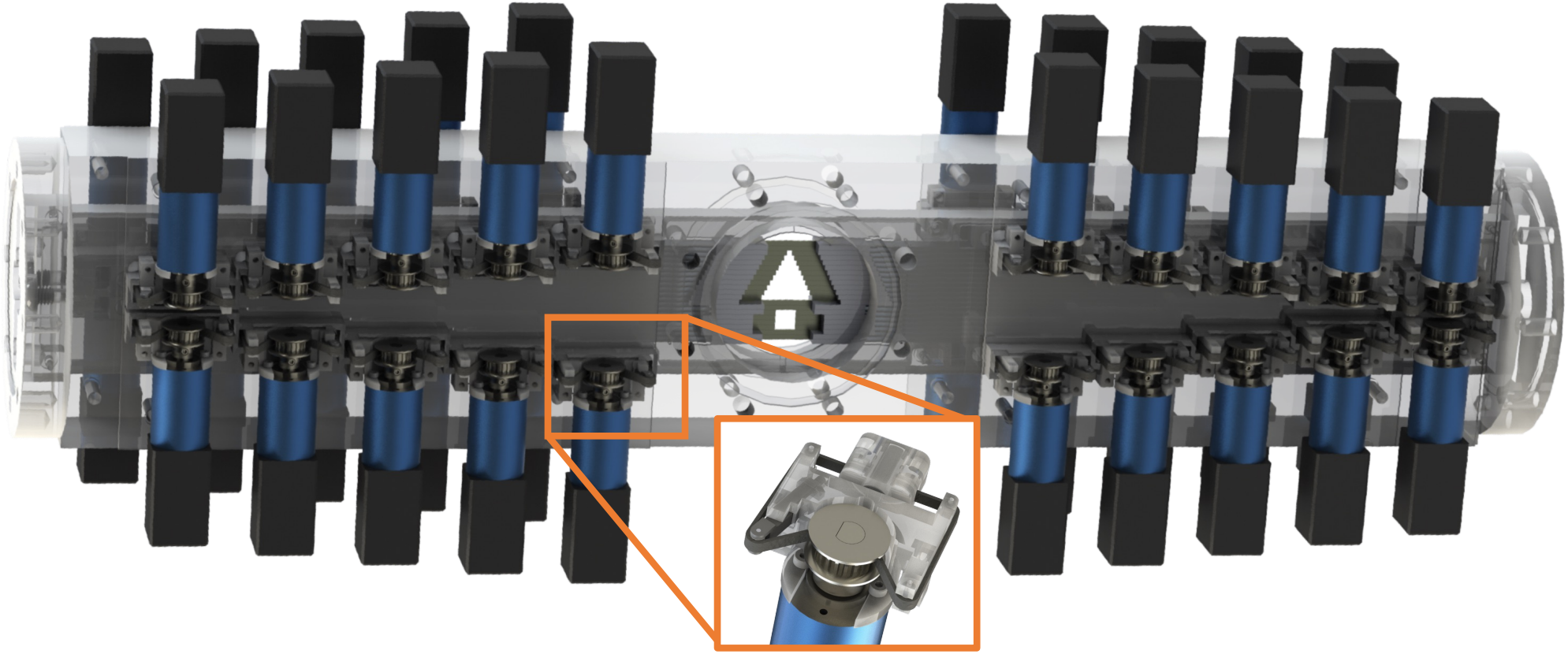


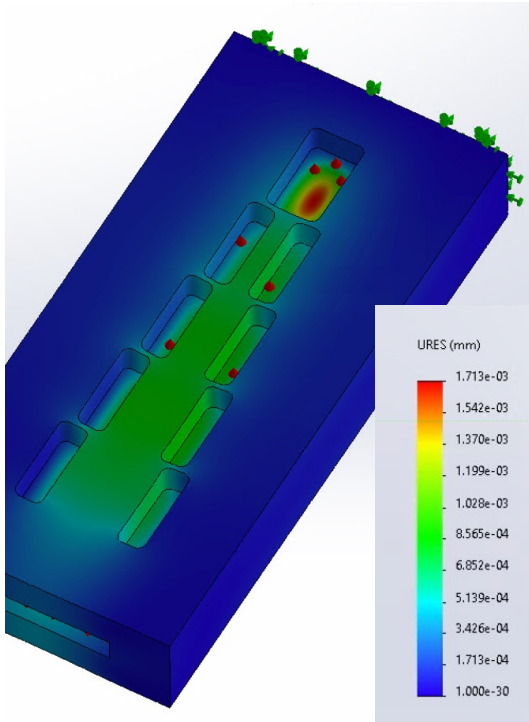
40 leaf MLC functionally equivalent to existing AWA masks

Design

- **UHV compatible**
- 40 leaves (20/side)
- Constant 2 mm spacing
- Magnetic coupling

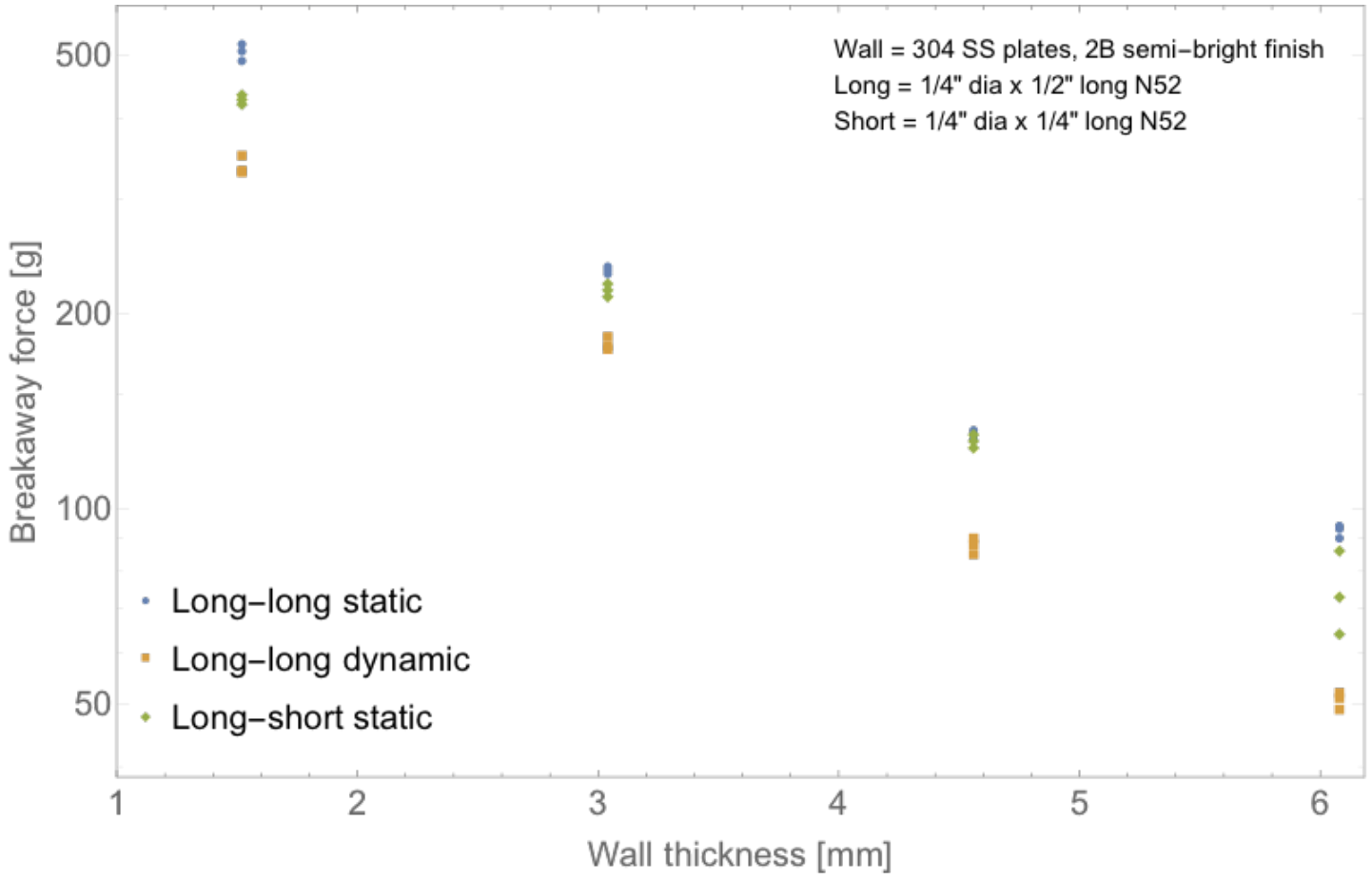
- 3D printed, micro-timing belt bidirectional drivetrain modules
- 10 mm travel/leaf
- Assumes camera-based feedback





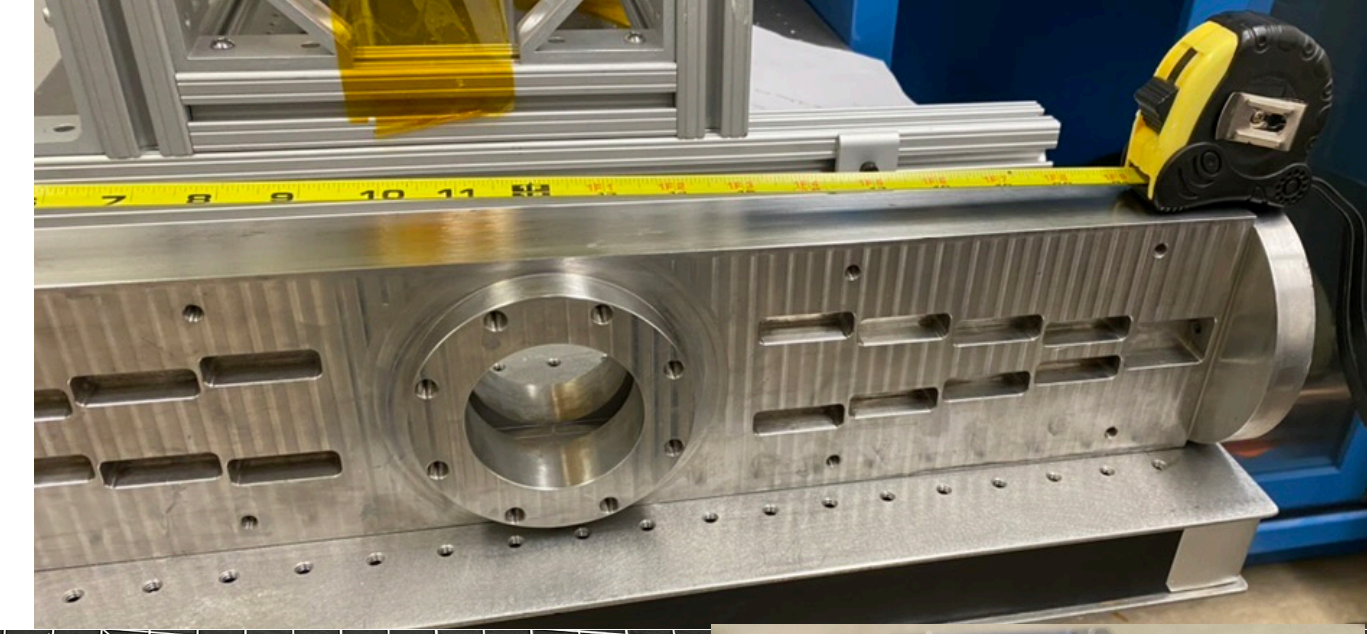
Initial friction test

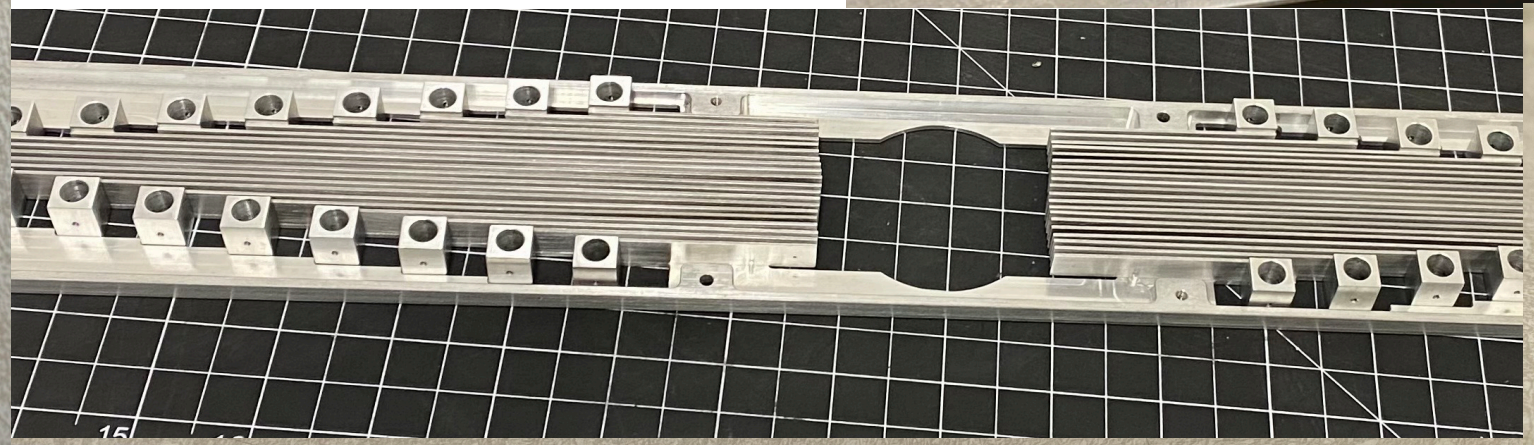
- Need to ensure that the magnetic coupling is sufficient
  - Tradeoff between coupling strength and compactness
  - Breakaway force must exceed leaf+carrier weight, all friction sources, and some safety margin
  - Friction expected to be dominated by magnet-chamber interface due to substantial normal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

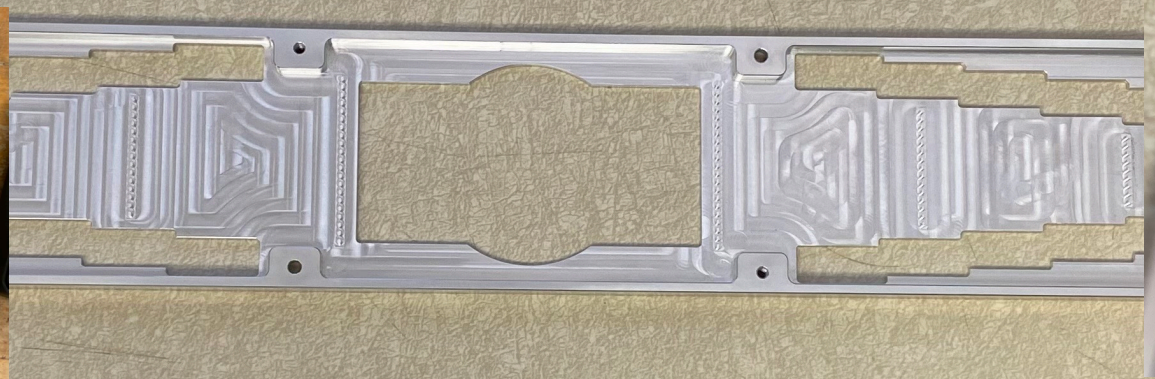


Fabrication

- 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

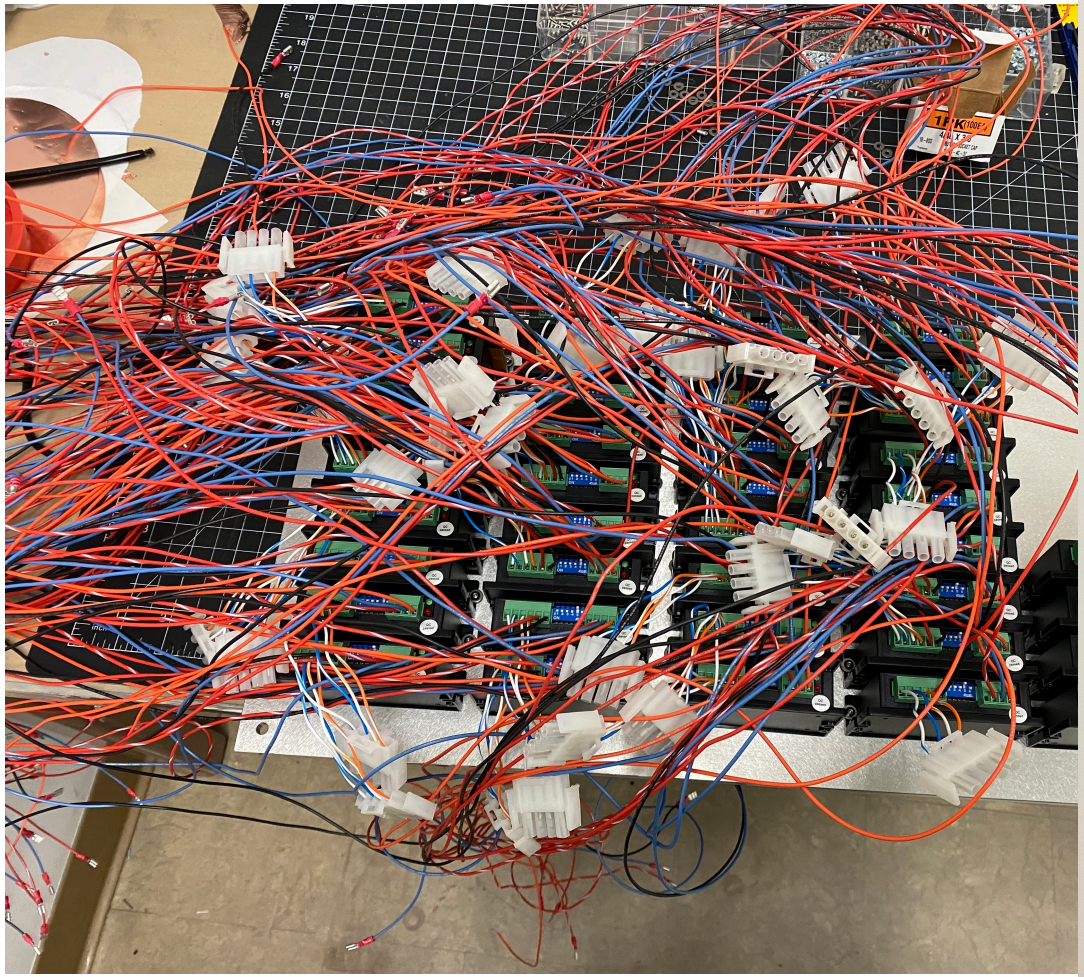






Spaghetti and software

- 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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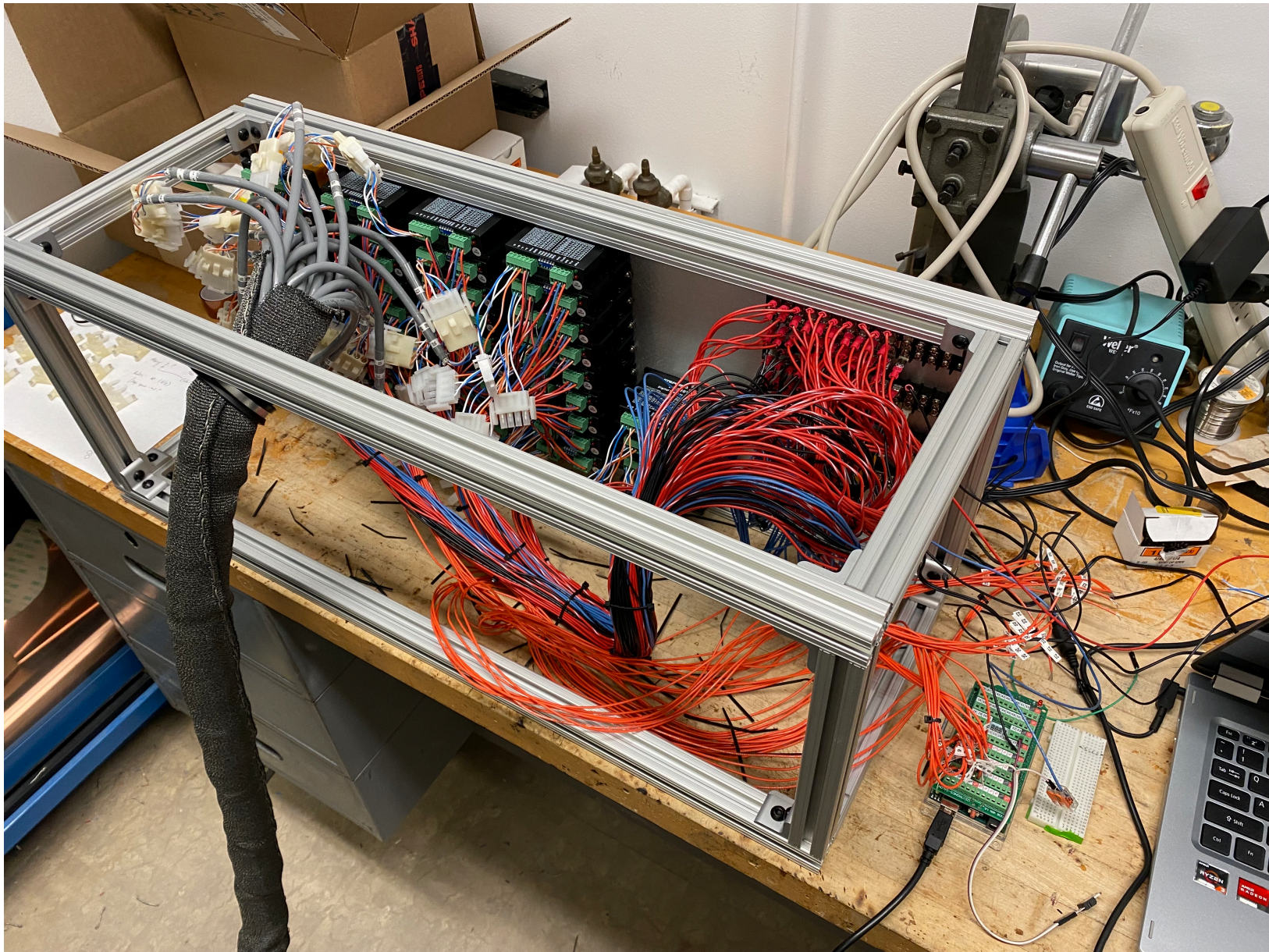
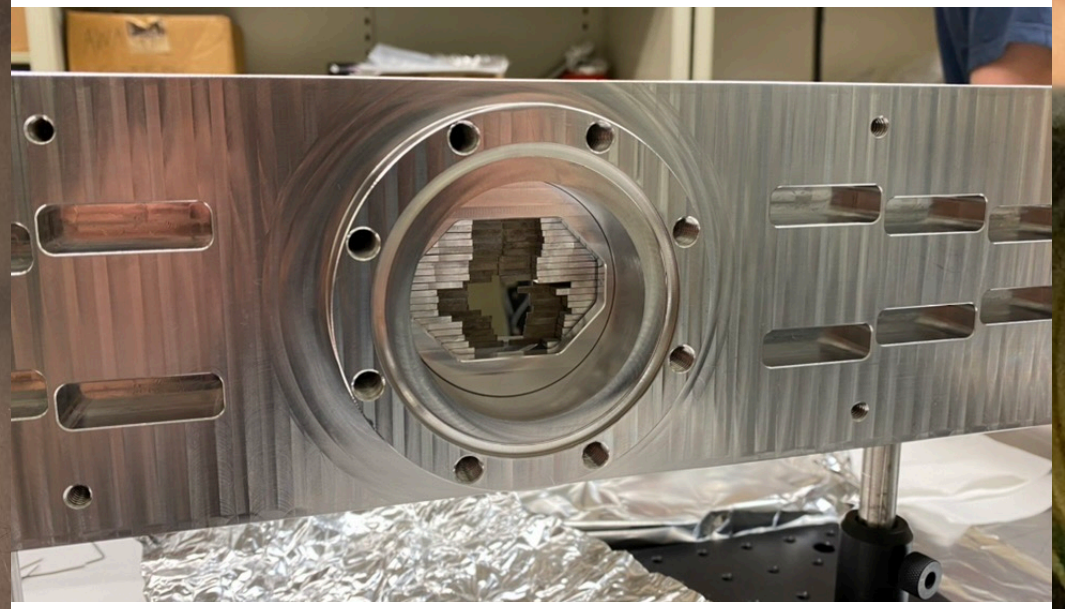
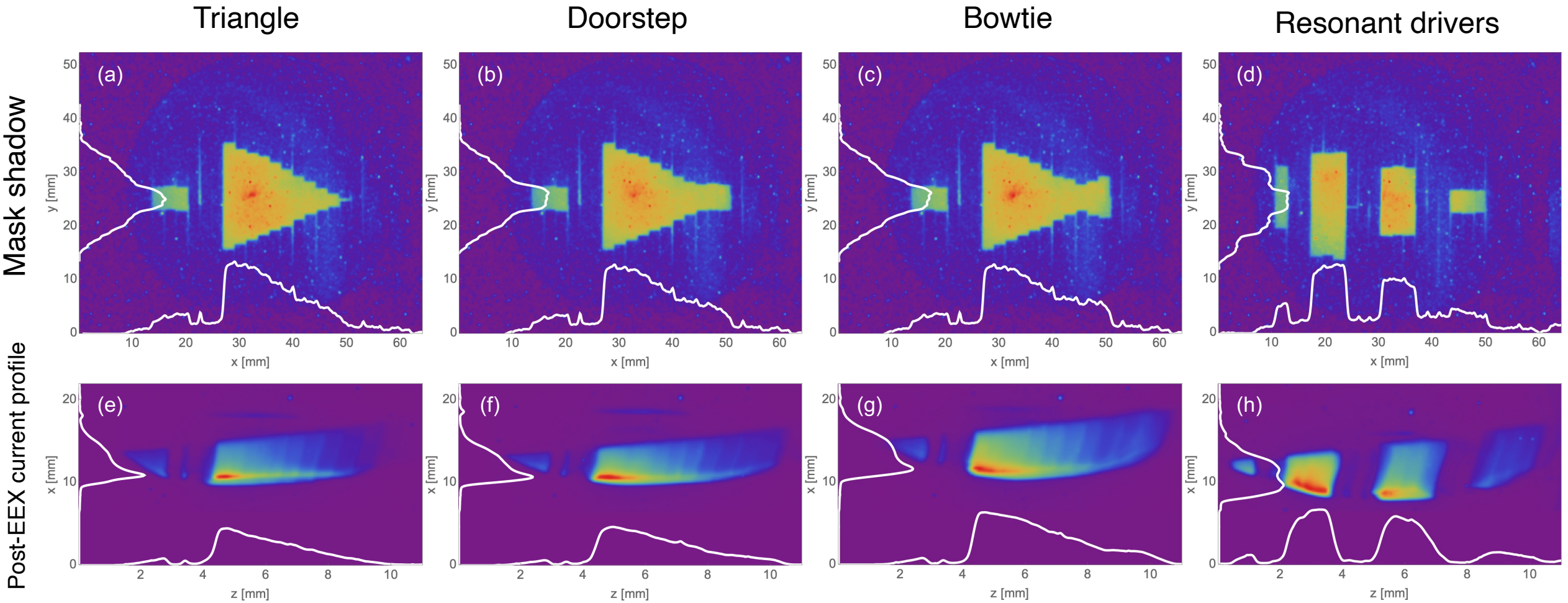


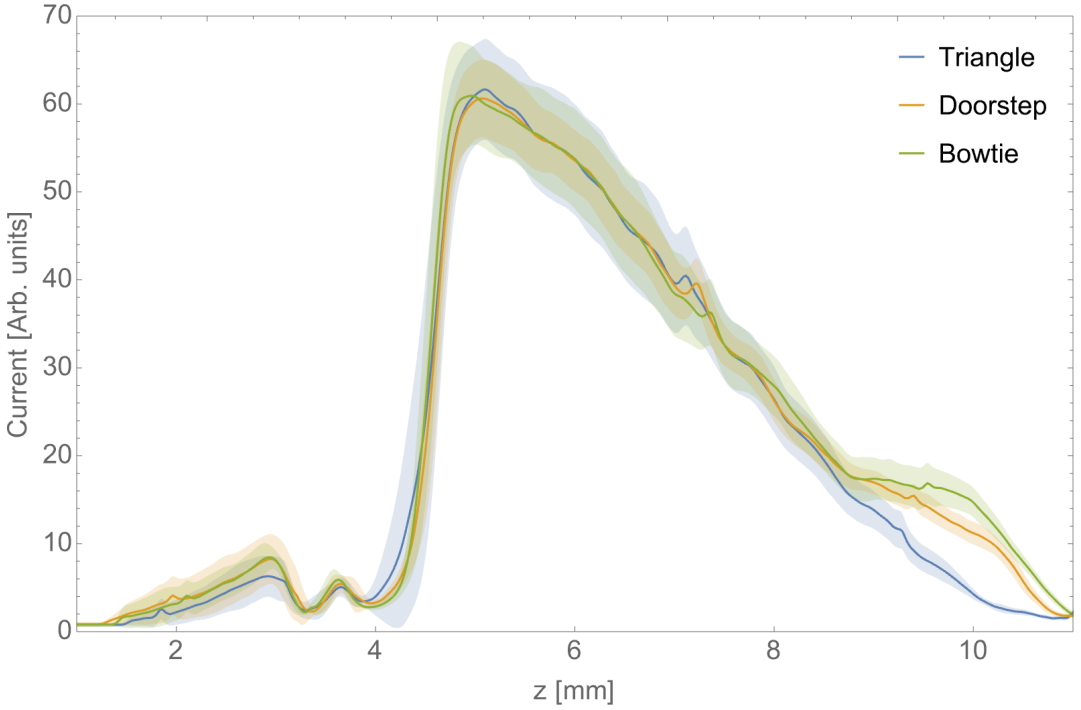
Cleaning and installation

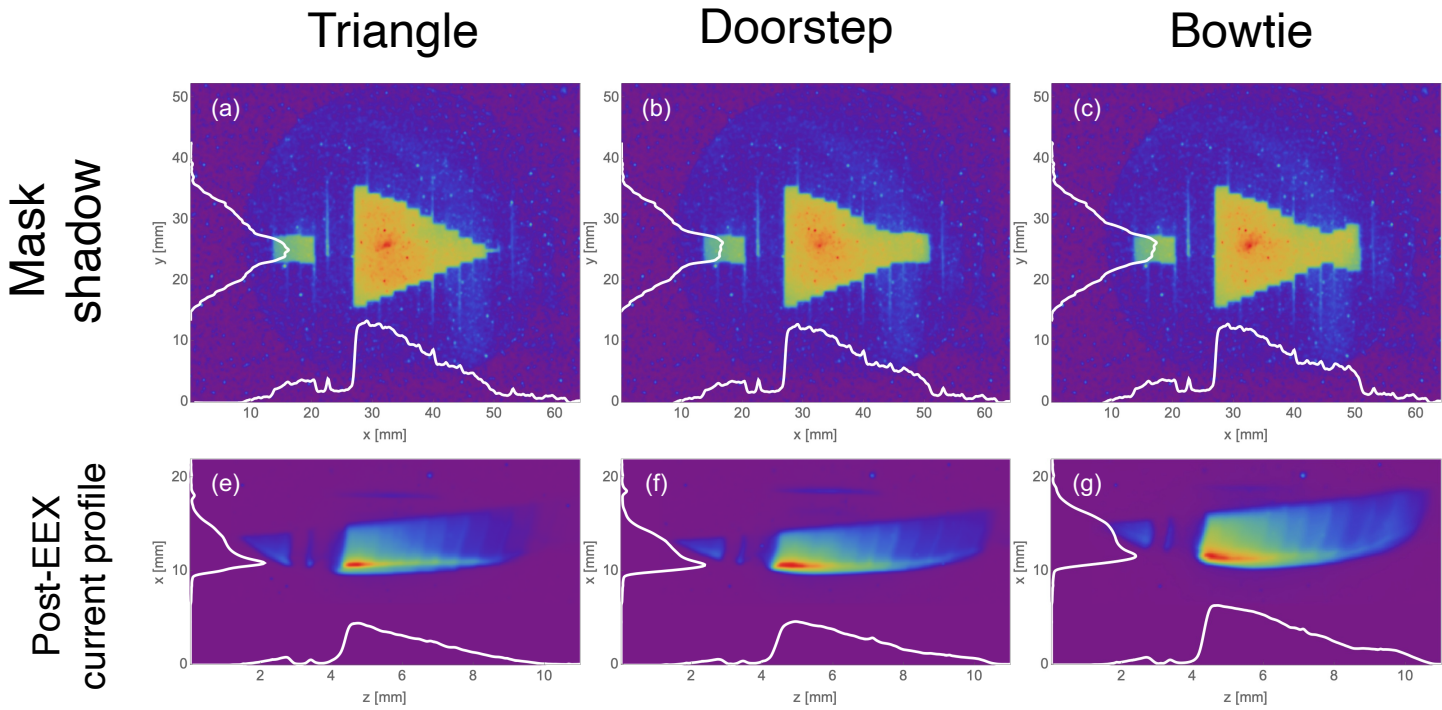


Beam shaping



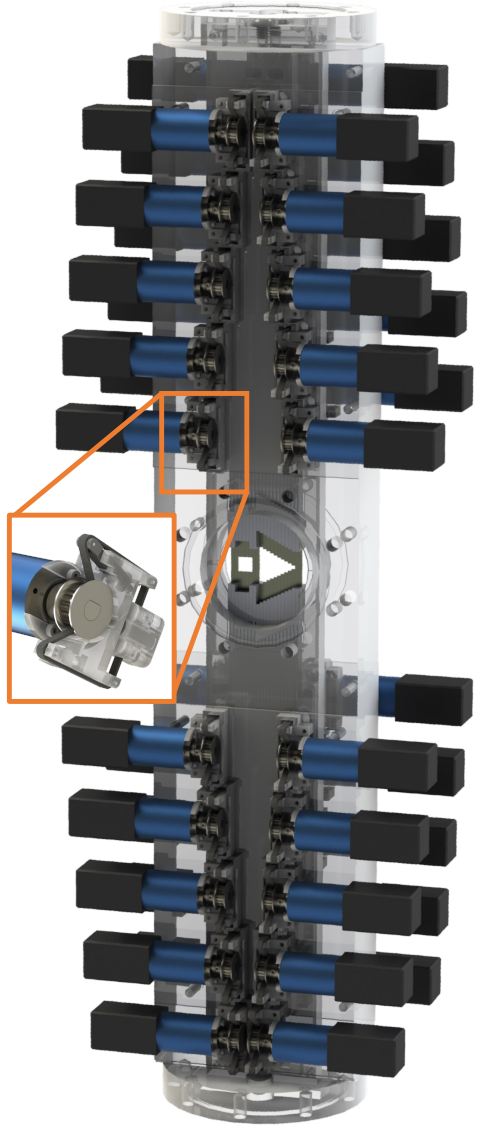
Beam shaping detail





Summary

- Replace laser cut tungsten masks with UHV-compatible multileaf collimator in EEX beamline
  - Beam dynamics simulations indicate that realistic MLC configurations are functionally identical to existing masks
- Permits real-time, nearly arbitrary control over drive and witness bunch shaping
  - Highly synergistic with machine learning
- Demonstrated ability to create wide range of beams and also control fine detail
- Next steps
  - New MLC design
  - Feed-forward control to match current profile to target
  - ML control to optimize transformer ratio



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References and acknowledgements

- [1] – Gao, Q., et al. "Observation of high transformer ratio of shaped bunch generated by an emittance-exchange beam line." *Physical review letters* 120.11 (2018): 114801.
- [2] – Roussel, R., et al. "Single shot characterization of high transformer ratio wakefields in nonlinear plasma acceleration." *Physical Review Letters* 124.4 (2020): 044802.
- [3] – Taşkin, Z. C., et al. "Optimal multileaf collimator leaf sequencing in IMRT treatment planning." *Operations Research* 58.3 (2010): 674-690.
- [4] – Roussel, R. *Single-Shot Characterization of High Transformer Ratio Wakefields in Nonlinear Plasma Acceleration.* Dissertation. University of California, Los Angeles, 2019.

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