Autoloader System for Inertial Fusion Targetry

GENERAL ATOMICS
UC San Diego FUSION ENGINEERING INSTITUTE

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Overview

- Breakthrough fusion ignition in 2022 has renewed interest in inertial confinement fusion (ICF) as a novel clean energy source [1,2].
- ICF uses lasers to implode tiny capsules, or targets, of fusion fuel to generate energy.
- UCSD's Fusion Engineering Institute and General Atomics are collaborating to develop scalable engineering solutions for fusion power plants.

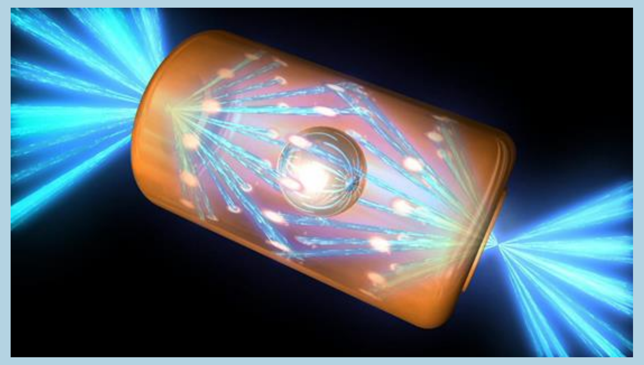

Fig. 1: Artist's depiction of a inertial fusion Image courtesy of U.S. Dept. of Energy

Problem Statement

- To be commercially viable, an inertial fusion power plant must explode targets at around 10 Hz [2].
- Current inertial fusion campaigns are limited by low shot-rate and can take hours to set up for just one fusion experiment.

Our Solution

- Our mechanical autoloader system delivers a steady stream of fueled fusion targets at a nominal cycle rate of 0.25 Hz, while being immediately adaptable for in-vacuum and cryogenic experimental conditions.

System Constraints and Requirements

Fusion Targets are Fragile

- The targets are small spherical shells
  - 4.5 mm diameter
  - 10 um nominal shell wall thickness
- Ansys simulations show they can withstand 3-4 N of point loading before rupture.

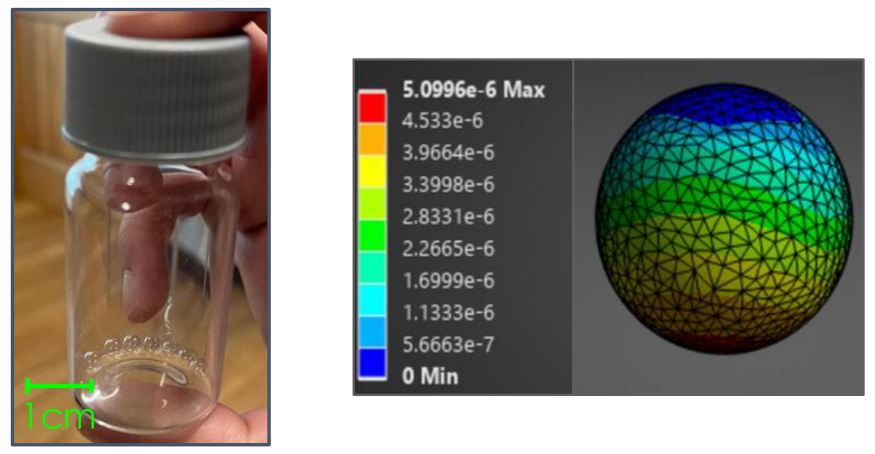

Fig. 2: (a) Vial of inertial fusion target shells. (b) Ansys static point-load simulation of target shell.

System must adapt to experimental conditions

- Experiments are done in
  - High Vacuum (~1 mTorr) → Minimize outgassing, thermal management
  - Cryogenic Conditions (~10 K) → Minimize sliding contacts, account for brittle transitions, etc.

The Design

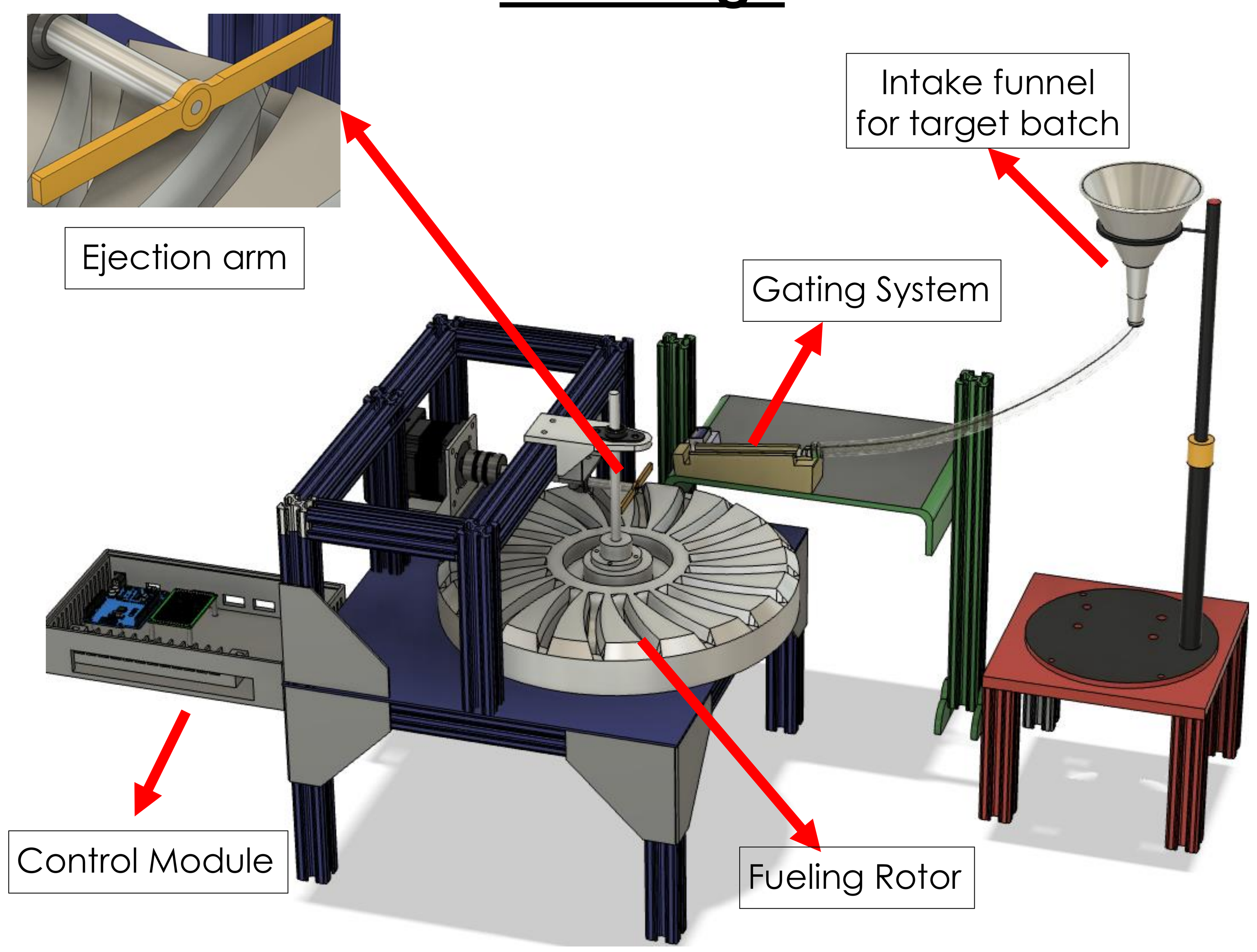

Fig.3: Full System CAD Assembly

Where We Fit in the Big Picture

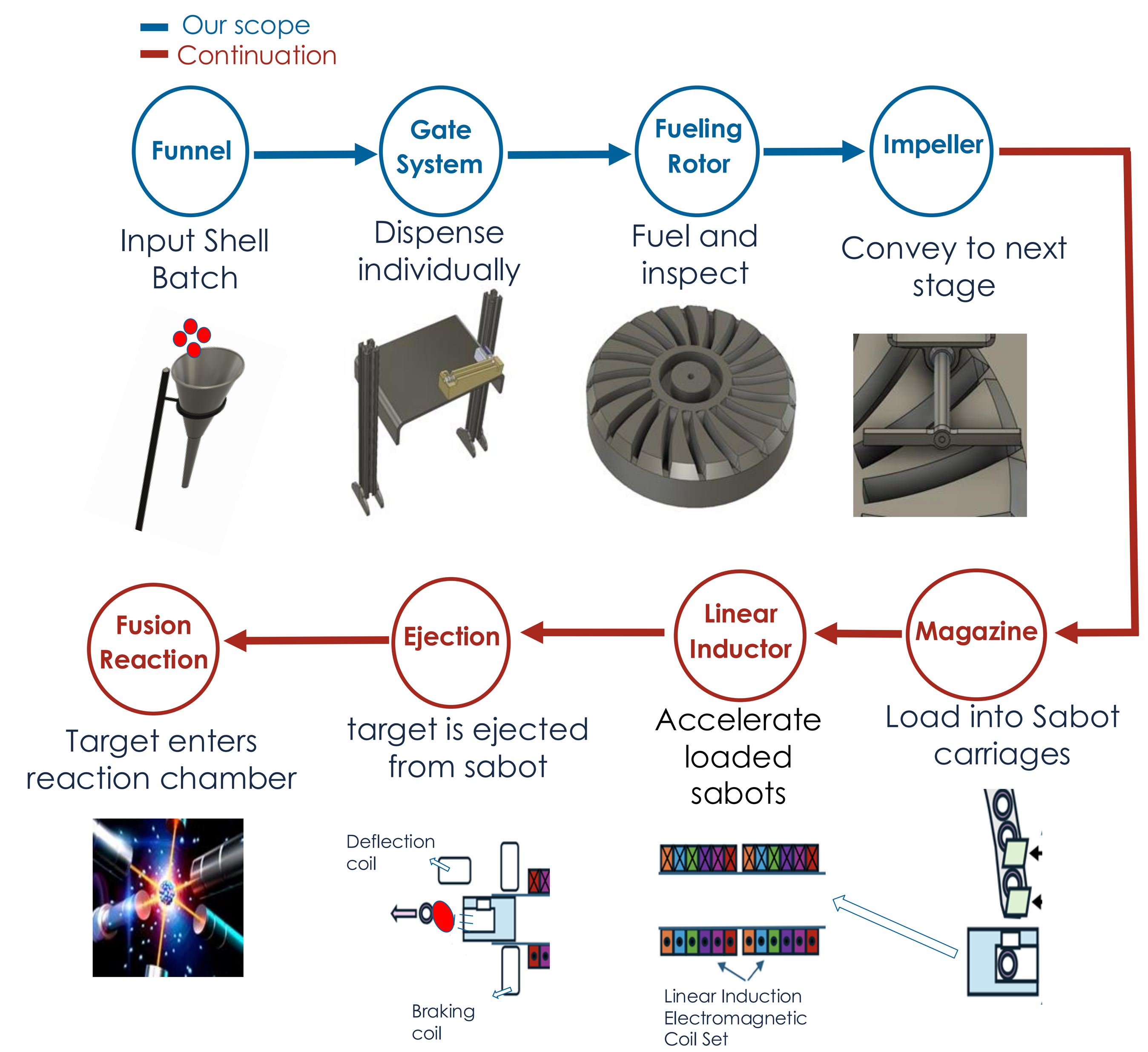

Fig.4: Flowchart of inertial fusion target staging, including our component

Gating System Analysis

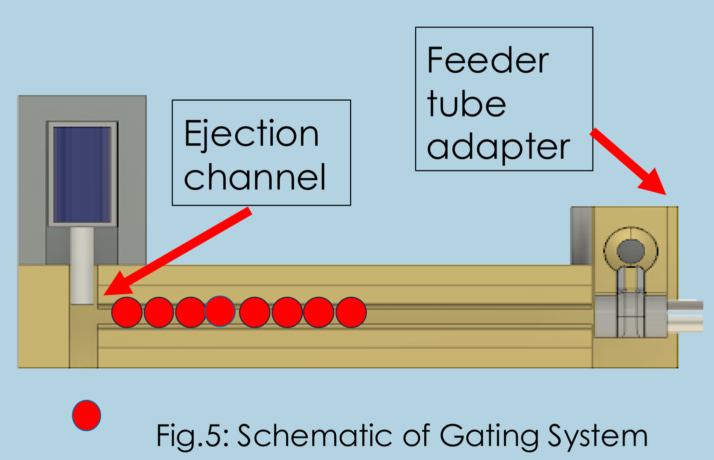

Fig.5: Schematic of Gating System

- 12V push-pull solenoid serves as a gate and dispenser
  - Shaft retracts to let one target into ejection channel
  - Shaft extends to eject target, and blocks upstream line.
- Channel is gravity fed
- Outputs 4gm-force thrust
  - 4 gm-force = 39 mN, well below fracture strength of target shell

Input Funnel

Fig.6 Input Funnel

- Input funnel organizes target batch ahead of gating
- 6 mm ID PVC tubing to ensure smooth target flow into the gate system
- Tubing collects targets into single-file line
- Can be placed outside of vacuum chamber with longer vacuum compatible tubing and seal

Fueling System

- Empty target shells are fueled with liquid hydrogen in grooves along rotor
- Ejection arm passes through spiral arc groove defined by system geometry to scoop the target out

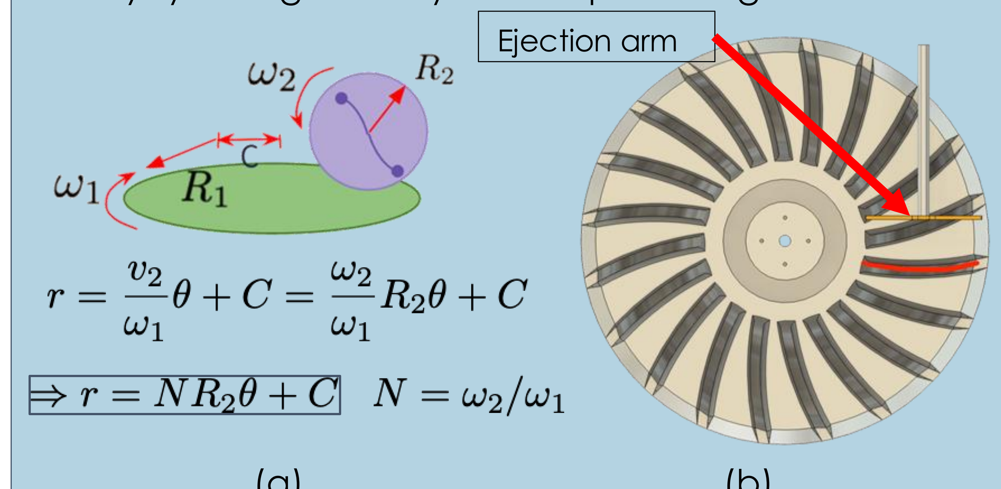

Fig. 7: (a) Equation of grove spiral in polar coordinates derived from kinematic model. (b) Illustration of spiral segment in groove design.

- Rotor has no areas where fuel can leak through
- Line-of-sight through grooves for adsorption inspection
- Targets must soak in fuel for ~10 seconds
- Cycle rates above specified 0.25 Hz can be achieved while meeting this constraint

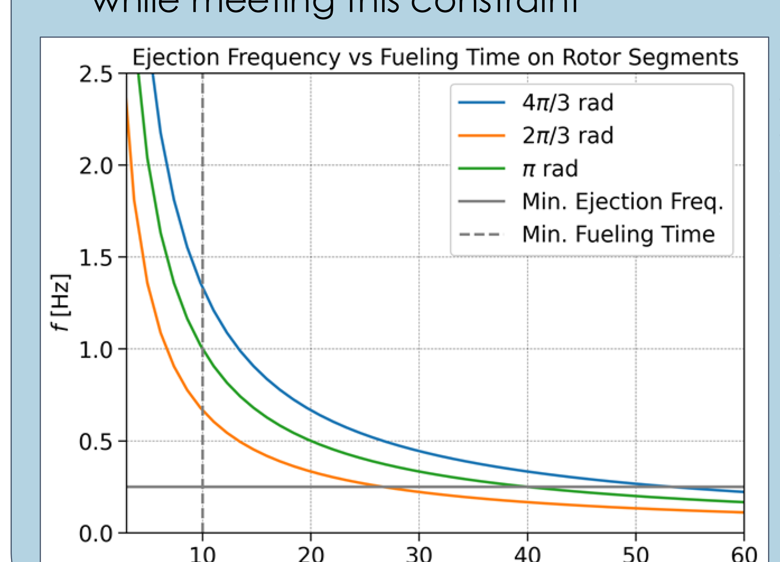

Fig. 8: Ejection frequency as a function of fueling time for different angular segments of rotor surface.

Control Module

- Fueling rotor and ejection arm each controlled with separate stepper motors.
  - LEESN IG57E Steppers; 24 VDC/4 A; 2 Nm of holding torque
- Both motors and gating system solenoid controlled using independent electronics module with Arduino

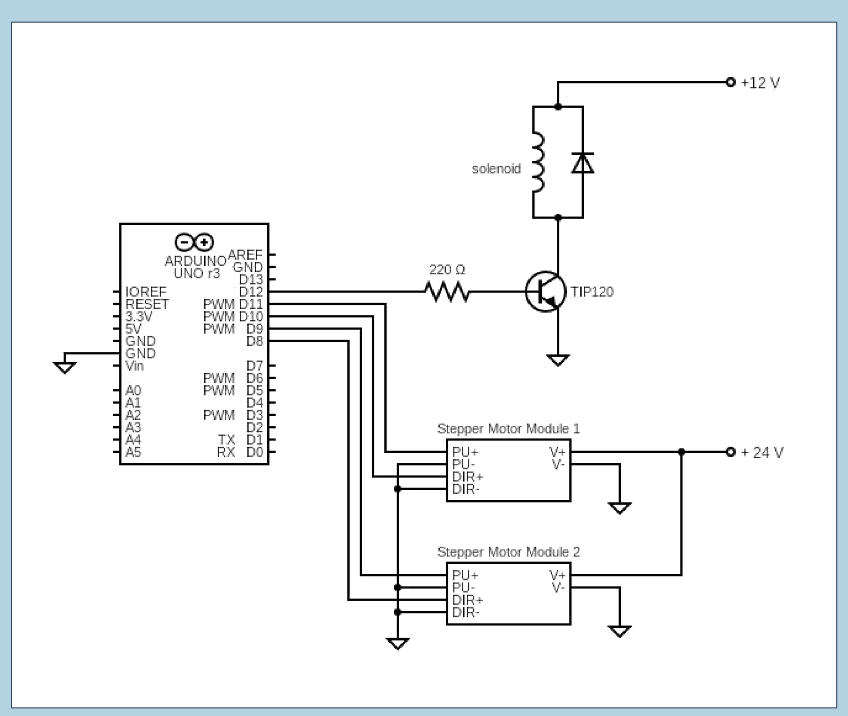

Fig. 9: Circuit diagram for arduino-controlled stepper and solenoid module.

- Stepper speeds and solenoid thrust frequency set digitally
- Users set fueling rotor stepper speed and gate solenoid frequency.
- Ejection arm speed automatically computed from fueling rotor speed.
- Control script created with basic GUI

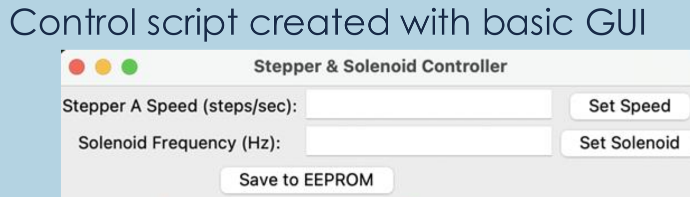

Fig. 10: Controller GUI.

Performance

- Effectively dispenses targets at minimum specified rate of 0.25 Hz
- Both motors are successfully synchronized to avoid ejection arm interference with disk
- Funnel can accommodate batches of roughly 75 targets at a time
- System is adjustable for precision alignment

Rotor Speed (rad/s)	Ejection Success Rate (Avg. of 3 Trials)
0.523	90%
0.418	75%
0.349	65%

Table. 1: The successful system ejection rate for 20 targets for several different speeds. The percentage is an average ejection rate over 3 trials

Next Steps

- The project extends to an automated sabot loading system
- Solenoid-driven staging and sabot loading.
- Design work is completed, relative placement is critical.

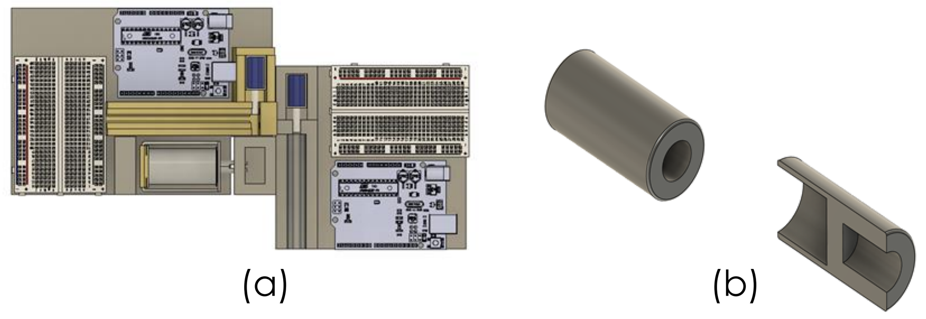

Fig. 12: (a) preliminary CAD drawings for the solenoid-driven sabot loaders. (b) CAD of an individual sabot carriage with cross-section.

Future Recommendations

- Modify with vacuum and cryogenic components.
- Actuators can be placed on shaft extenders outside of vacuum chamber
- Thermal analysis under cryogenic conditions
- Feedback control in control module

Impact on Safety

- Reduces human intervention in fusion experiments
- Automates part of fusion target processing that would otherwise be done manually shot-to-shot

Impact on Society

- Fusion can supply sustainable energy, reduce fossil fuel reliance, and fight climate change.
- We have made a mechanical solution to increase shot-rate in fusion experiments towards reactor-relevant experimental conditions.

Acknowledgments

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References

[1] S. Nakai and K. Mima, "Laser driven inertial fusion energy: present and prospective," Rep. Prog. Phys., vol. 67, no. 3, pp. 321–349, Mar. 2004, doi: 10.1088/0034-4885/67/3/r04.
[2] E. I. Moses, "Ignition on the National Ignition Facility: a path towards inertial fusion energy," Nucl. Fusion, vol. 49, no. 10, p. 104022, Oct. 2009, doi: 10.1088/0029-5515/49/10/104022.