Analysis of Fast Shutter and Gaussian Telescope Mirror Moving Mechanisms for ITER

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MOTIVATION

- Critical components of ITER can potentially be exposed to a 6kW unabsorbed ECH microwave
- Takes >10 msec to deactivate microwave, so a fast shutter was explored to act as a last resort safety fuse
- A 65 mm aperture shutter created by Uniblitz® can close in 52 msec
- To decrease close time, several possible solutions were proposed using analytical models, prototype generation, and prototype tests

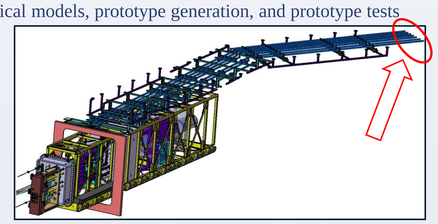


Figure 1: Equatorial Port 11, proposed shutter location

BACKGROUND

An iris shutter mechanism consists of four fundamental parts: a base plate, a rotating ring, shutter blades, and an actuation input.

The Uniblitz® CS65 65 mm Optical Shutter was considered as a baseline 65 mm aperture fast shutter (52 msec close time) for application within ITER.

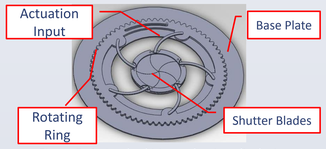


Figure 2: A standard iris mechanism displaying fundamental parts [1]

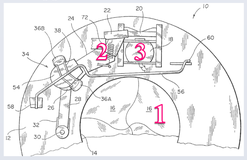


Figure 3: Uniblitz® CS65 65mm Optical Shutter activation mechanism [2]

- Discharge electromagnet which holds spring
- Spring returns to its natural length, closing the shutter
- Design modifications explored:
  1) decrease blade mass
  2) increase spring force
  3) alter electromagnet properties

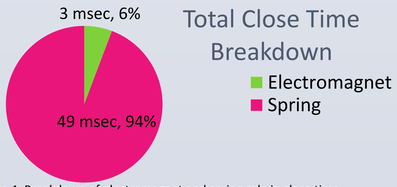


Figure 4: Breakdown of electromagnet and spring role in close time

- A majority (94%) of the total close time is governed by the spring-linkage actuation

OBJECTIVES

- Explore current fast shutter mechanisms and capabilities
- Allow wave to pass through 65 mm aperture
- Close shutter in ~10 msec
- Use material that can withstand 6kW microwave

To identify factors to decrease close time, an energy analysis was performed:

$$E = \frac{1}{2}mv^2 \rightarrow E = \frac{1}{2}m\left(\frac{d}{t}\right)^2 \rightarrow t = \frac{d\sqrt{m}}{\sqrt{2E}}$$

Can decrease time to close t by:
- Decreasing blade mass, m
- Increasing input energy, E

ANALYSIS AND RESULTS

- Current blades stainless steel or BeCu
- Less massive carbon-impregnated polyethylene terephthalate (PET), "Carbon Feather" was proposed
- Comparable masses for 2in^2 samples* of blade materials are shown below, and the improved close time is predicted

BeCu	Stainless Steel	Carbon Feather
1.2 g	0.6 g	0.4 g

*Samples courtesy of Vincent Associates®

$m_1 = 1.2$ g
$m_2 = 0.4$ g
$t_1 = 49$ msec

$$E = \frac{1}{2}mv^2$$
$$E_1 = E_2$$
$$m_1v_1^2 = m_2v_2^2$$
$$\frac{1.2}{0.4} = \left(\frac{v_2}{v_1}\right)^2$$
$$\begin{cases} v = \frac{d}{t};\ d_1 = d_2 \\ \left(\frac{v_2}{v_1}\right)^2 = \left(\frac{d/t_2}{d/t_1}\right)^2 = \left(\frac{t_1}{t_2}\right)^2 \end{cases}$$

Solving for t:

$$3 = (t_1/t_2)^2$$
$$\sqrt{3} = t_1/t_2$$
$$t_2 = t_1/\sqrt{3}$$
$$t_2 = 49/\sqrt{3}$$
$$t_2 = 28.3 \text{ msec}$$

Upon prototyping and testing this new blade material, the close time was found to be 28.8 msec, a 41% reduction, with slight losses due to frictional factors.

Blades must block a 6 kW microwave. A prediction of the thermal failure time of the blades was made based on thermal properties of PET [3], assuming total absorption:

Specific heat	C_p	1200 J/kg·K
Melting point	T_m	530 K
Latent heat of fusion	ΔHf	1.35 x 10^5 J/kg
Blade mass	m	0.5147 g
Room temp	T_o	300 K
Microwave power	P	6000 W
Power absorption %	α	100%

$$t_m = \frac{m \cdot (C_p(T_m - To) + \Delta Hf)}{\alpha \cdot P} = 35.3\ msec$$

- Shutter to be used as fuse: block the wave until it can be deactivated, which takes ~100 msec
- Lower-bound estimate of failure time
- Tubes of coolant can surround shutter to prevent failure and extend lifetime

- Increase spring constant for the return mechanism to increase input E
- A new required spring constant value was calculated:

$$t = \sqrt{\frac{m}{k}} \longrightarrow k = \frac{m}{t^2}$$

$$\frac{k_2}{k_1} = \frac{m_2/t^2{}_2}{m_1/t^2{}_1} = \frac{0.0004/0.007^2}{0.0012/0.049^2} = 16.33$$

- Electromagnetic force must equal spring force at its extended length to hold shutter in stationary open position

$$F_{spring} = -kx$$

$$F_{EM} = \frac{LI^2l}{2d^2}$$

for static state (held open):

$$F_{spring} = F_{EM}$$

$$-kx = \frac{LI^2l}{2d^2}$$

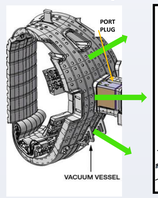
- Increasing k will require an increase in F_{EM}
- Can increase F_{EM} by increasing the current I into the electromagnet

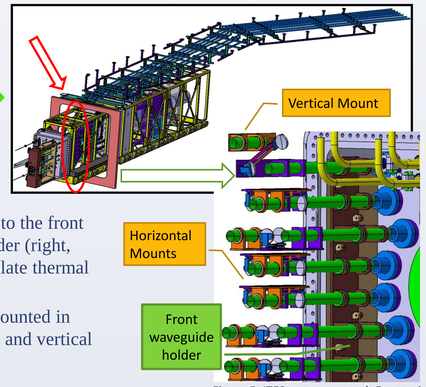
CONCLUSIONS

- Carbon feather blades decrease total close time t by 41%
- Need spring constant k to be ~16.33× greater for a ~10 msec close time
- Increasing k requires a larger F_{EM}
- Can increase I to increase F_{EM}

MOTIVATION

- ITER vacuum vessel expands and contracts thermally, making it impossible to maintain a direct alignment of reflectometry microwaves
- Mechanism designed for Equatorial Port 11 to maintain the alignment of reflectometry waves into a small interspace waveguide





- Forces applied to the front waveguide holder (right, brown) to simulate thermal expansion
- Mechanisms mounted in both horizontal and vertical directions

Figure 5: ITER vacuum vessel: Equatorial Port 11, location of 7 Gaussian Mirror Moving Mechanisms

OBJECTIVES

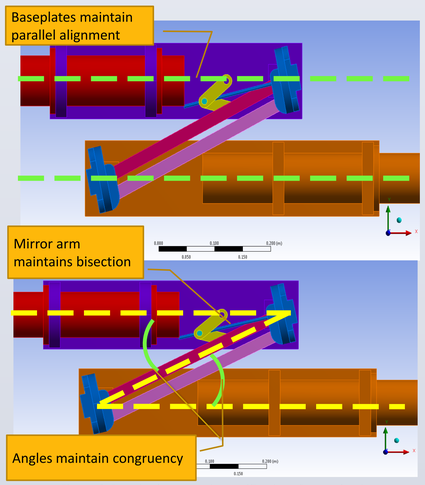


Figure 6: Required geometric specifications for mechanism

ANALYSIS

- Mechanism tested under spring-reinforced and non spring-reinforced cases (see GIF)
- 10 N preloaded 5000 N/m spring added to limit displacement and return mechanism to nominal position

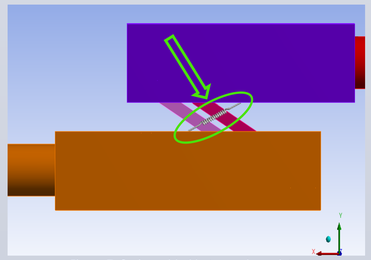


Figure 7: Spring added between baseplates

RESULTS

- Forces applied in +Y, +Z and then –X to simulate thermal expansion of ITER vacuum vessel
- Spring was added to limit displacement and return mechanism to its nominal position (see GIFs)
- Resulting displacements for X, Y, and Z shown below for both horizontal and vertical mounts
- Parallel alignment and angles were studied for all load cases

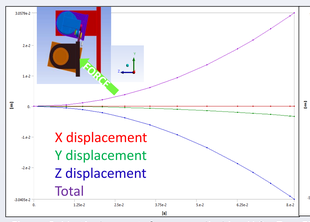


Figure 8: Vertical mount, forces applied in +Y & +Z to simulate vacuum vessel expansion

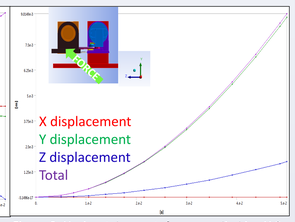


Figure 9: Horizontal mount, forces applied in +Y & +Z to simulate vacuum vessel expansion

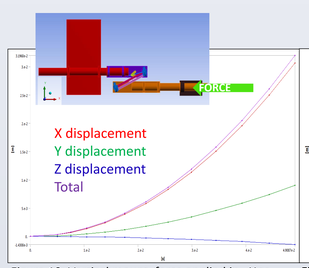


Figure 10: Vertical mount, force applied in –X to simulate vacuum vessel expansion

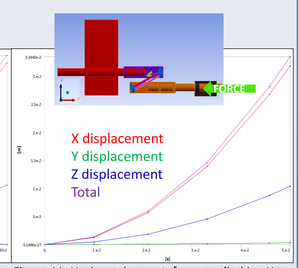


Figure 11: Horizontal mount, force applied in –X to simulate vacuum vessel expansion

FUTURE WORK

- Assemble ½ size 3D printed prototype of mechanism
- Test prototype under simulated displacement cases shown above
- Submit invention disclosure and work towards patenting

CONCLUSIONS

- Mechanism maintains the **parallelism**, **angle bisection**, and **angle congruency** of the Gaussian mirror setup under all simulated load cases
- Mechanism has appropriate degrees of freedom to allow the thermal deformation
- The addition of a spring between the mirror base plates limits the total displacement and returns mechanism to nominal position

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