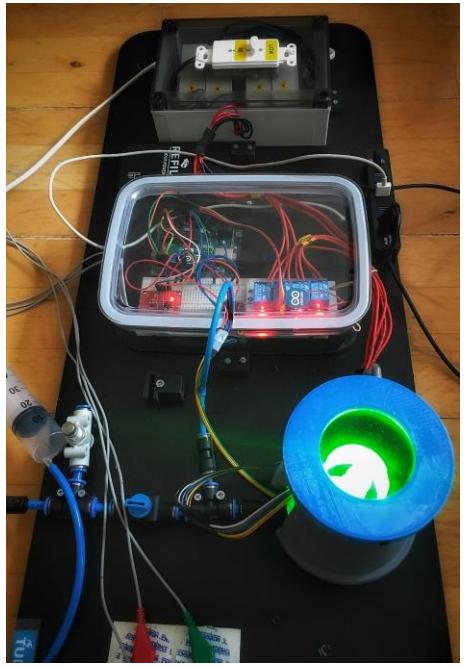
LED-stimulated Liquid Crystalline Elastomers as Contractile Units for Assisting Cardiac Contraction



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25 November 2021

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What are LCEs ?

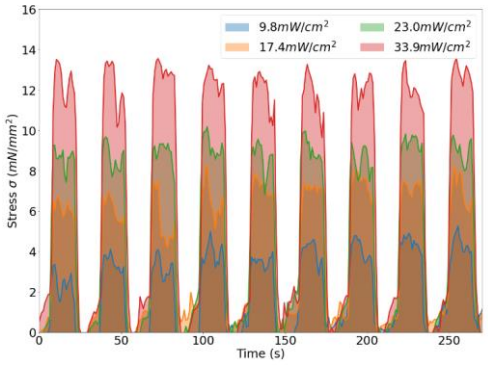
'..artificial muscle..'
P. De Gennes, 1972

LED light

+

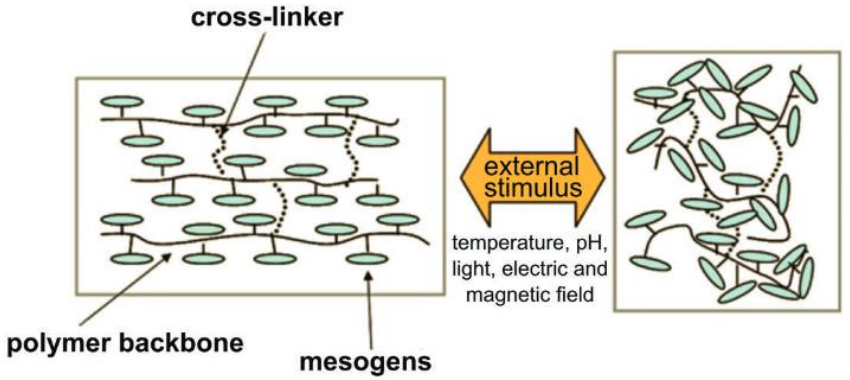
LCE strip (MM10)

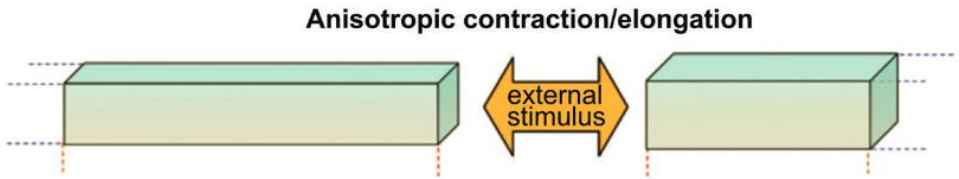
→



Force generation

- Biocompatible elastomer
- Can produce force (stress) in response to light
- LCE transform reversibly from anisotropic (ordered) to isotropic (unordered) state
- Reversible





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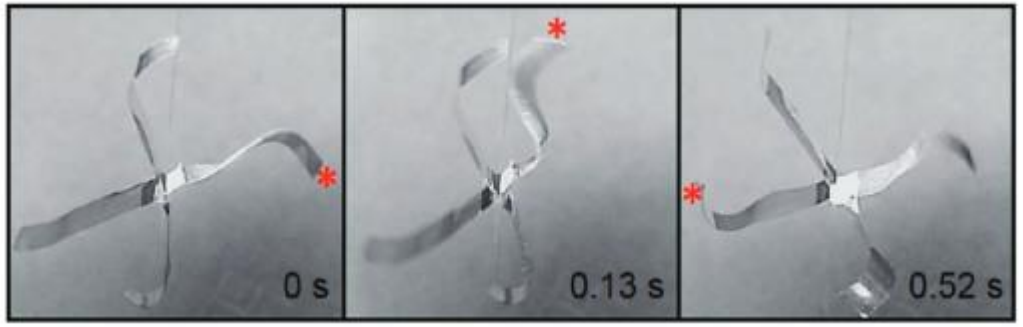
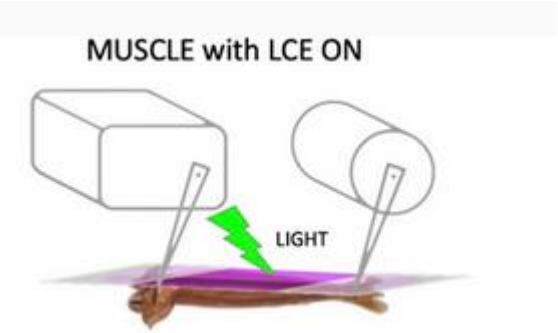
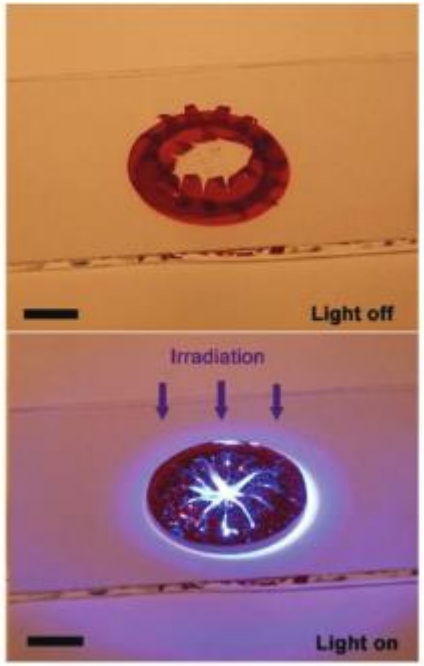
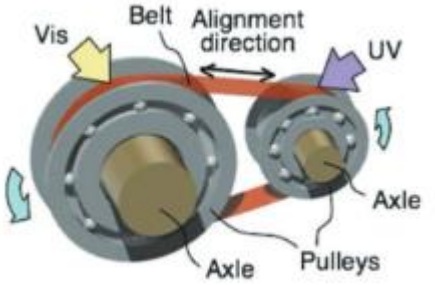
Examples


0 s
0.13 s
0.52 s

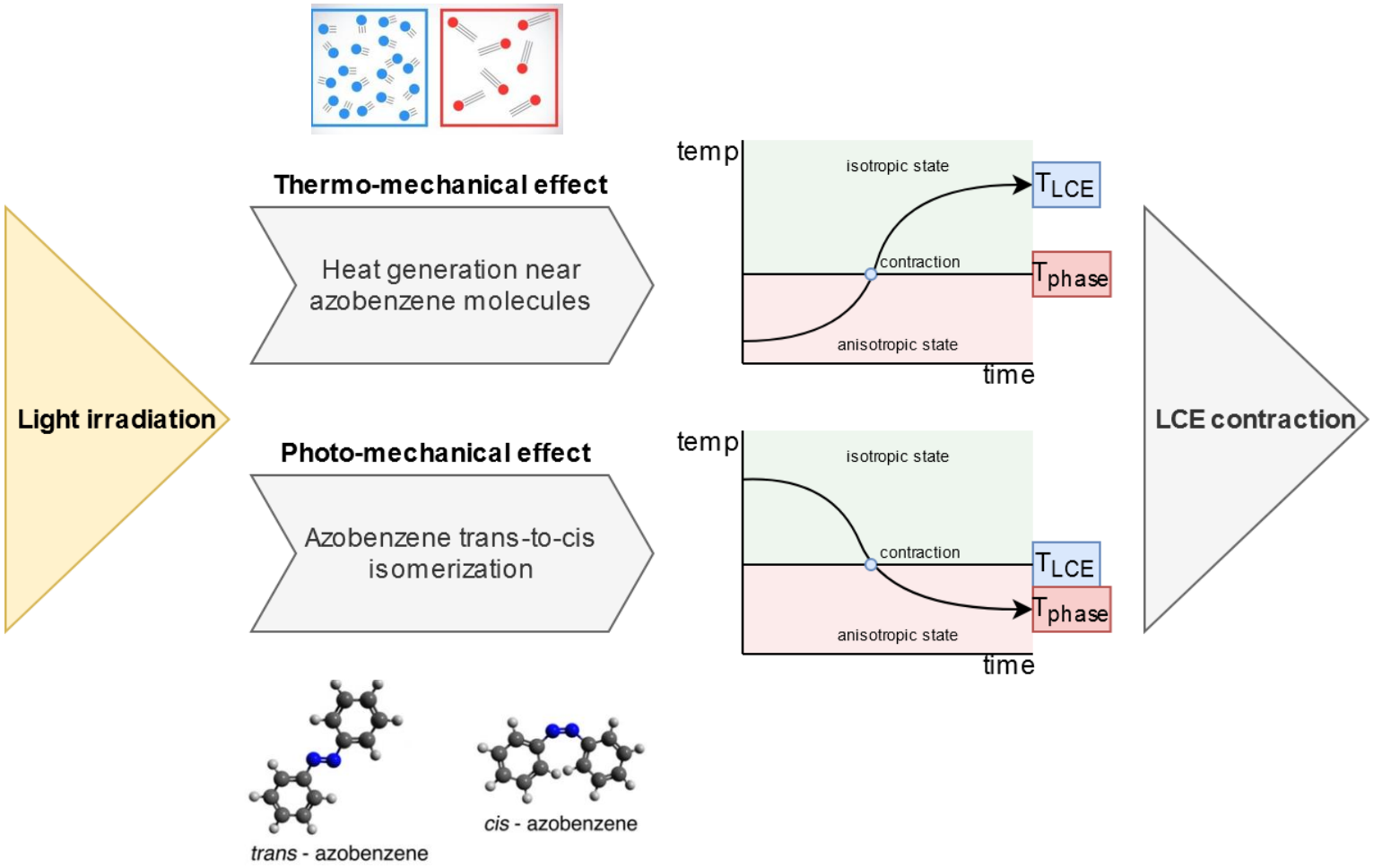

MUSCLE with LCE ON
LIGHT


Light off
Irradiation
Light on

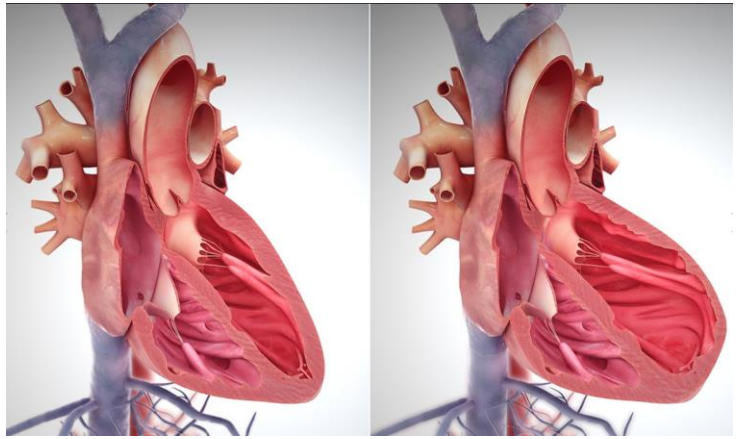

Vis
Belt
Alignment direction
UV
Axle
Axle
Pulleys

MM10

Green light-responsive **azobenzene molecules** within the LCE cause contraction upon illumination

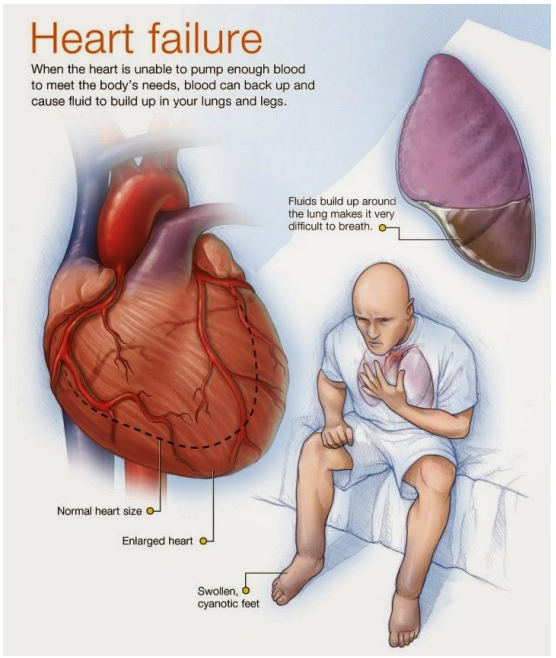


Heart Failure

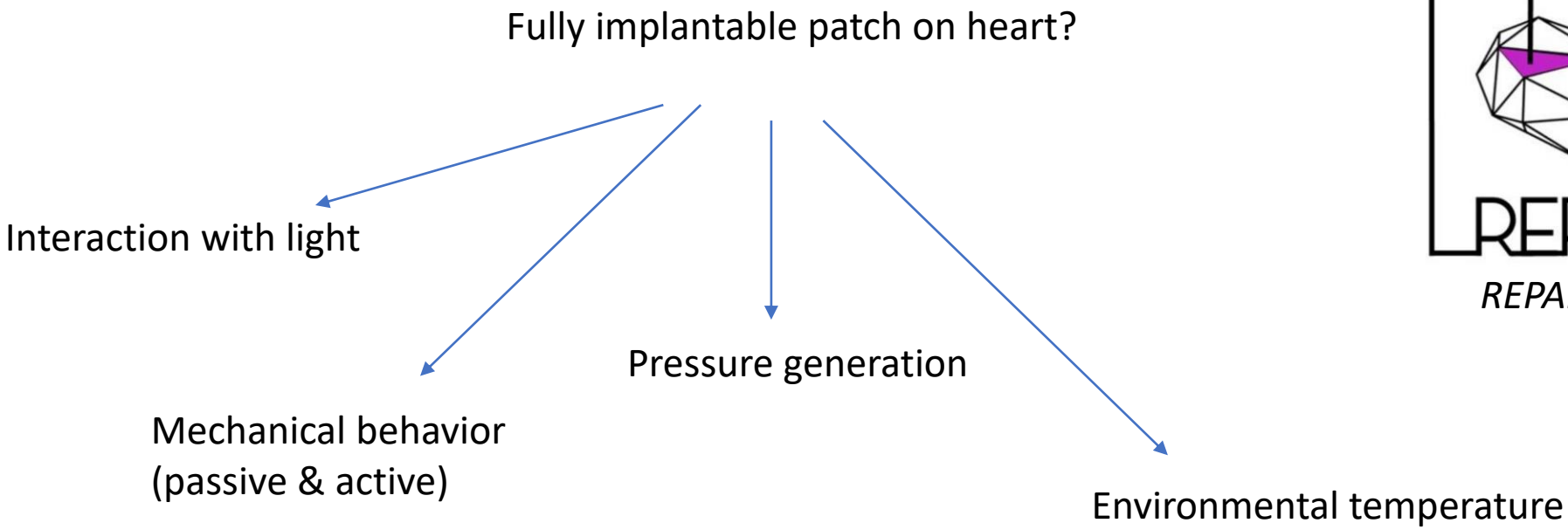


- Decreased contractile function of the heart muscle
- Large pressure on health care due to excacerbations
- Current treatments symptomatical
- LVADs only as bridging therapy towards transplantation

- <u>High need for fully implantable cardiac assistance device</u>



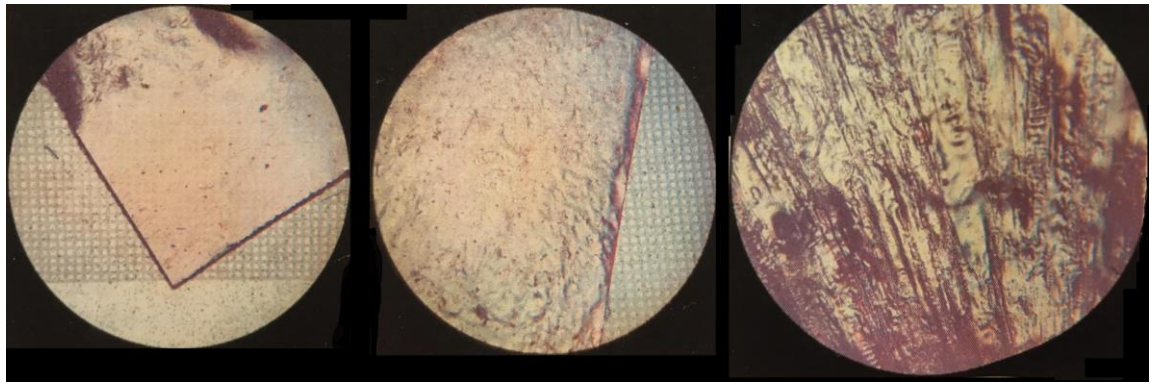
Can MM10 be used to assist cardiac contraction?



REPAIR project

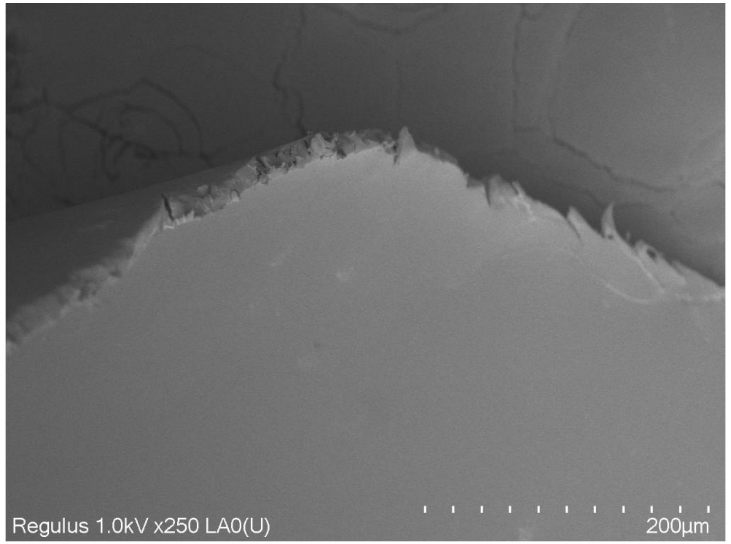
Optical parameters of MM10

Light microscopy

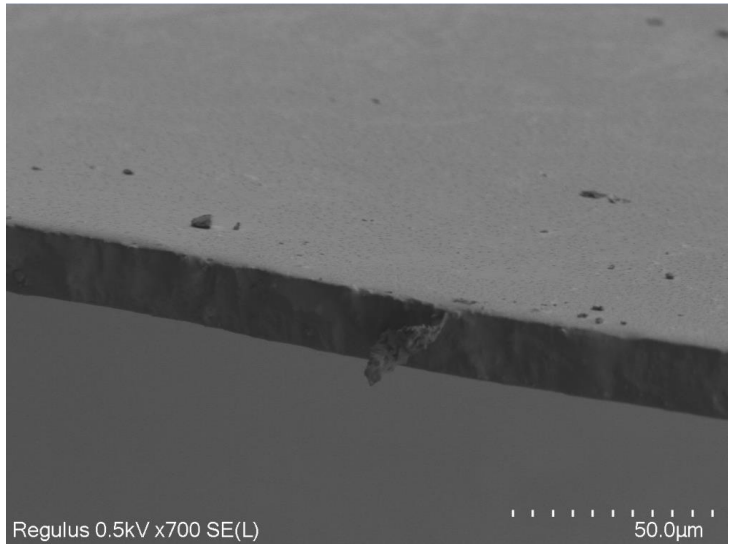


50x 100x 200x

Electron microscopy



250x



700x

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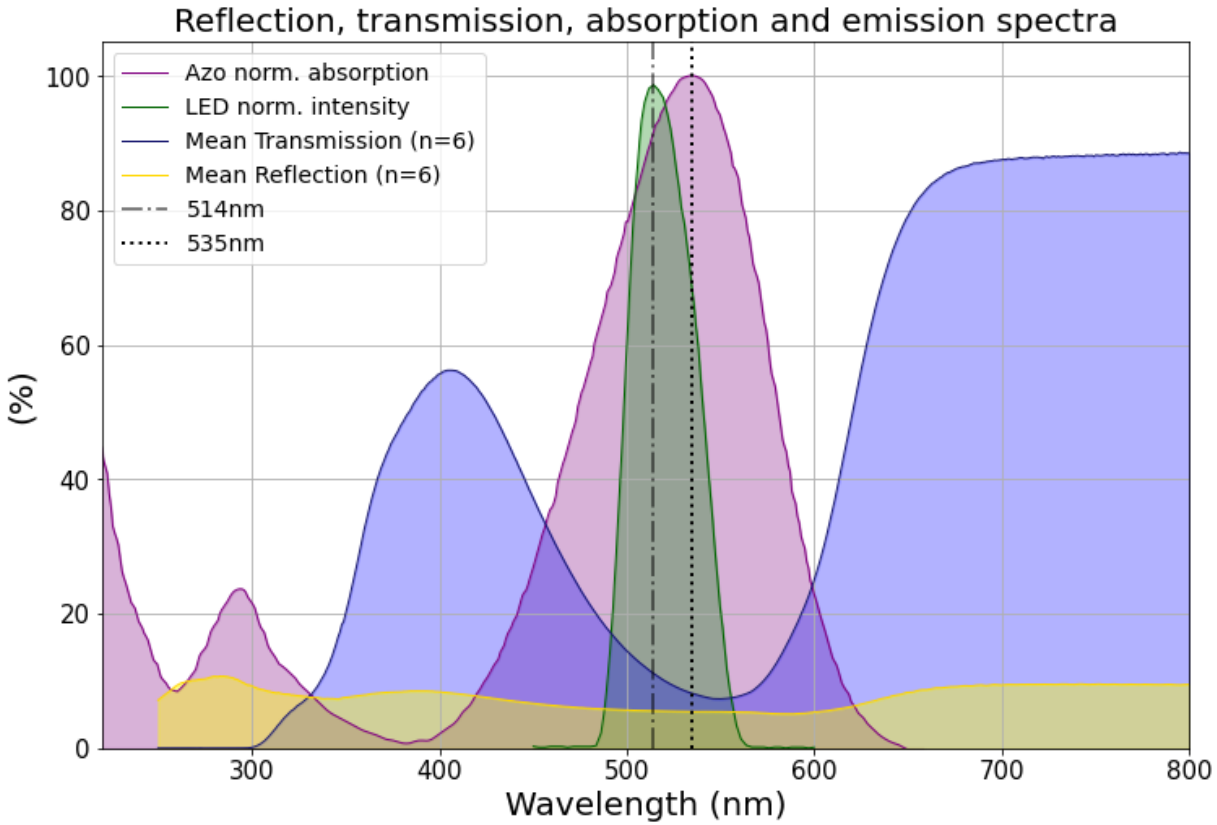
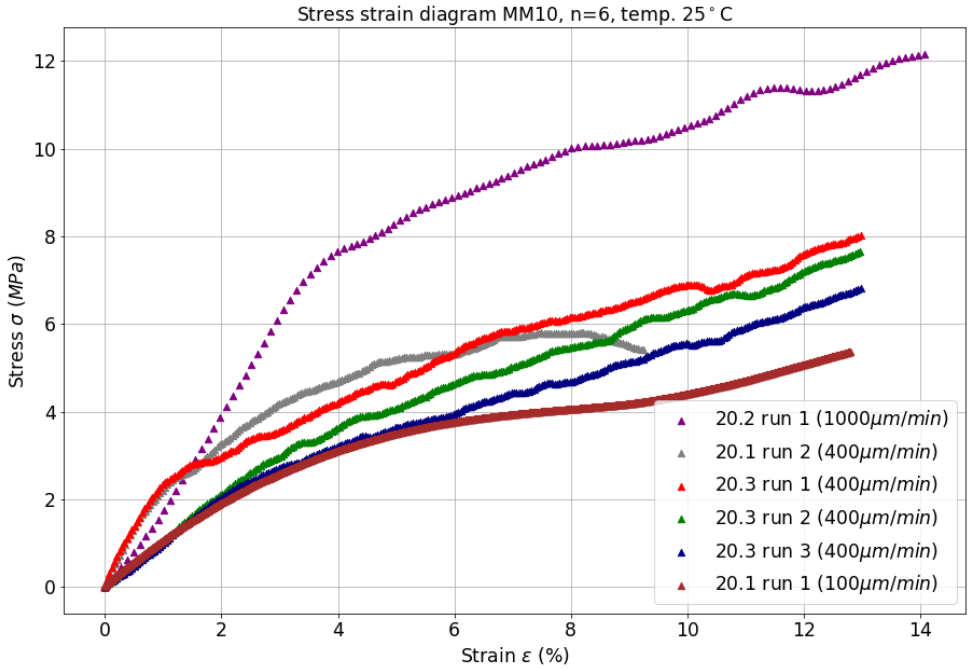
Reflection and transmission



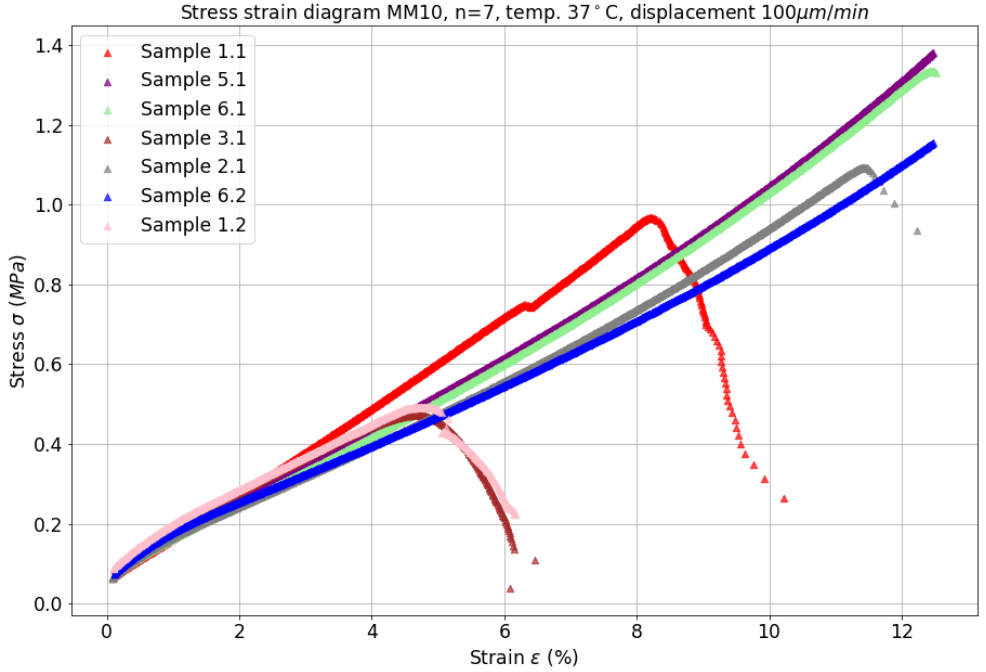
Good overlap light-azobenzene spectrum
Low reflection and transmission in 400-600nm spectrum (=high absorption!)

Passive mechanical behavior: stress-strain

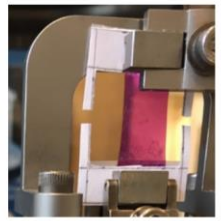
25°C



37°C

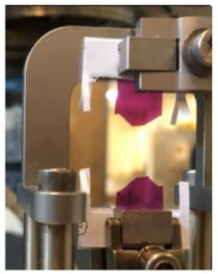


Sample MM10	**25°C** (n=6)	**37°C** (n=7)	Change (%)
Cross. Area, mm^2	0.23±0.01	0.16±0.03	-30.43
Young's modulus, $0.1 < \sigma < 2\%$	135.96±38.30	10.05±0.50	-92.61
Young's modulus, $4 < \sigma < 6\%$	46.63±12.64	9.11±1.34	-80.46
Max. tensile str. (MPa)	>7.64±2.23	0.99±0.34	-87.04
Elongation at break (%)	>11.30±2.24	9.07±3.24	-19



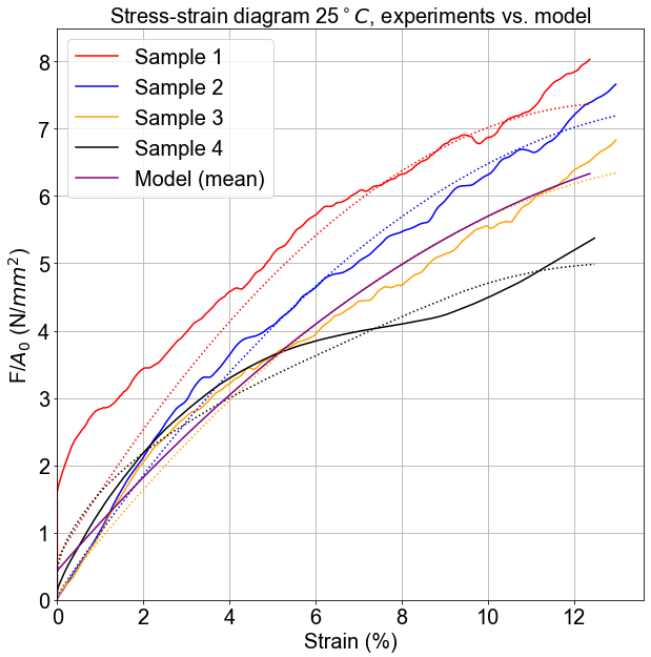
(a) Strained

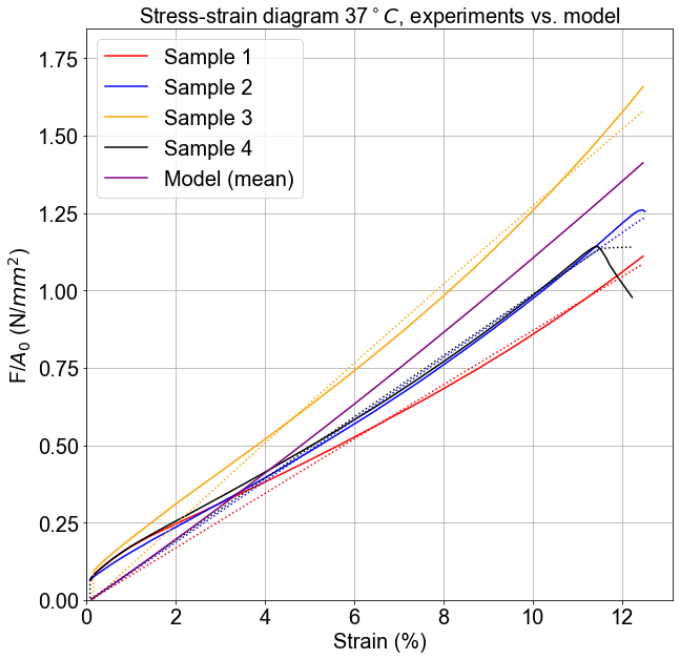
(b) Formation of tear



(c) Sample break

Approximation using LCE main-chain model





As such, we find the approximations for $25°C$:

$$G(t) = 0.0021\left(\frac{\lambda_t}{1+2Q} - \frac{1}{(1-Q)\lambda_t^2}\right) + 0.0011\dot{\lambda}\left(\lambda_t^2 - \frac{1}{2\lambda_t^4}\right)$$

And $37°C$:

$$G(t) = 0.0661\left(\frac{\lambda_t}{1+2Q} - \frac{1}{(1-Q)\lambda_t^2}\right) - 0.1247\dot{\lambda}\left(\lambda_t^2 - \frac{1}{2\lambda_t^4}\right)$$

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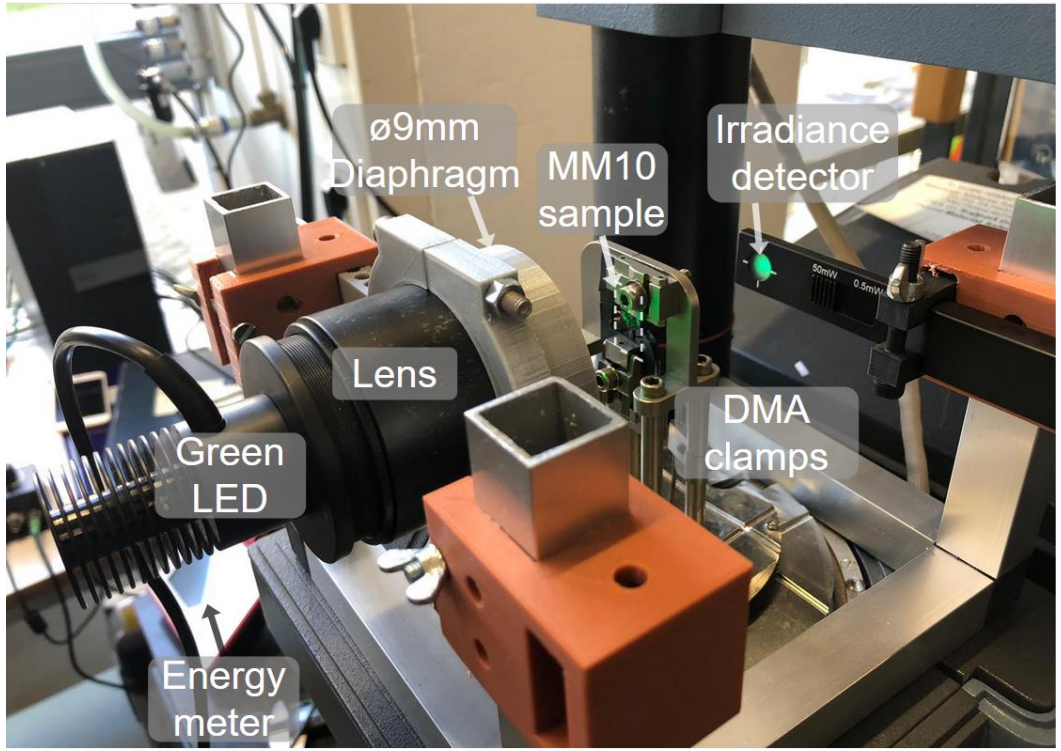
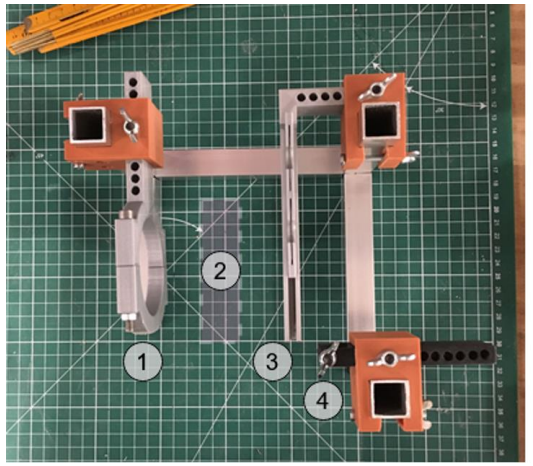
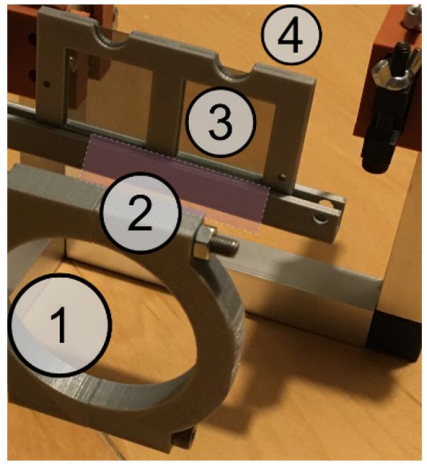
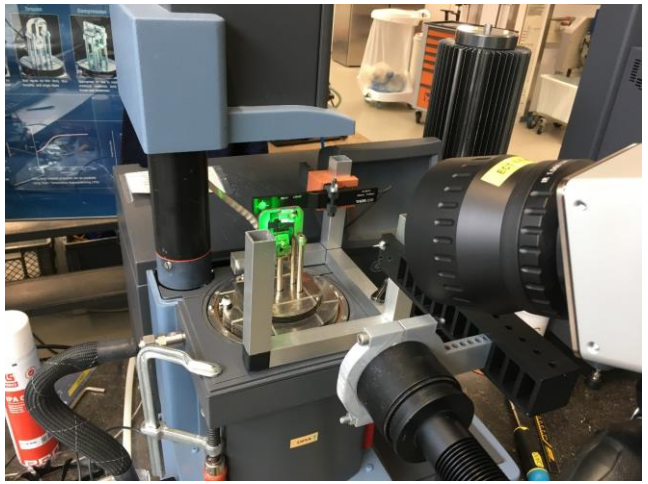
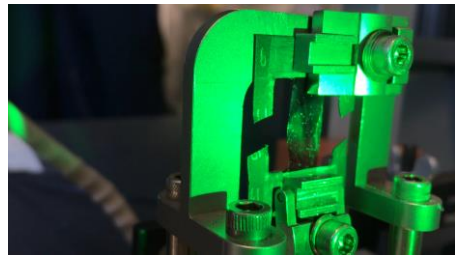
Mechanical parameters (active)



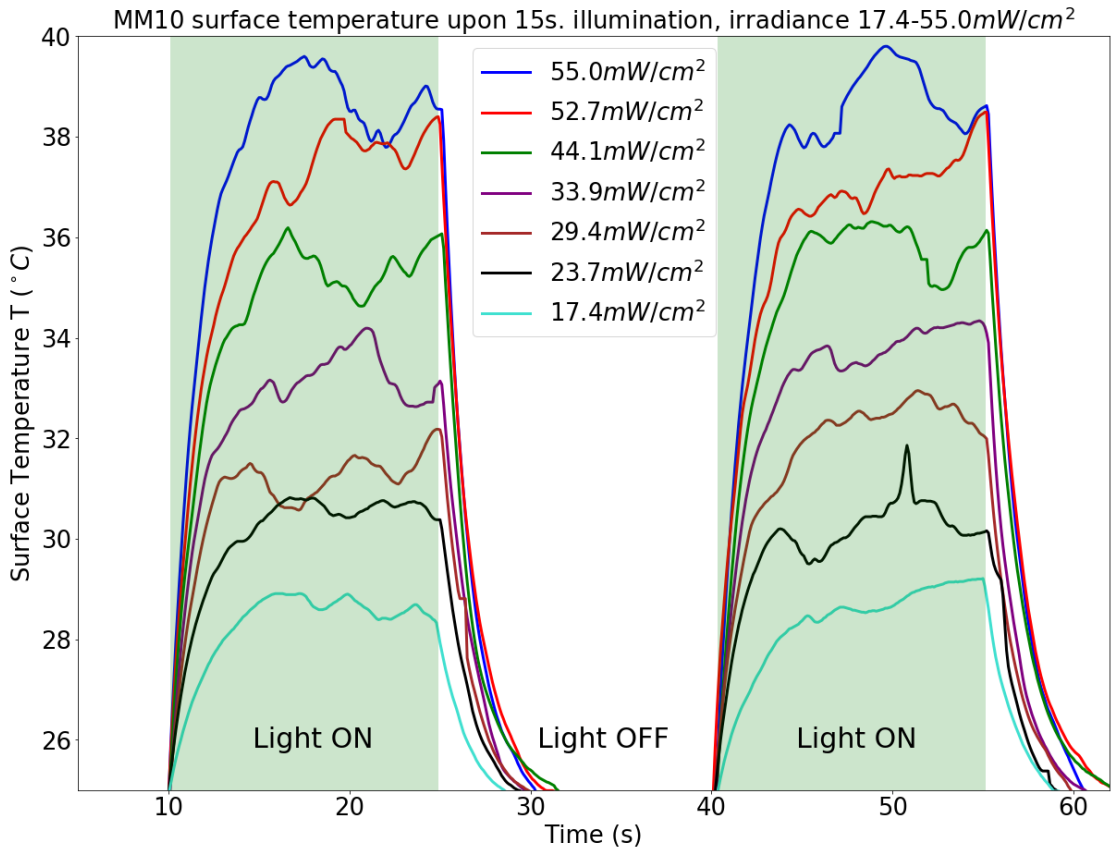


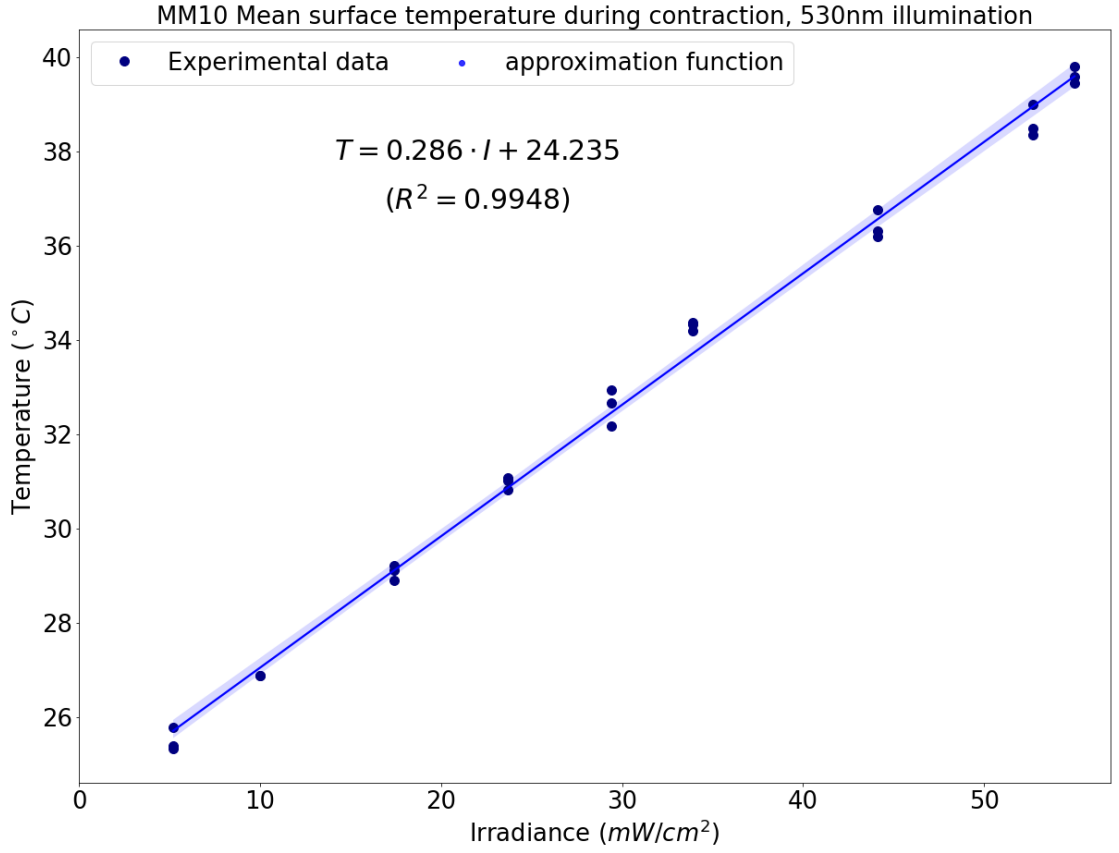






Infrared Surface Temperature measurements





Higher irradiance causes higher MM10 surface temperature in a linear fashion

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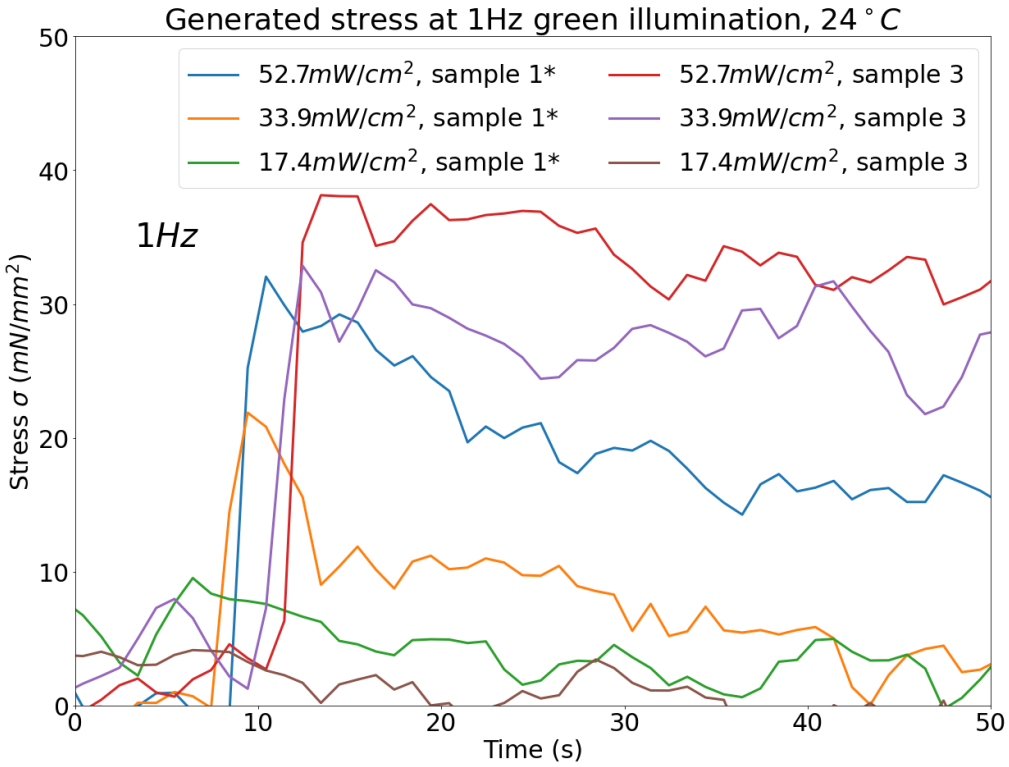
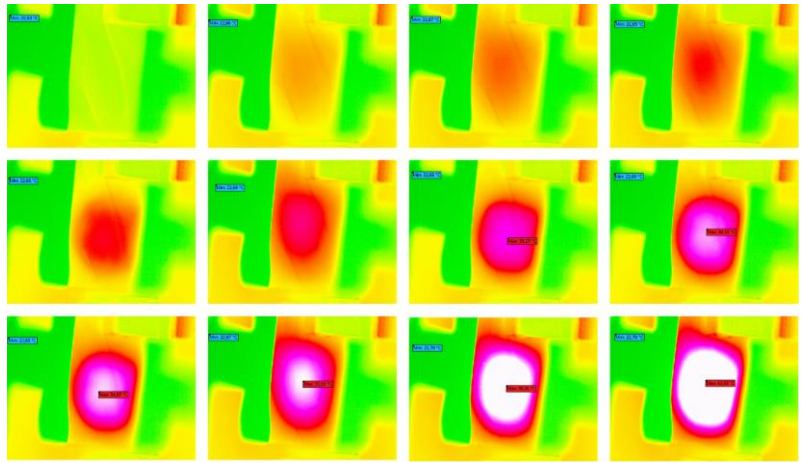
IR Light pulse measurements





Force generation not fast enough for effective contraction at normal heart rate (with current irradiance)

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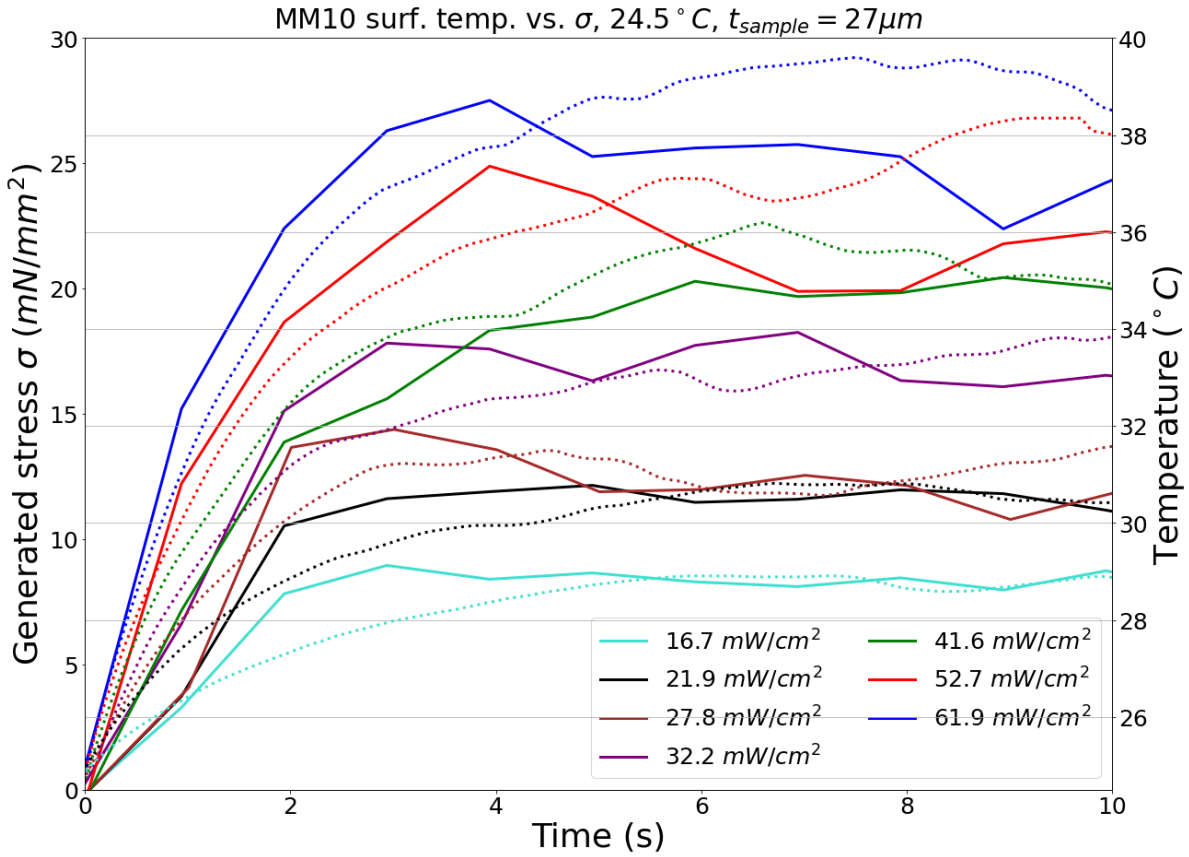
Increased irradiance



Faster response

Higher surface temperature

Higher force production

Faster break of sample

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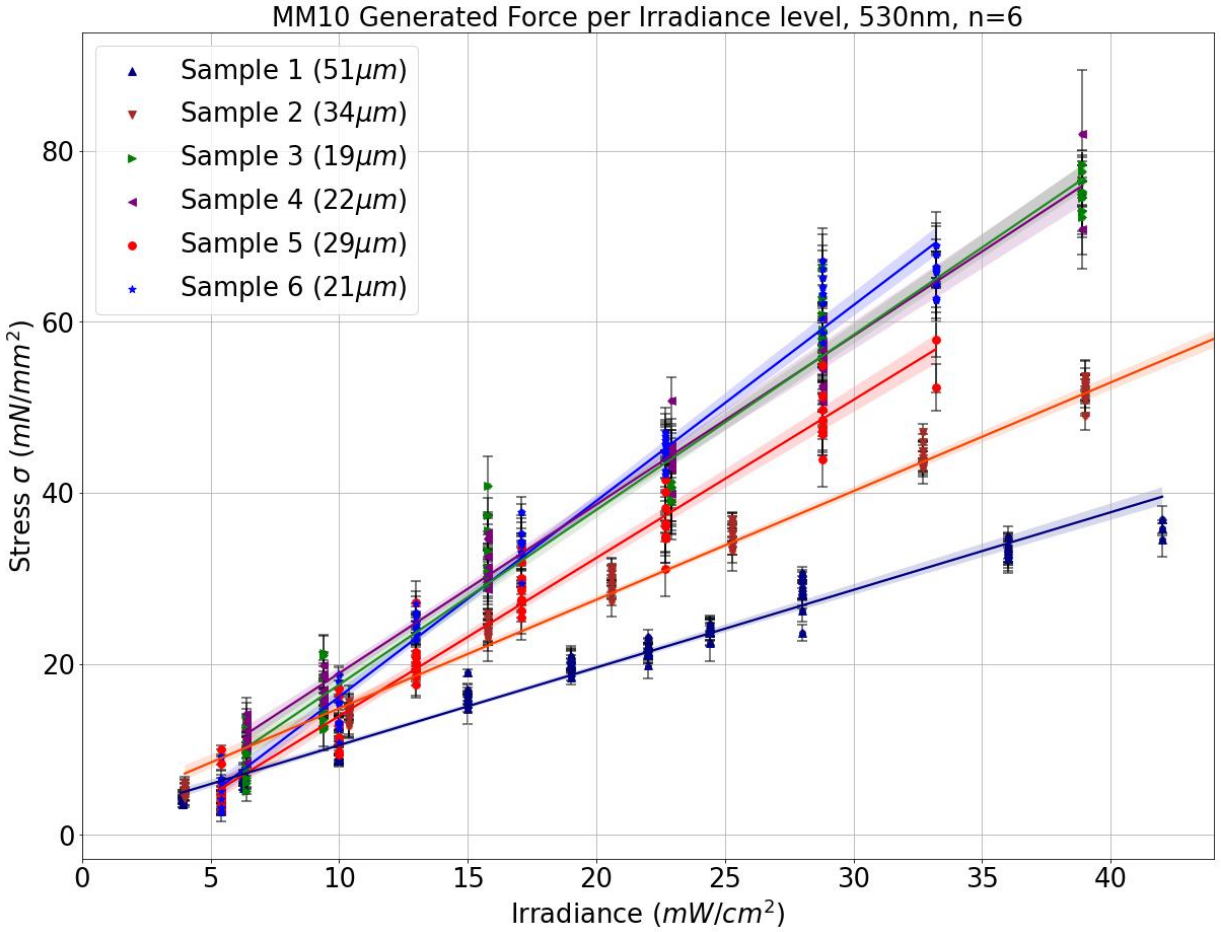
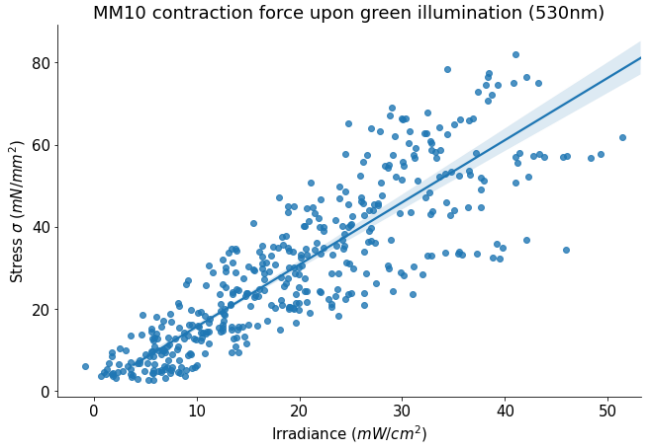
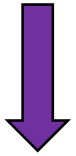
Contraction force tests





Higher sample thickness



Lower force generating efficiency

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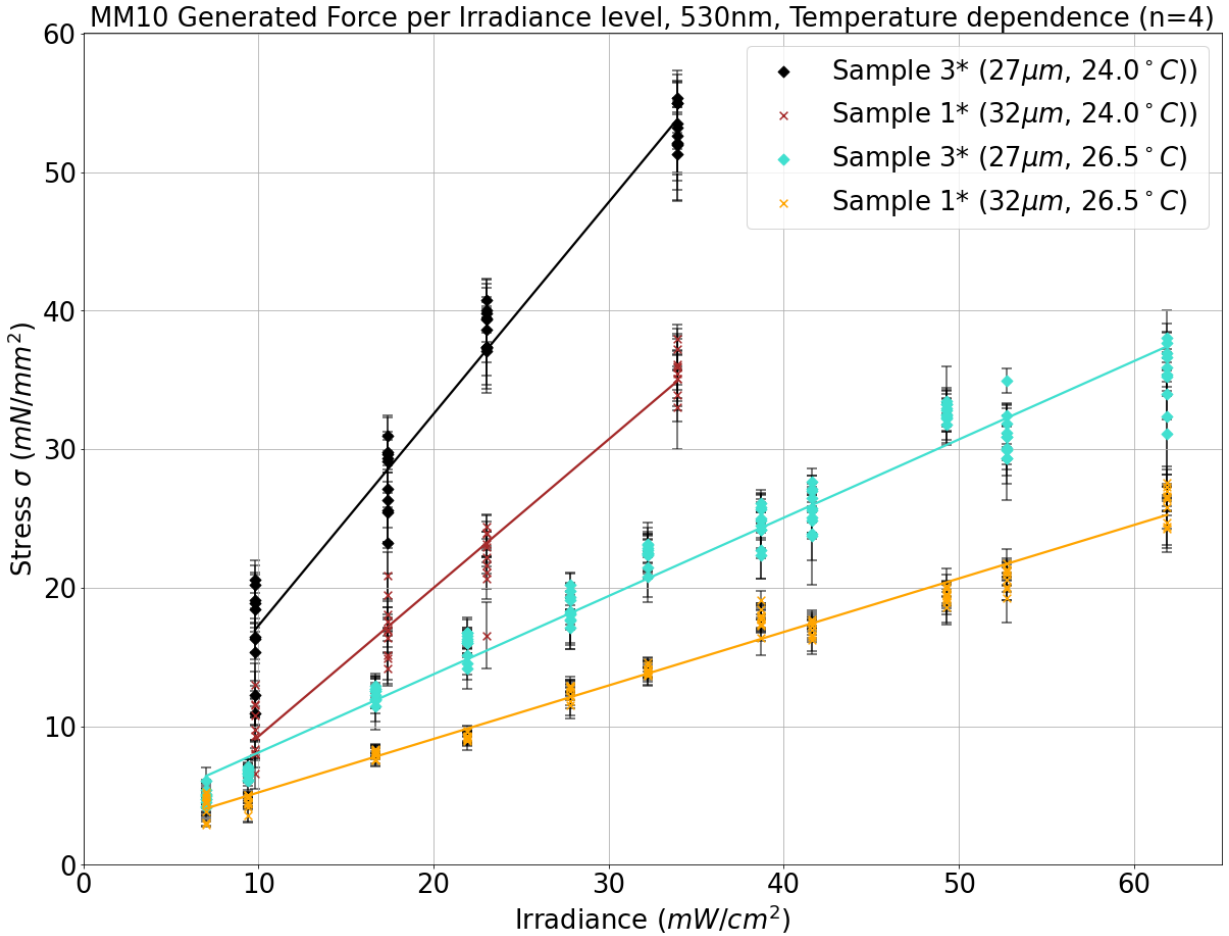
One day in summer...



Higher environmental temperature

Lower force generating efficiency

Can endure higher light intensities before break

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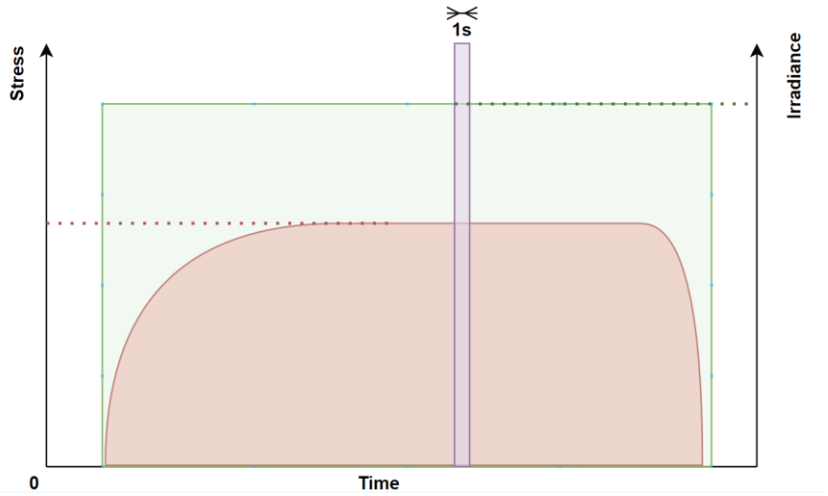
Mathematical model for maximum stress generation



Beer-Lambert Law: $$I_{(z)} = I_0 * e^{-az}$$

$$a = ln\left(\frac{I(z)}{I_0}\right) / -z$$

$I_0(mW/cm^2)$	$I(z=27.1)_{LCE1*}$	a_{LCE1*}	$I(z=32.3)_{LCE3}$	a_{LCE3}
6.53	0.64	0,0859	0.61	0,0732
15.19	1.42	0,0874	1.36	0,0747
28.50	2.63	0,0879	2.50	0,0753
33.93	3.10	0,0882	2.96	0,0755

Find a: $a = 0.081 \pm 0.006$

Irradiance minus reflection $I_{eff} = 0.9447 \cdot I_0$

Light penetration: $I_{(z)} = I_{eff} \cdot e^{-0.081 \cdot z}$

Total absorbance: $$I_{abs} = I_{eff} \cdot \int_0^{t_{samp}} e^{-0.081 \cdot t}\, dt$$

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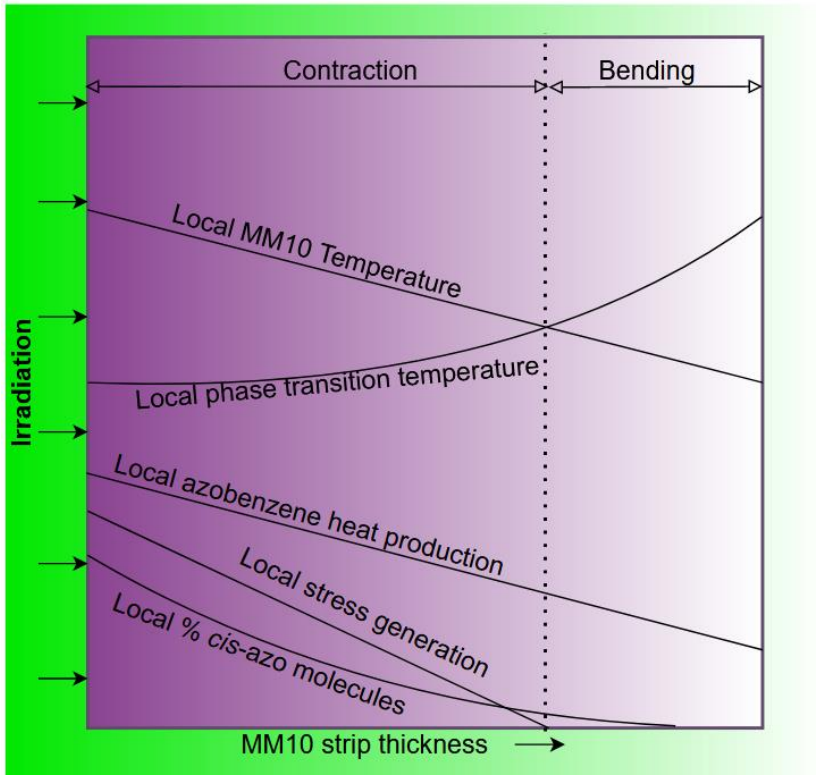


Influence of thickness

$$\sigma = \frac{I_{eff} \cdot \int_0^t e^{-0.081 \cdot t}\, dt}{t}$$

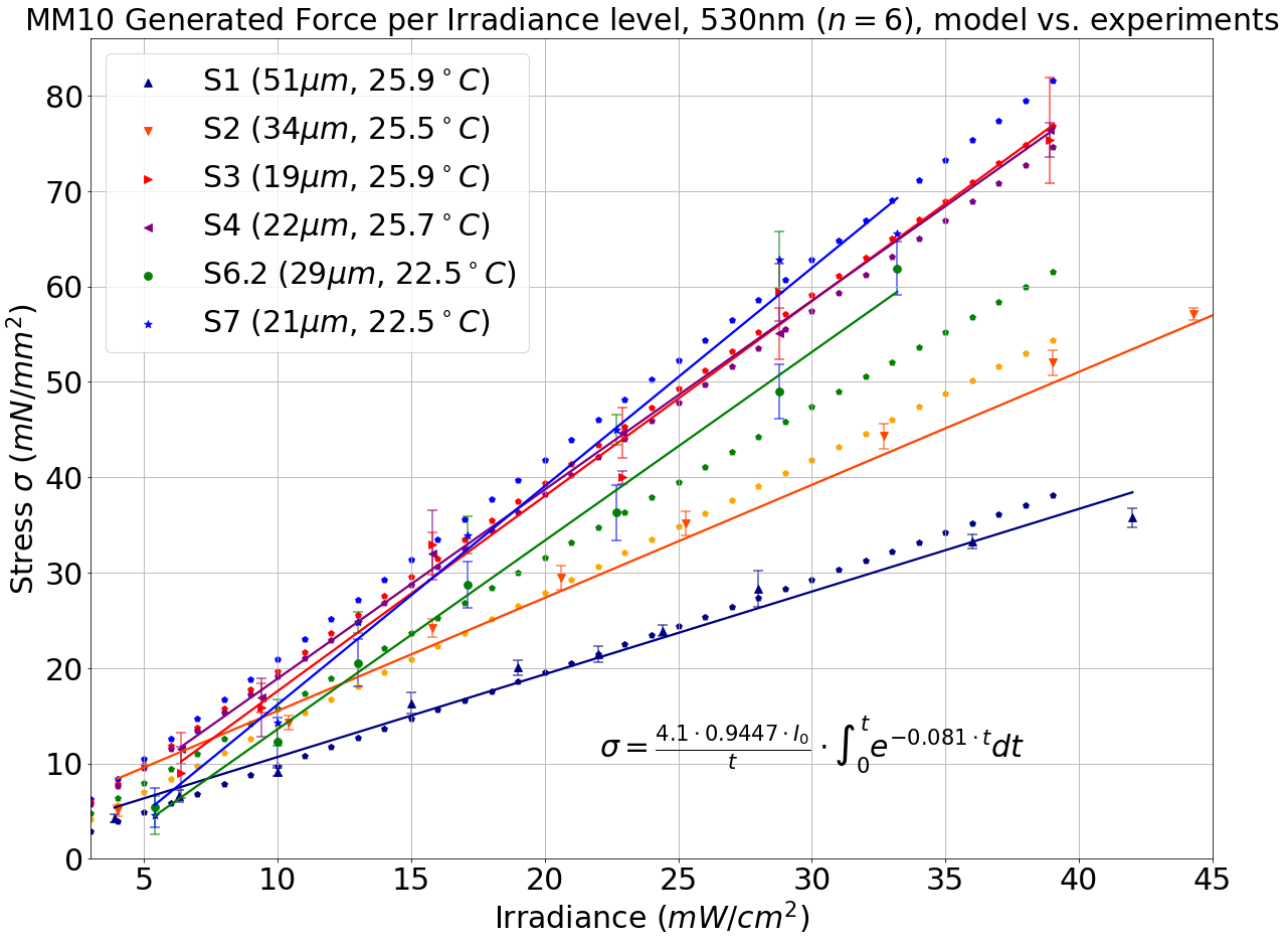
Influence of environment temp.

$$\sigma = \frac{A \cdot I_{eff} \cdot \int_0^t e^{-0.081 \cdot t}\, dt}{t}$$

Model:

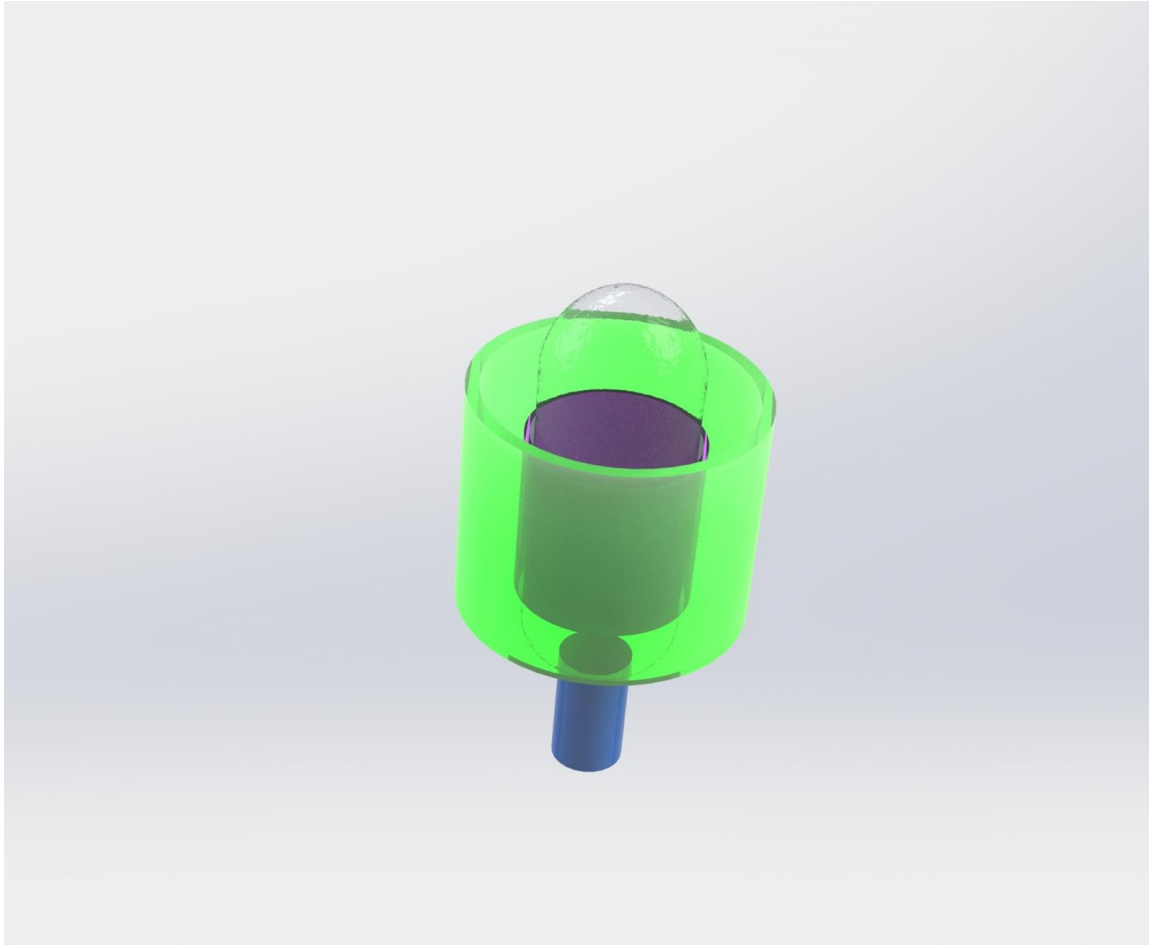
$$\sigma = \frac{A \cdot (0.9447 \cdot I_0) \cdot \int_0^t e^{-0.081 \cdot t}\, dt}{t}$$

Model vs. Experiments

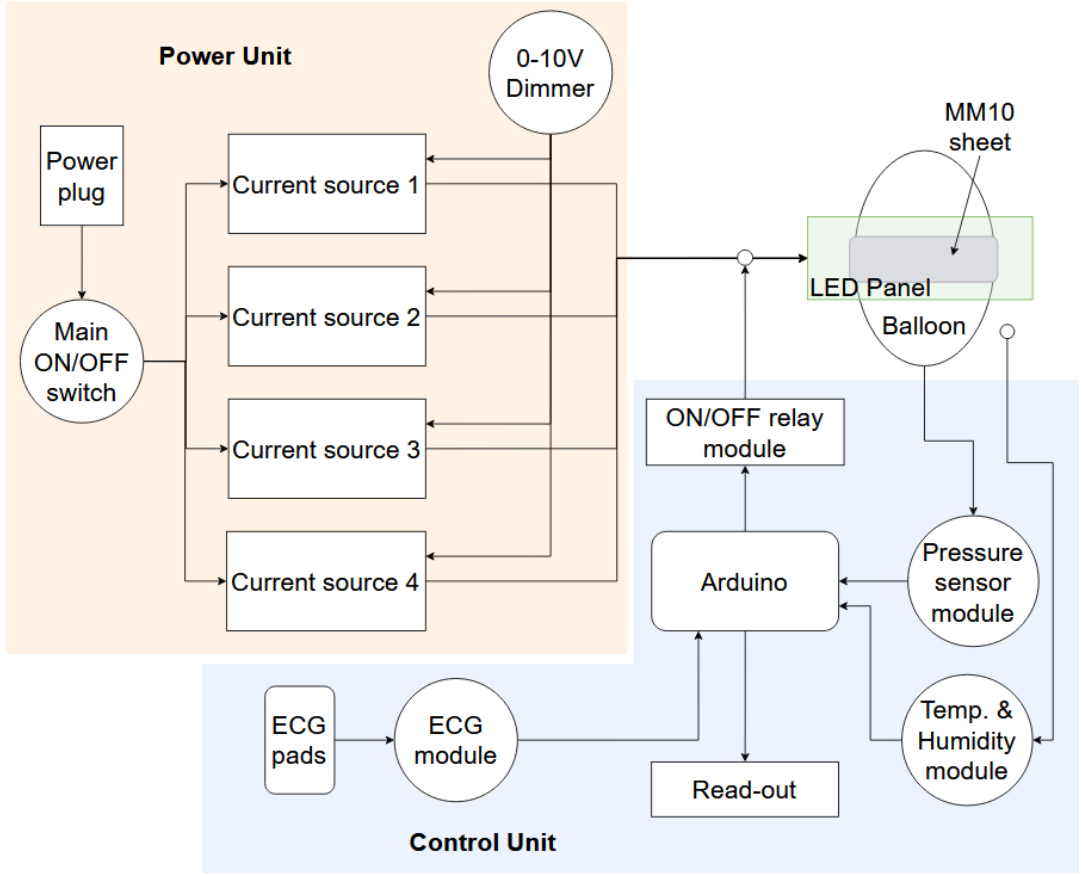


Can we measure concentric pressure?

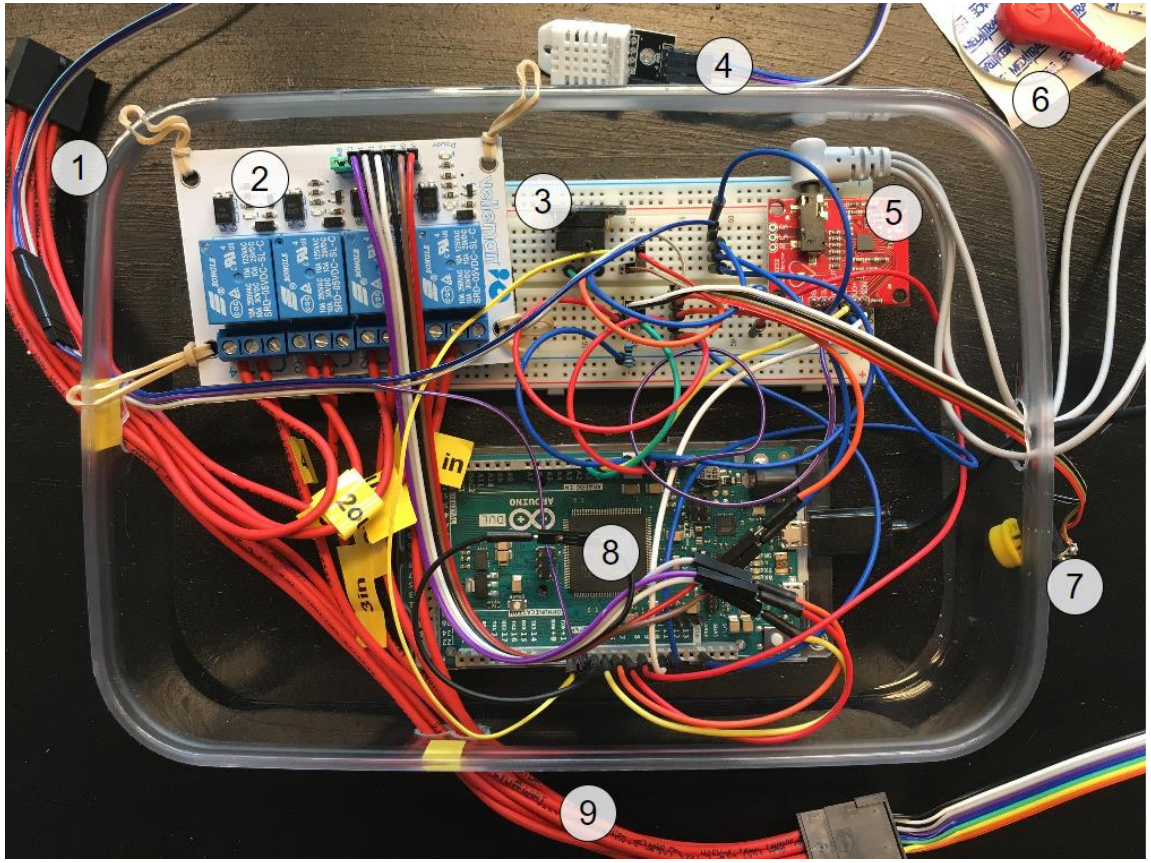
- Build a demonstrator
- Measure contraction force of MM10 strip around a balloon
- Live read out: pressure (2Pa acc.), humidity, temperature, ECG signal
- Live ECG signaled pacing



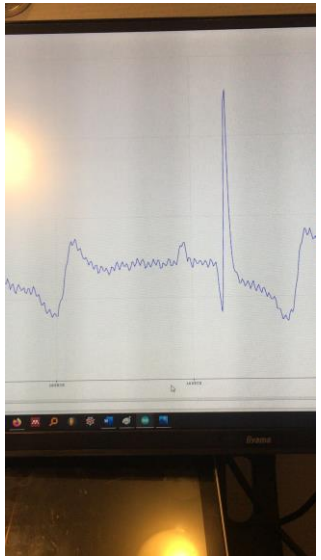
System design

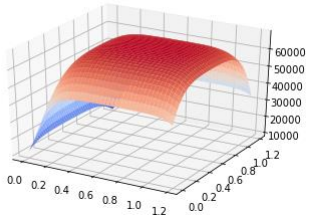


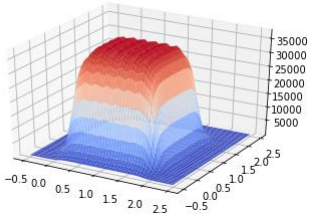
Control unit



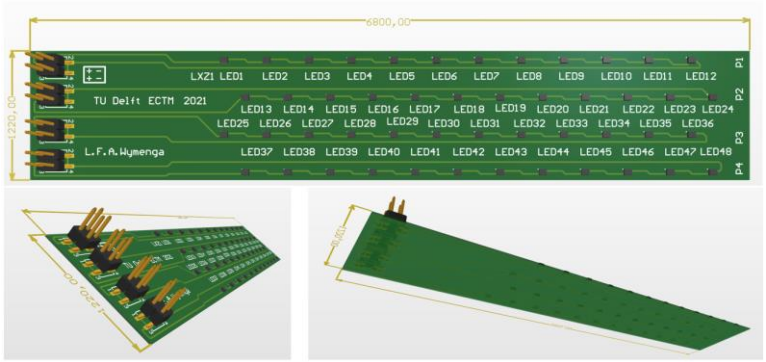
Live ECG



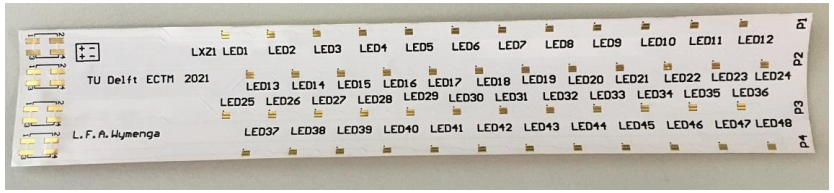


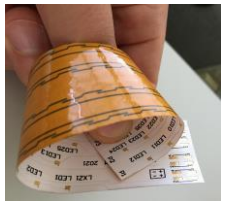


Model

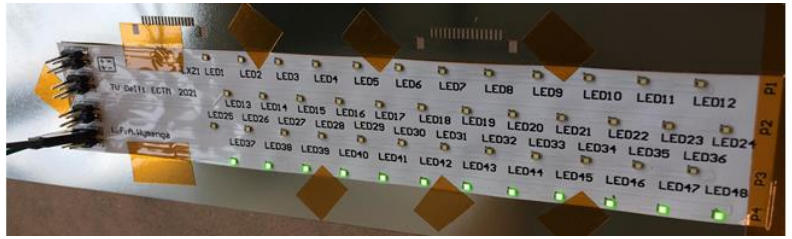


Design

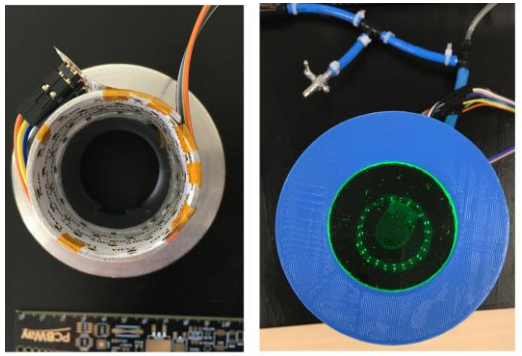




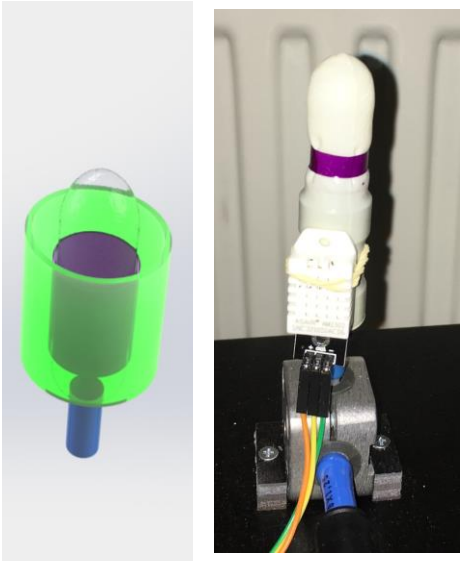
Print



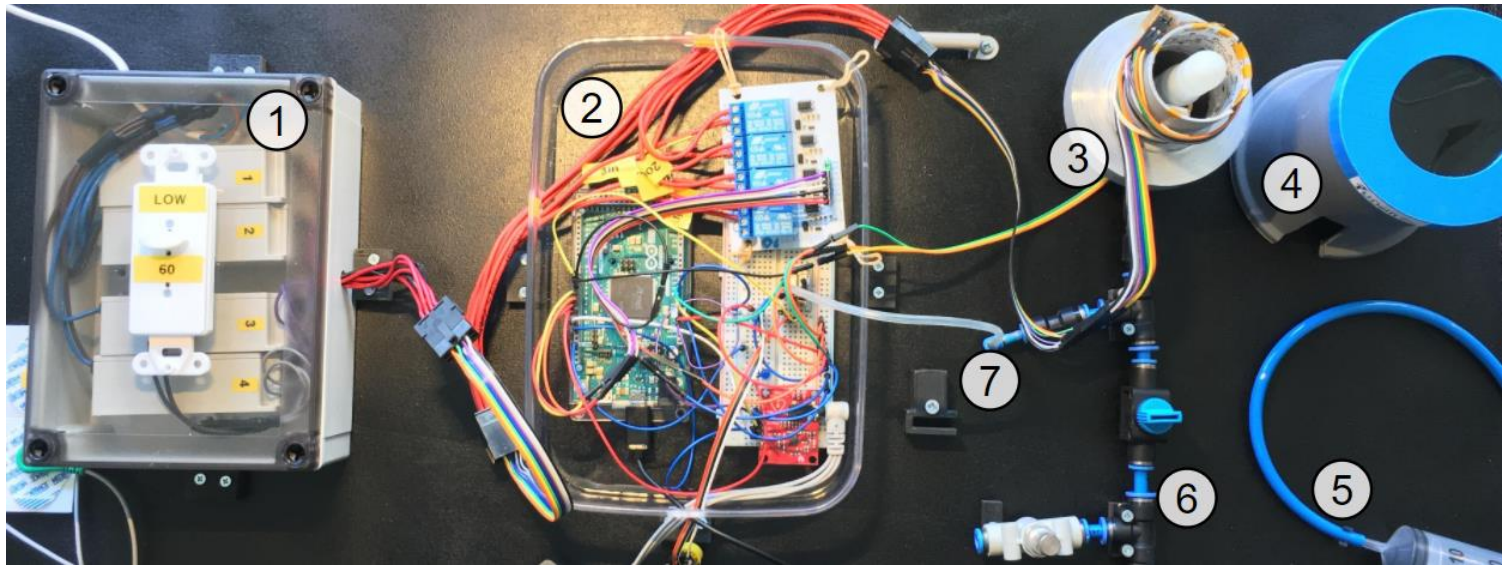
Assemble

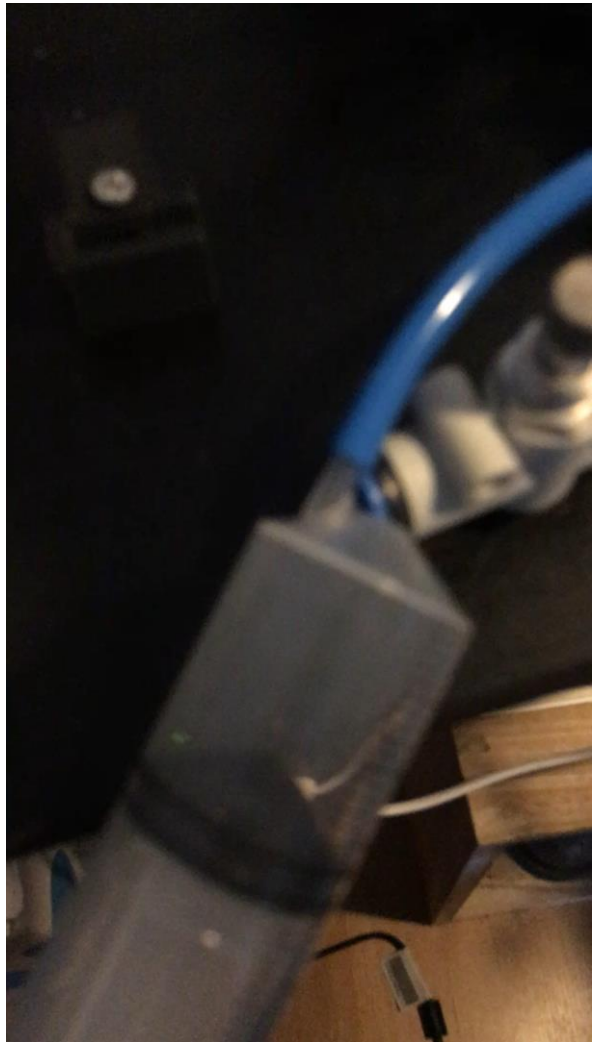


Build



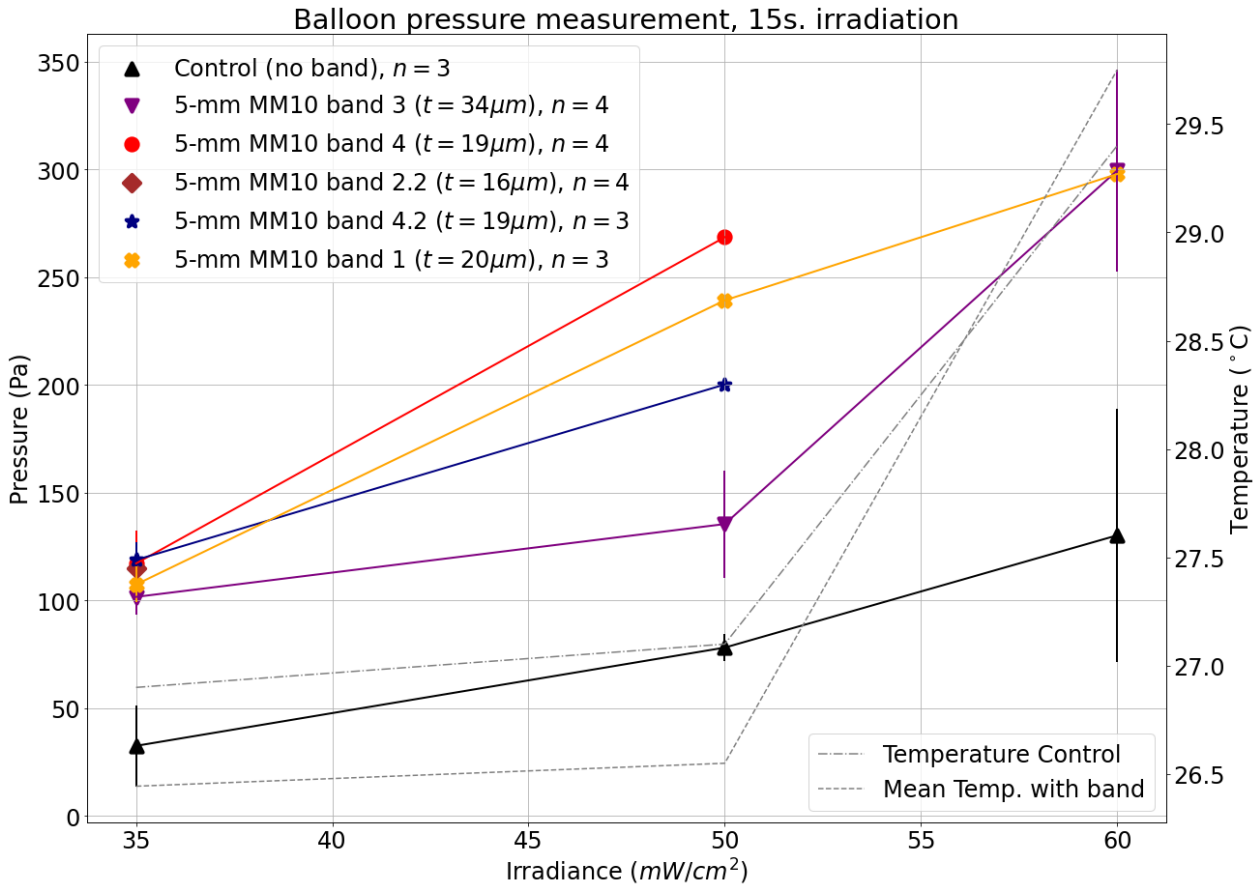
Full Setup





System in practice

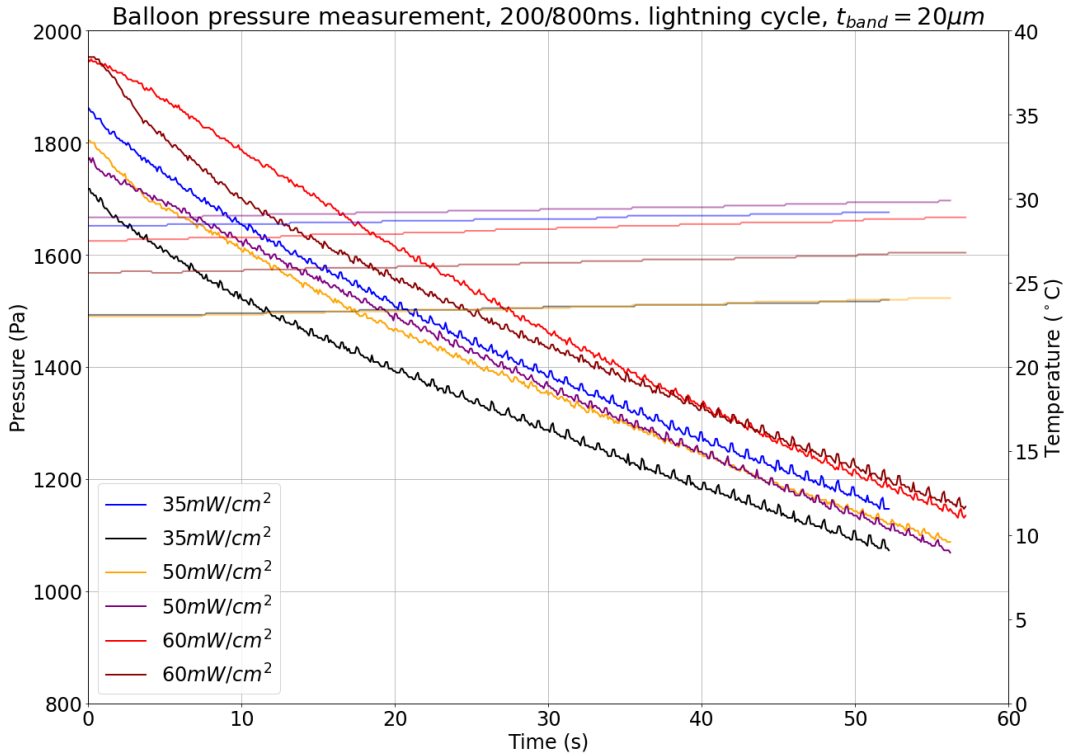
15s irradiation



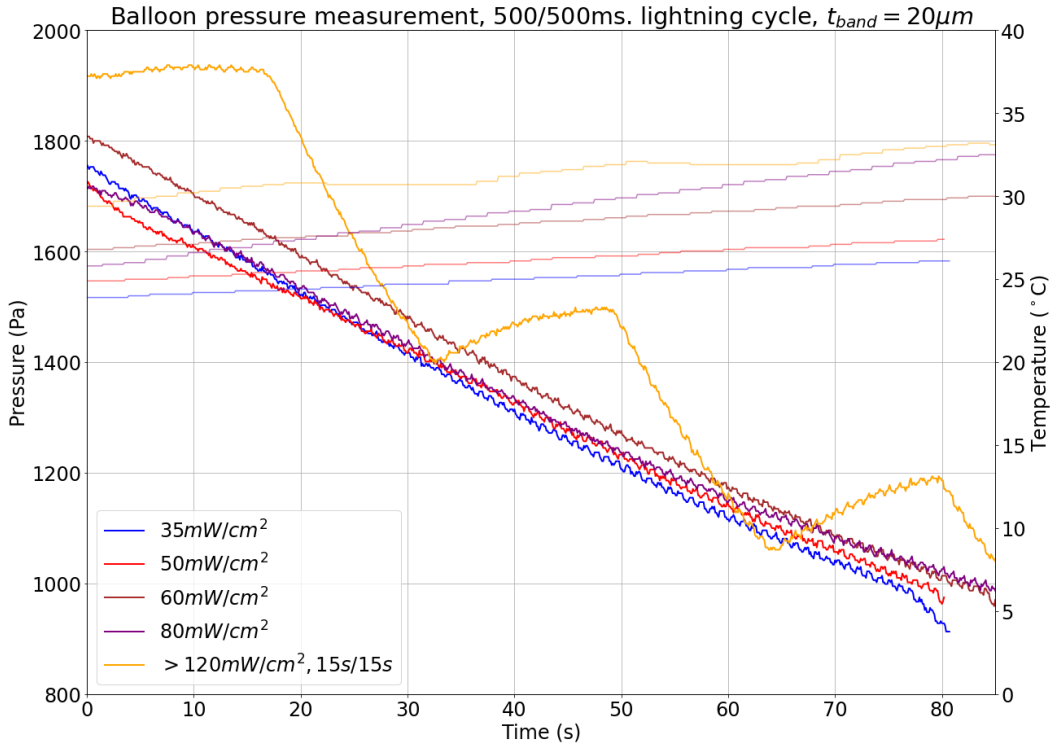
Up to 170Pa pressure generation with a 20μm MM10 band

Light pulse illumination 1Hz

200ms pulse



500ms pulse

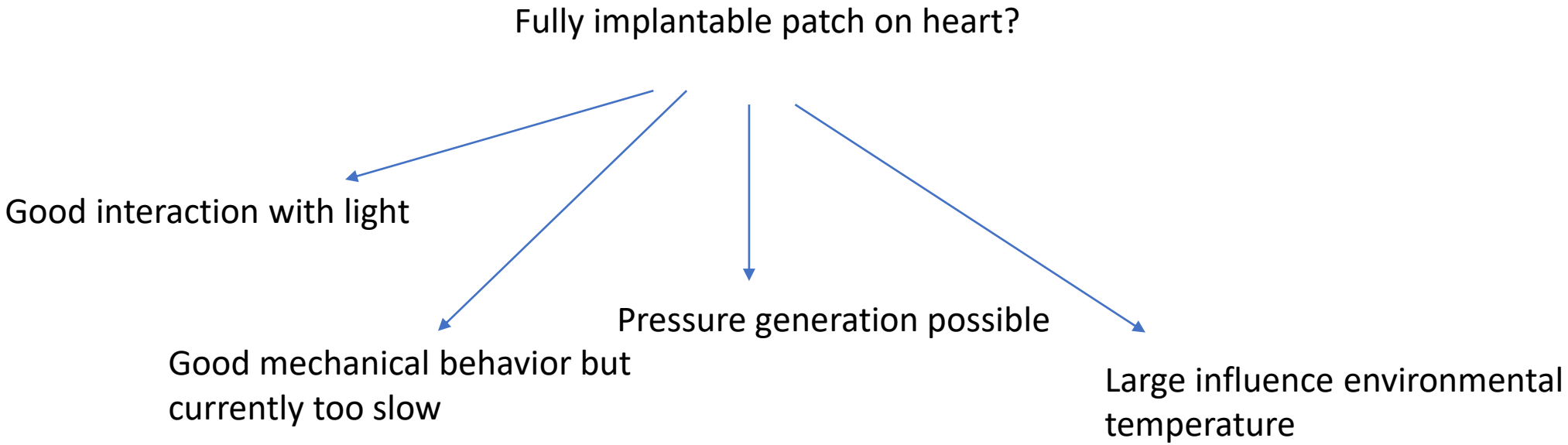


Pressure generation not fast enough for effective contraction at normal heart rate (with current irradiance)

Main conclusions

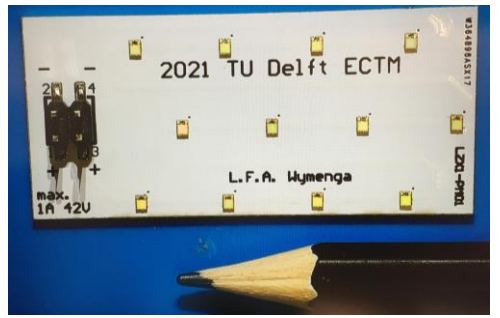
- Accurate models for passive and active mechanical MM10 behavior are found
- MM10 is able to generate high stress/pressure in response to green LED light
- MM10 is currently too slow to efficiently contract at normal human heart rates

Can LCEs be used to assist cardiac contraction?



Future directions

- Test LCE in controlled temperature environment
- Change MM10 recepture to achieve faster response times
- Think of other biomedical applications such as implanted drug micropumps
- Miniaturization → towards µLED-LCE contractile unit



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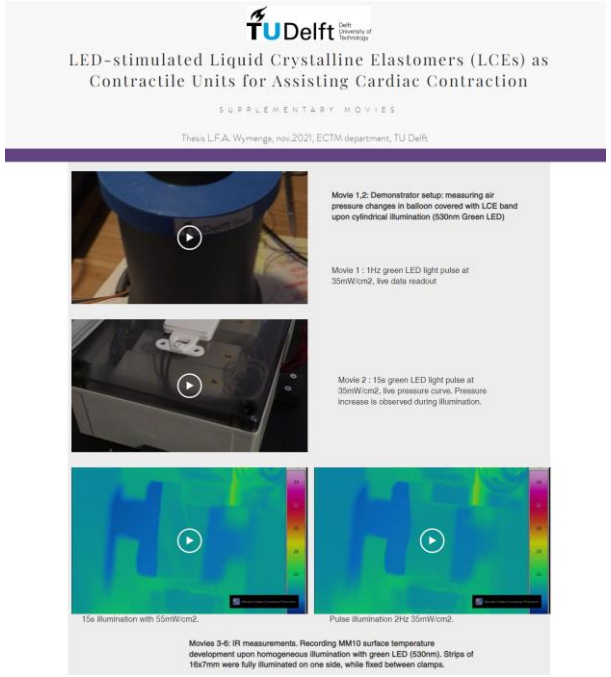
- *The Florence group: Ceci Ferrantini, Camilla Parmeggiani, Simone Donato et al.*



Watch more videos at:
https://delftao.wixsite.com/lces

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