MEDSI 2016

MECHANICAL ENGINEERING DESIGN OF SYNCHROTRON RADIATION EQUIPMENT AND INSTRUMENTATION

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Minimization of mechanical constraint effects of Eutectic GaIn as thermal interface

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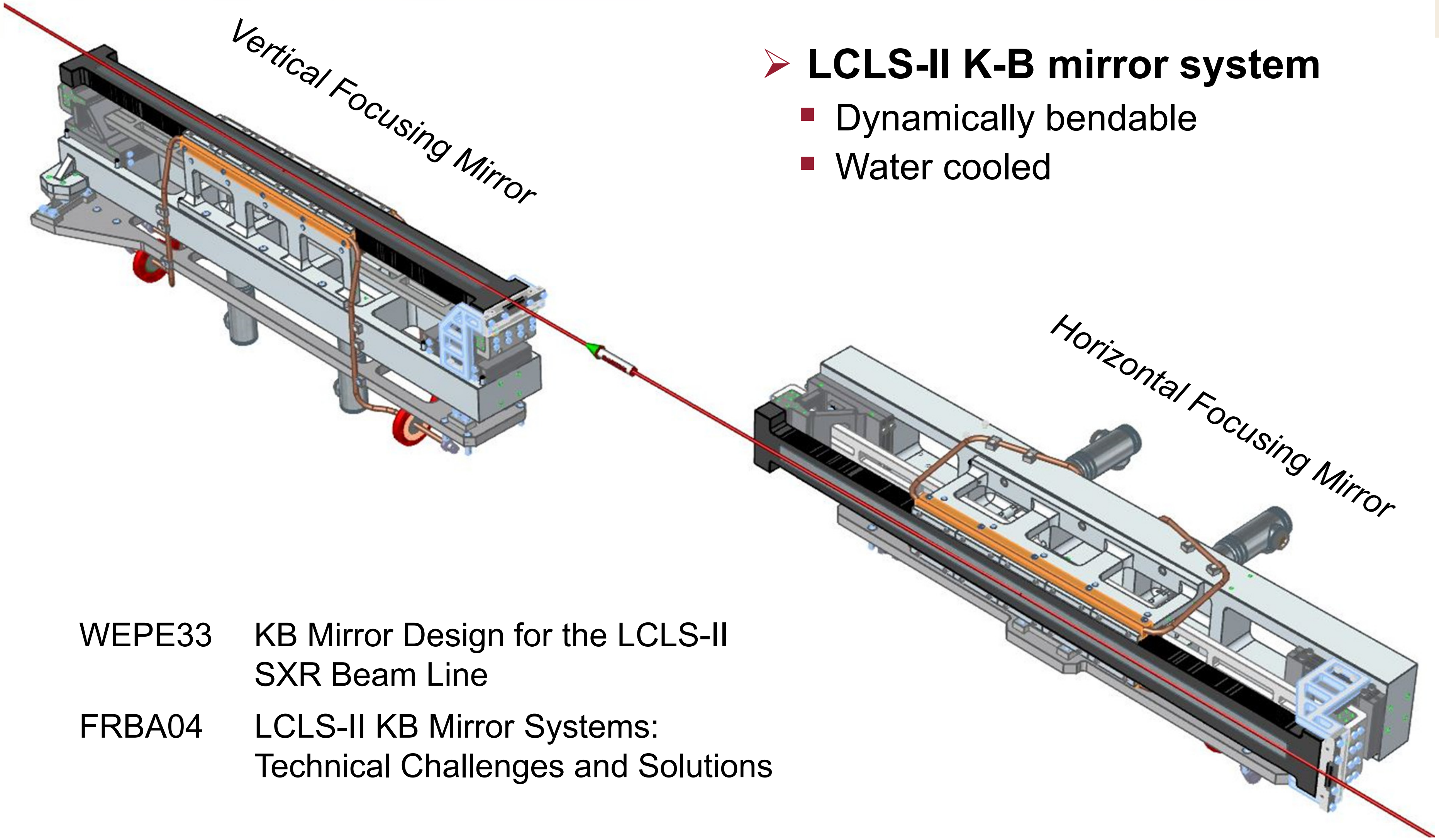
U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Background

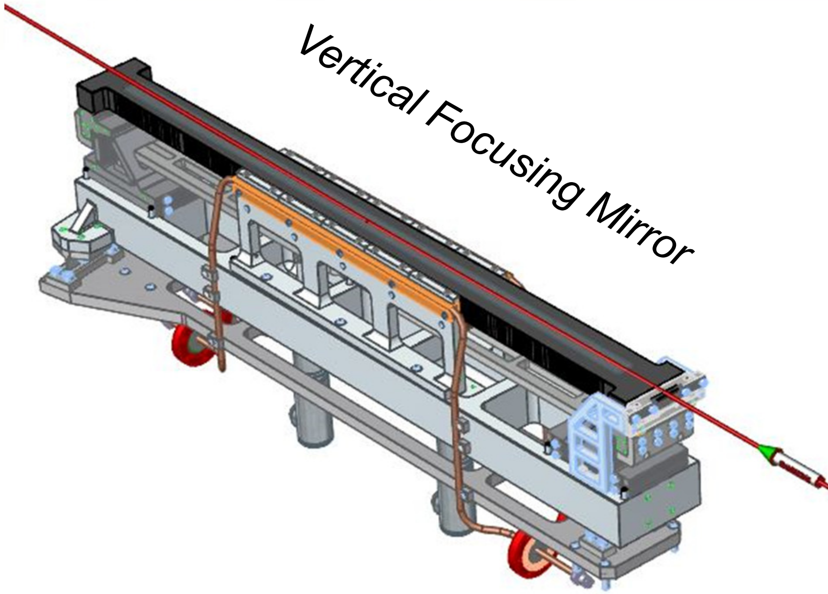


➢ **LCLS-II K-B mirror system**
- Dynamically bendable
- Water cooled

WEPE33 KB Mirror Design for the LCLS-II SXR Beam Line

FRBA04 LCLS-II KB Mirror Systems: Technical Challenges and Solutions

Background



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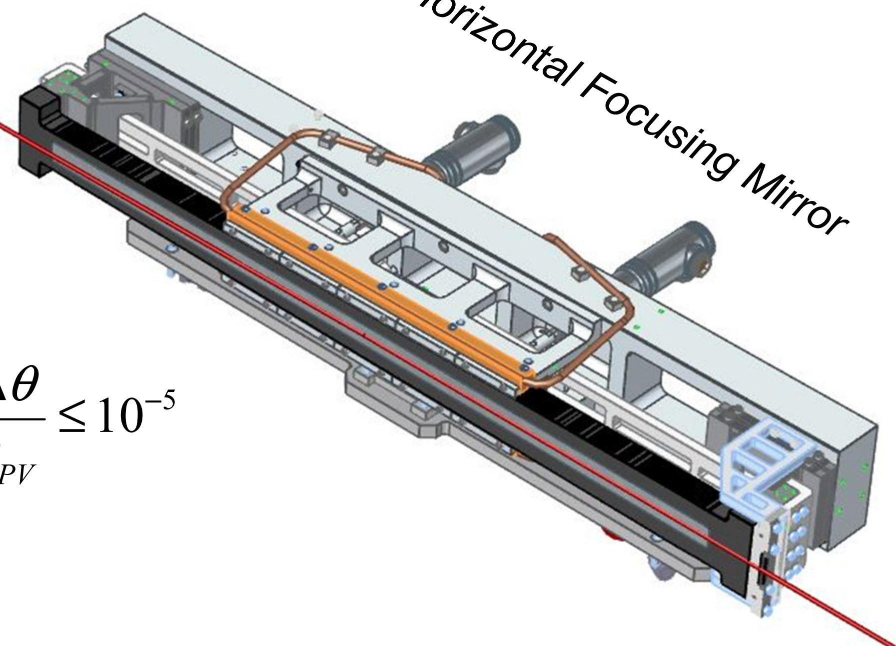

- **Requirements**
  - Accurate bent mirror shape
  - Effective cooling

$$\frac{\Delta\theta}{\theta_{PV}} \leq 10^{-5}$$

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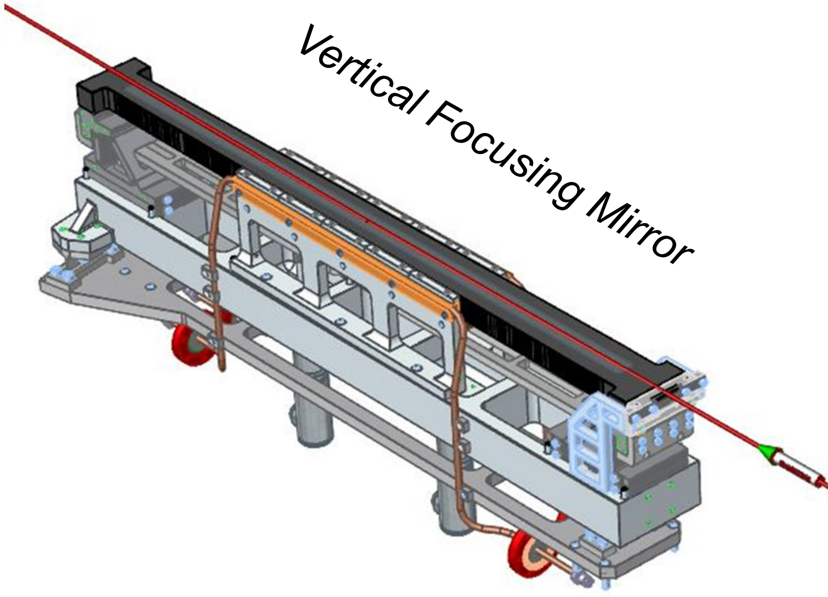

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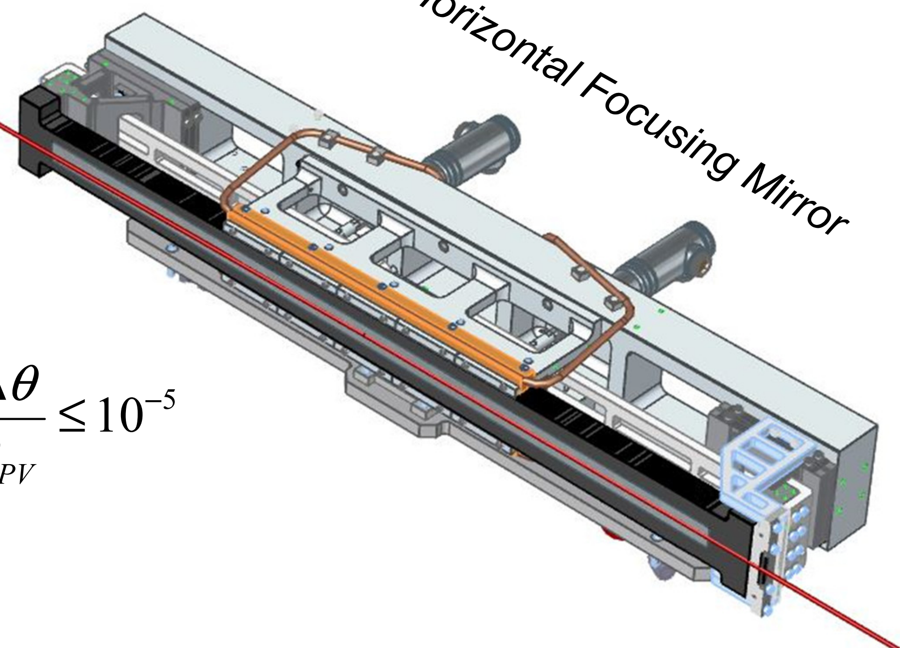

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→ **Eutectic GaIn (liquid metal)**
  - Good thermal contact
  - Mechanical de-coupling

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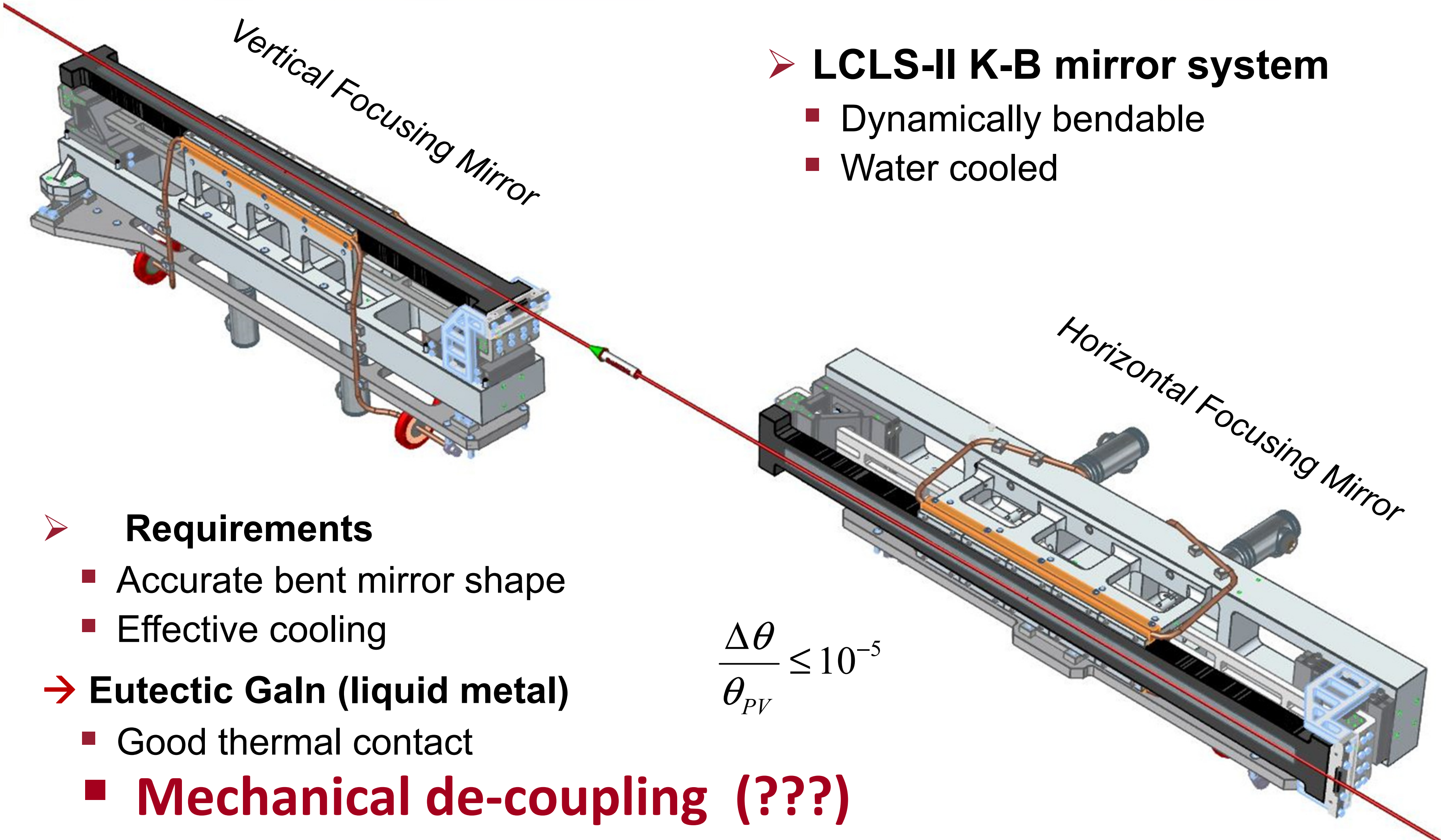

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  - Good thermal contact
  - **Mechanical de-coupling (???)**

Eutectic Gallium-Indium (eGaIn)

- **eGaIn: 75.5% Gallium (29.76ºC)**

  24.5% Indium (156.6ºC)

  $T_{melting}$=15.7ºC

- **Thermal interface**
  - Thermal conductance > 10^5 W/m^2.K, ~ 10 times better than Indium foil
  - Interface or trough / bath for indirect cooling of the X-ray mirrors

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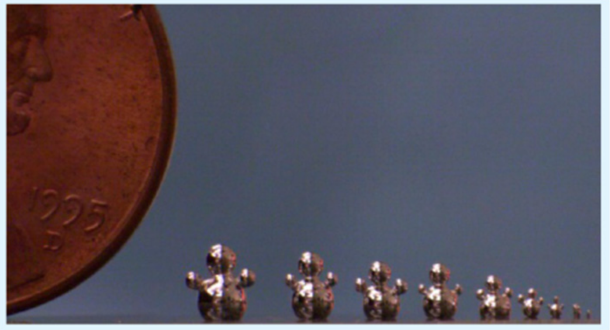
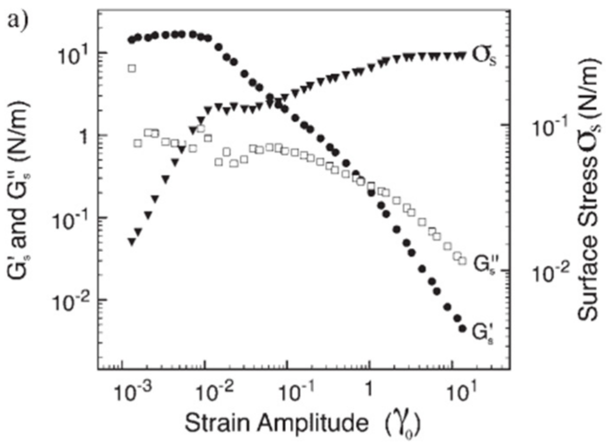
- **Mechanical properties**
  - Bulk viscosity ~ 2 mPa*s ($2\mu_{water}$)
  - Modulus **??**
  - Thin skin (oxides of Ga)

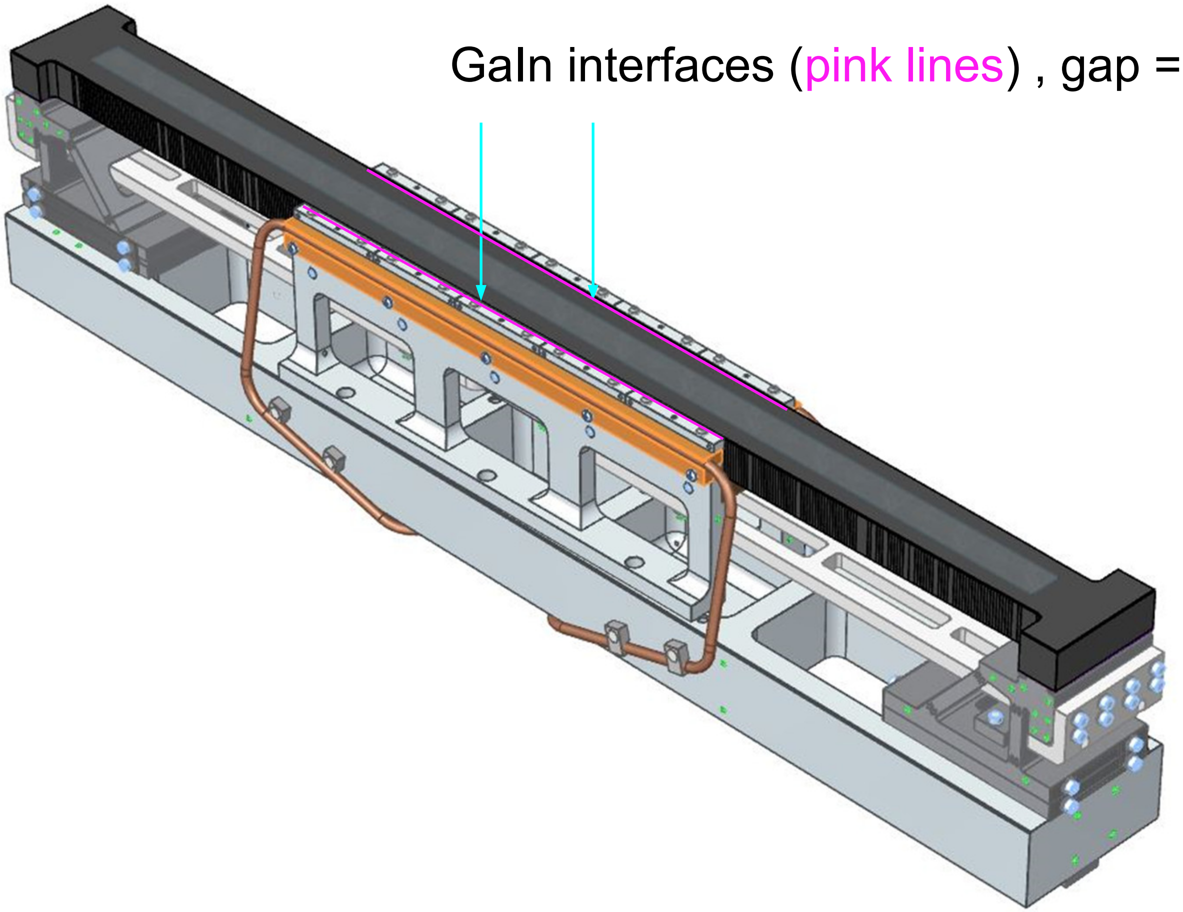




Dickey et al., Adv.Funct.Mater.2008,18,1097–1104

Dickey, ACSAppl.Mater.Interfaces2014,6,18369−18379

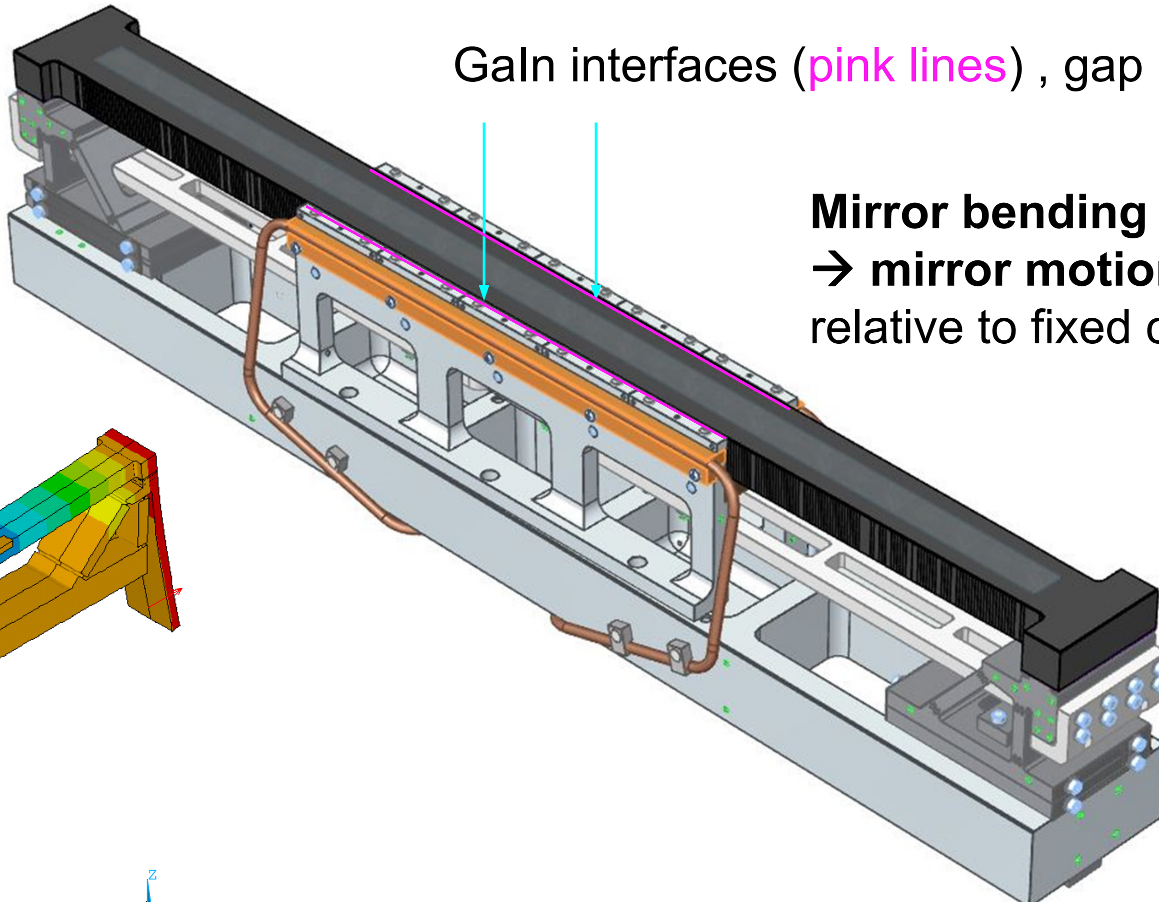
Eutectic GaIn as thermal contact interface

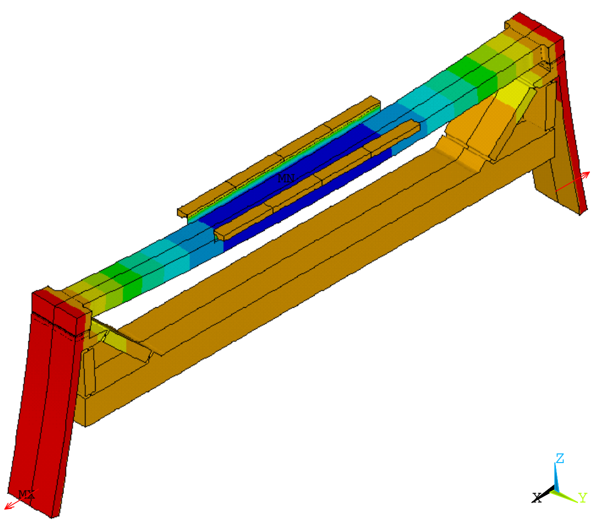


Eutectic GaIn as thermal contact interface

GaIn interfaces (pink lines) , gap = 50 µm

Mirror bending
→ mirror motion (up-down)
relative to fixed cooling blocks





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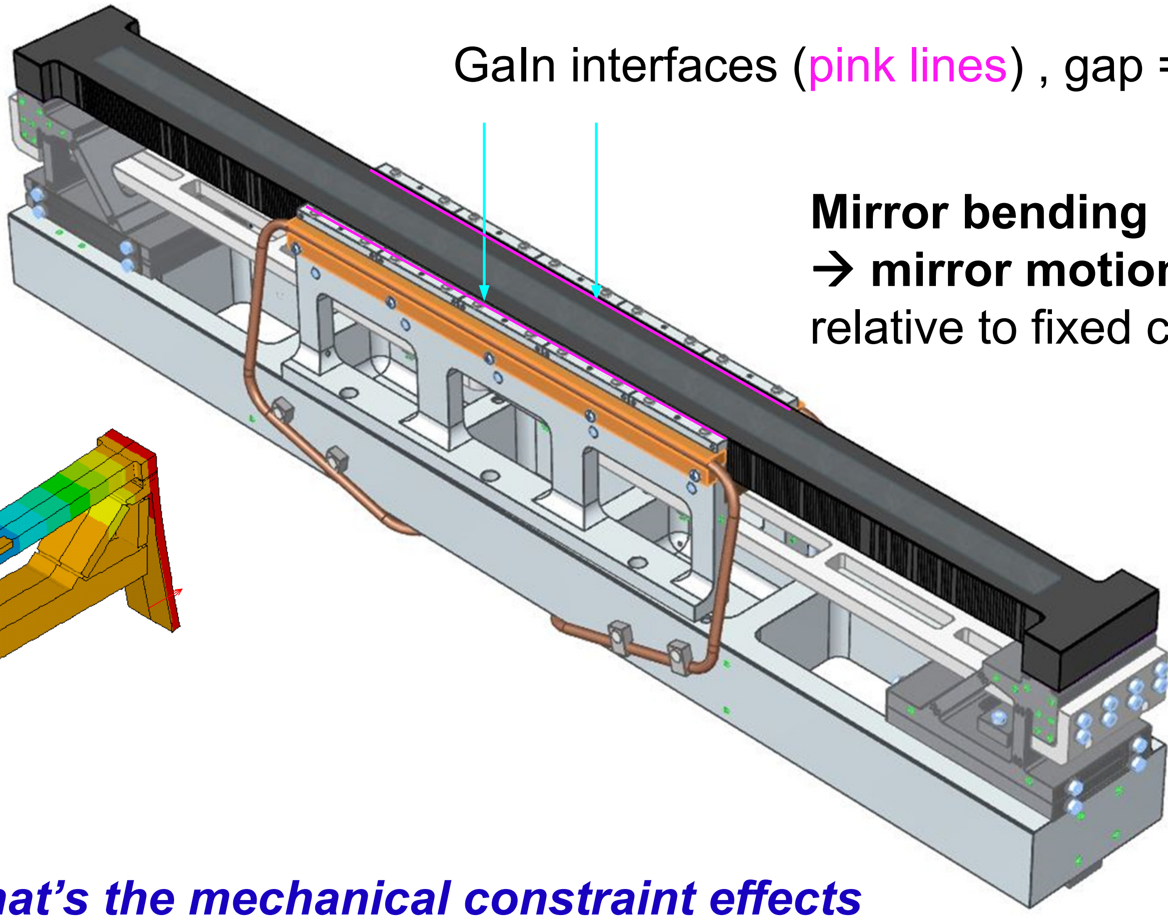

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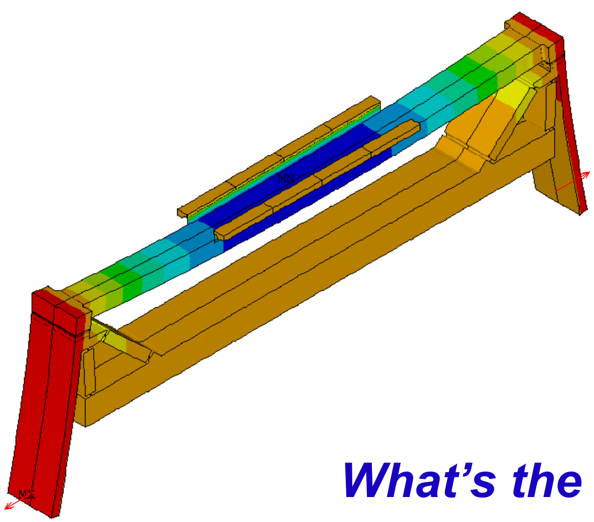

What's the mechanical constraint effects during the mirror bending?

GaIn test Setup

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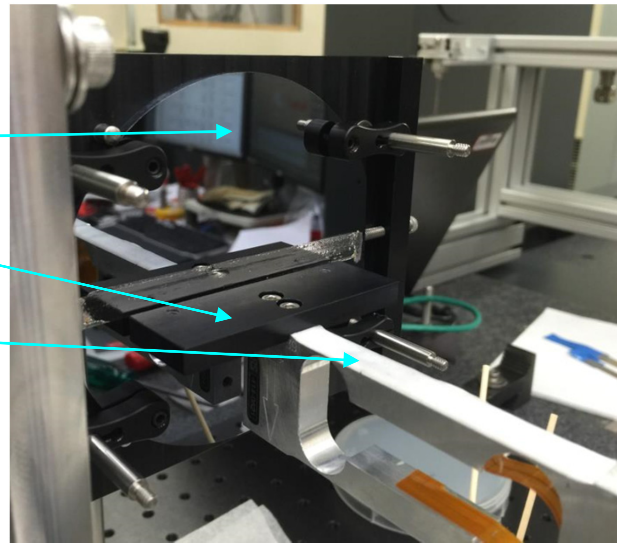
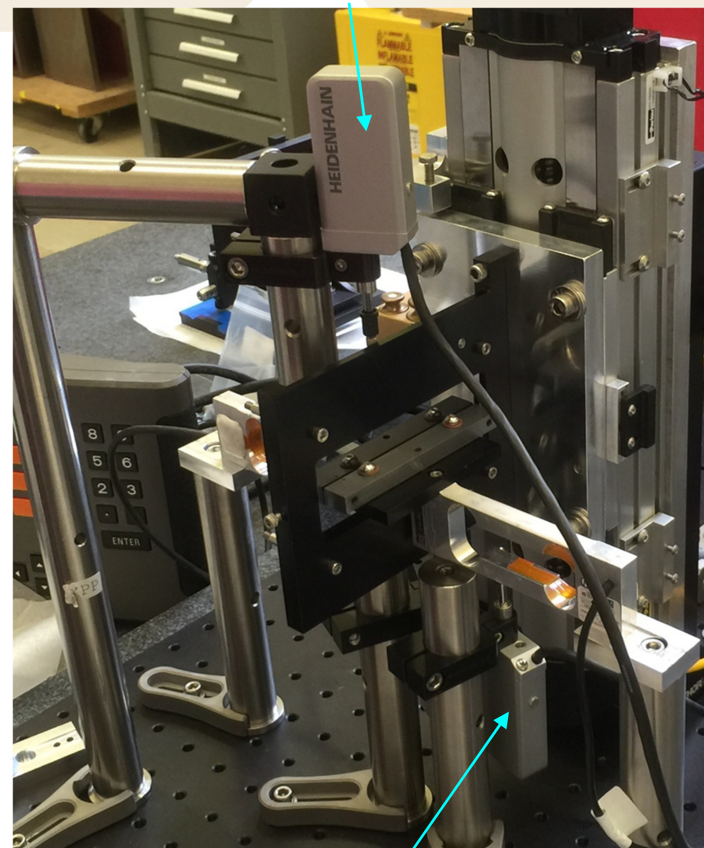
- Si-wafer (D=4”, **t = 4 mm**, both side polished)
- GaIn gap: (51, 102, 152, 203, 254 μm)

Silicon wafer
moving part

Silicon pad
fixed on a
force sensor



Displ. Sensor A

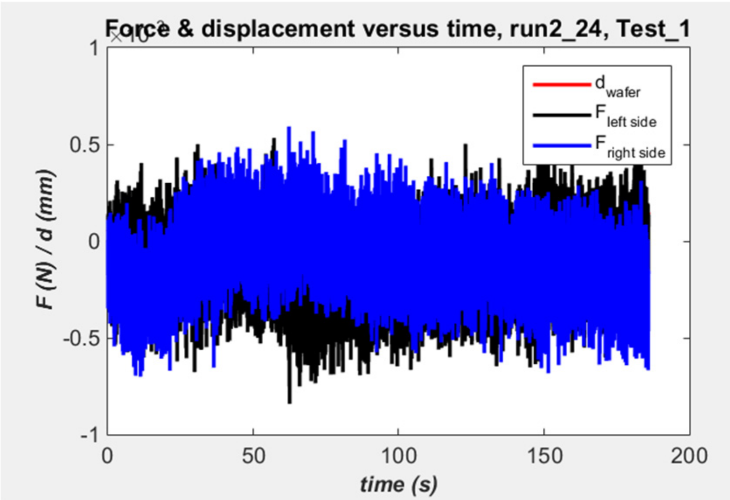


Displ. Sensor B

- **Measurements**
  - Displacement of Si-wafer d_{wafer}
  - Forces of Si-pads on
    Left side and Right side: F_L, F_R
  - Relative displacement between wafer and pads: $d_{pad} = d_{wafer} – (F – F_0)/ k_{FG}$
  - *Force gauge stiffness:* k_{FG} *= 10.57 N/mm*

GaIn test Setup – measurement accuracy

- Force & displacement measured when there is no motion

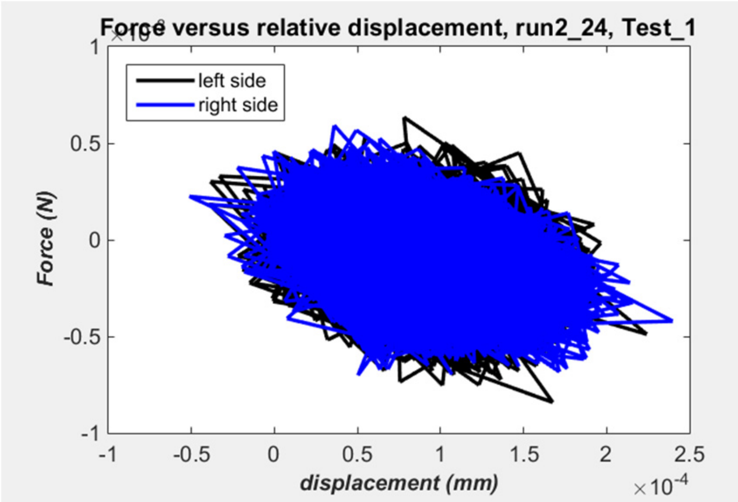


gap=100 μm

$\varepsilon_d = \pm\, 0.15\ \mu m$

$\varepsilon_F = \pm\, 0.7\ mN$

Sensors accuracy:
0.2 μm, 0.2 mN



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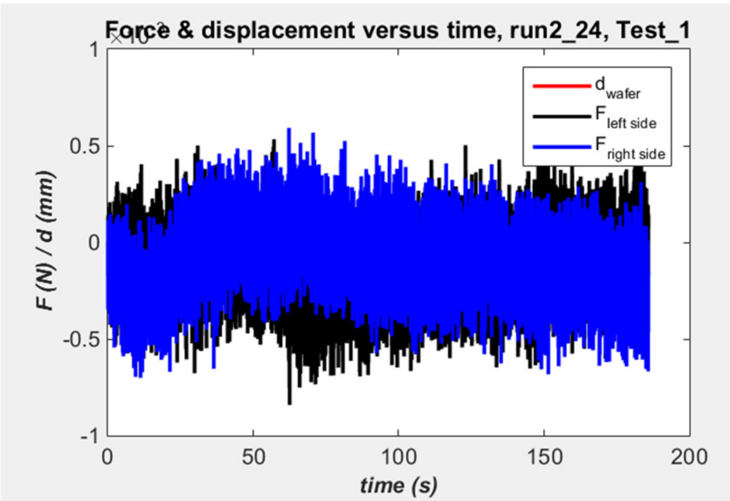

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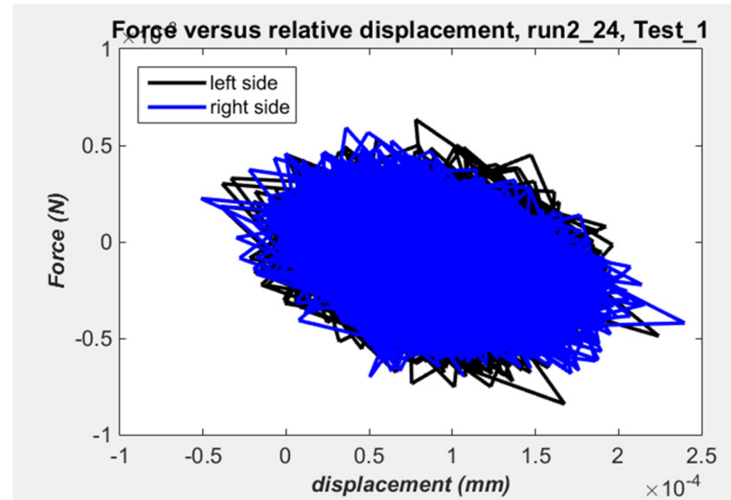

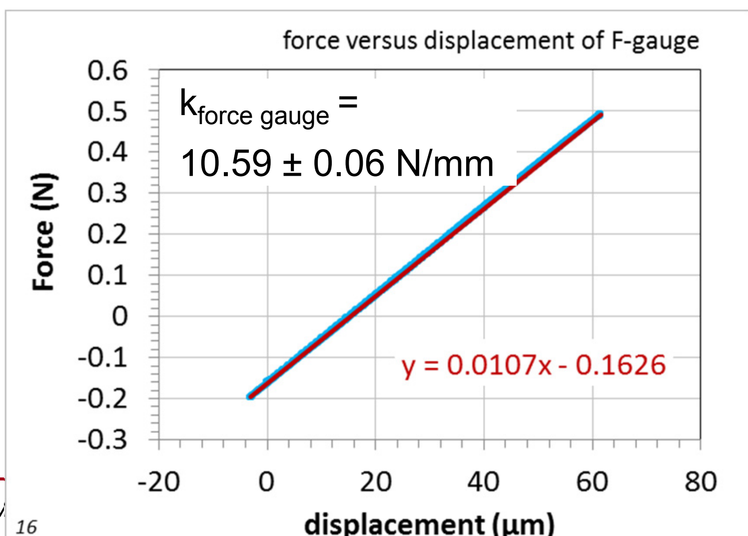

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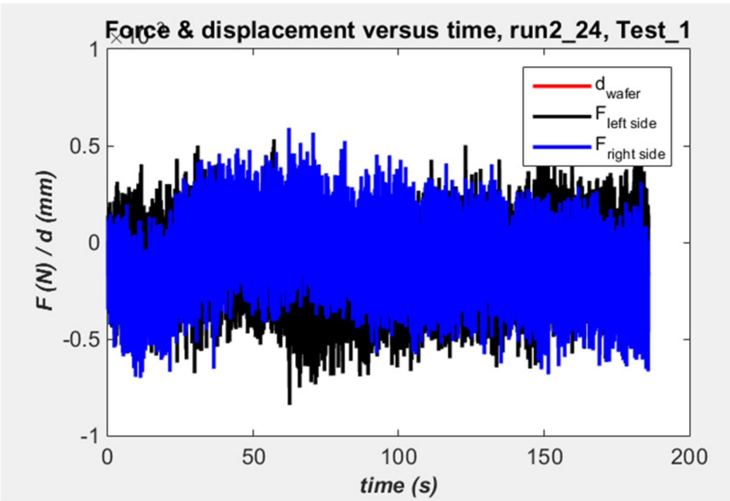

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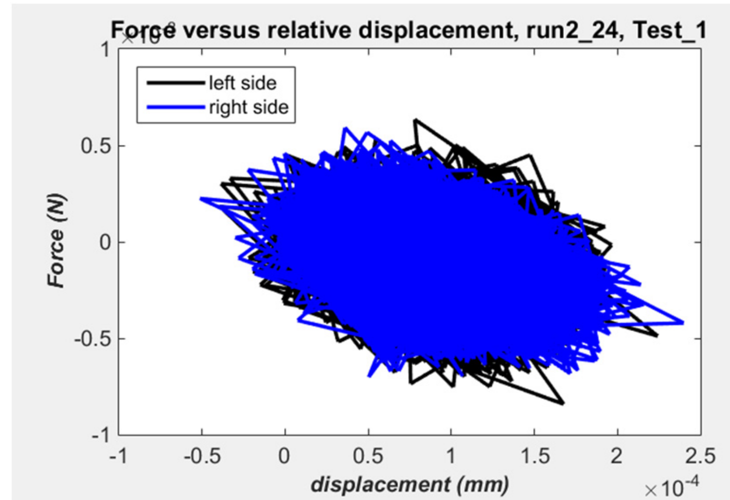
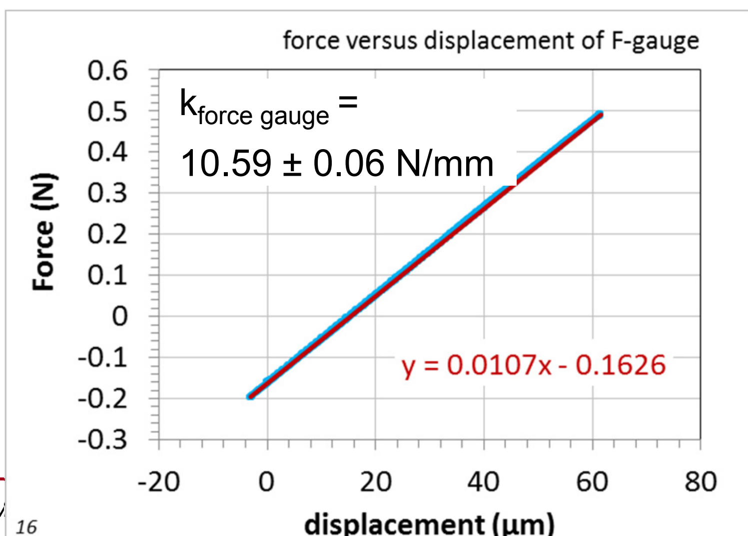
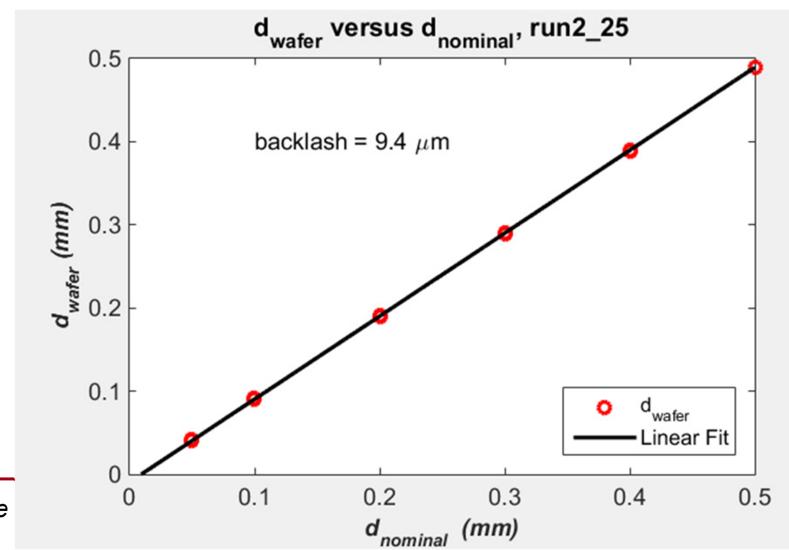
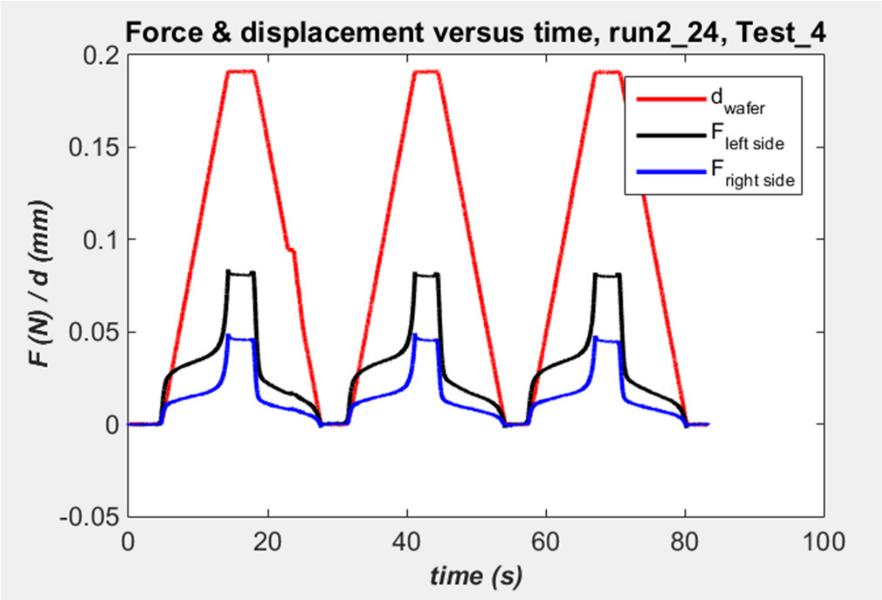






GaIn Test results – Repeatablity



- *GaIn gap = 100 µm*
- *Si-wafer displacement d_{wafer} = 200 µm, at speed 20 µm/s*

➢ 3 – cycles measurements → **Good repeatability**

GaIn Test results – Repeatablity

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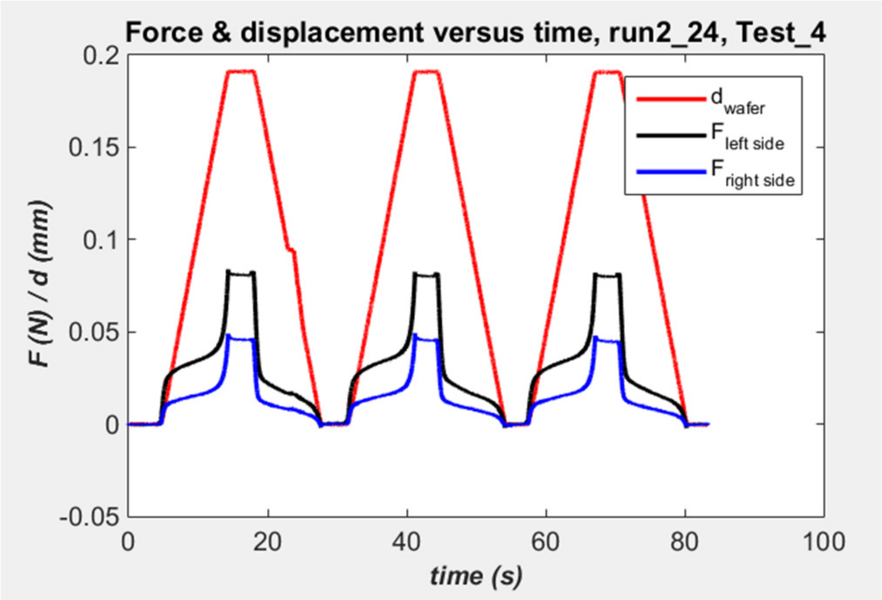
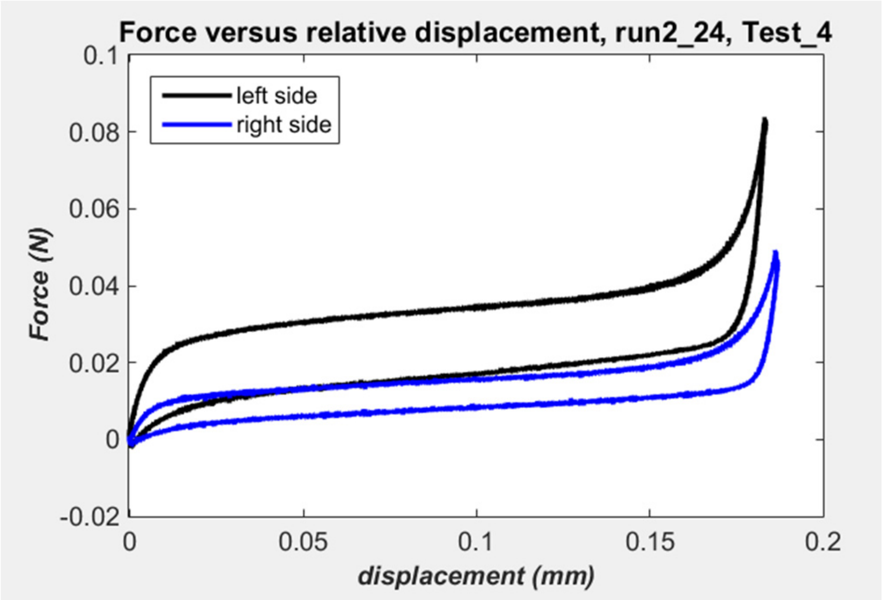
Share stress ~ $F/A_{contact}$





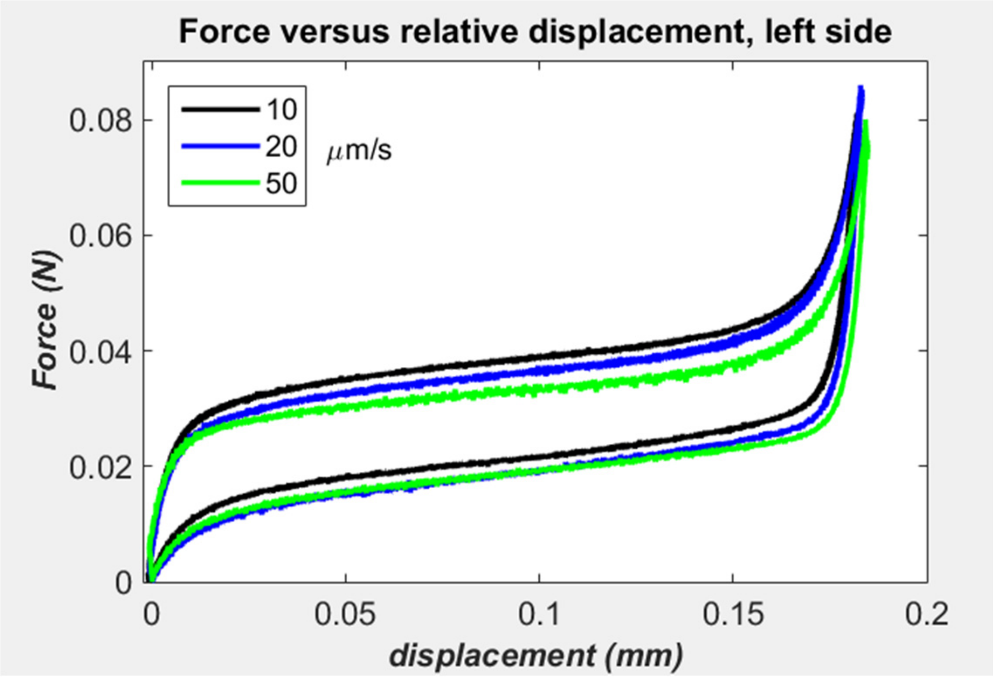
Share strain ~ d/gap_{GaIn}

- *GaIn gap = 100 μm*
- *Si-wafer displacement d_{wafer} = 200 μm, at speed 20 μm/s*

➢ 3 – cycles measurements → **Good repeatability**

GaIn Test results – at different speed of displacement

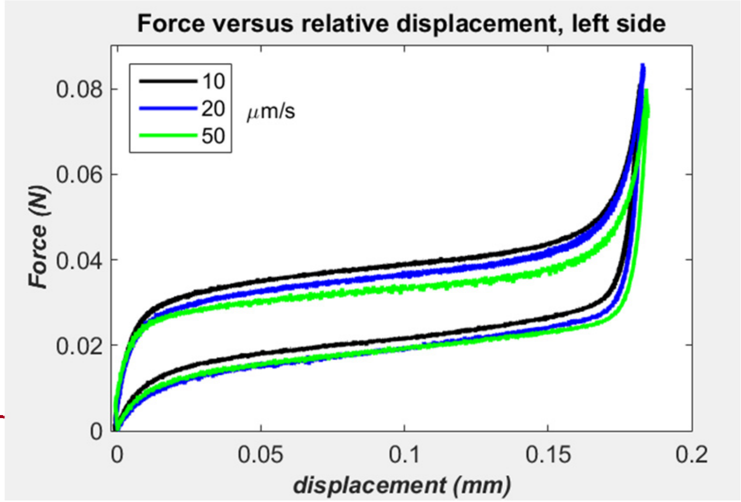
- **Si-wafer displacement d_{wafer} = 200 µm, at speed 10, 20, 50 µm/s**
- **3 cycles measurements per speed → Repeatable**



- **Speed 20 µm/s is mostly used in other measurements**

Which type of material model ?

Shear strain:100% ~ 400%



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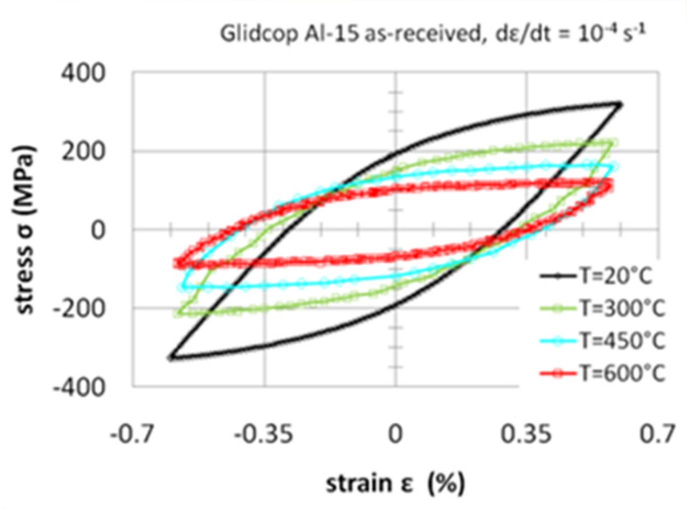
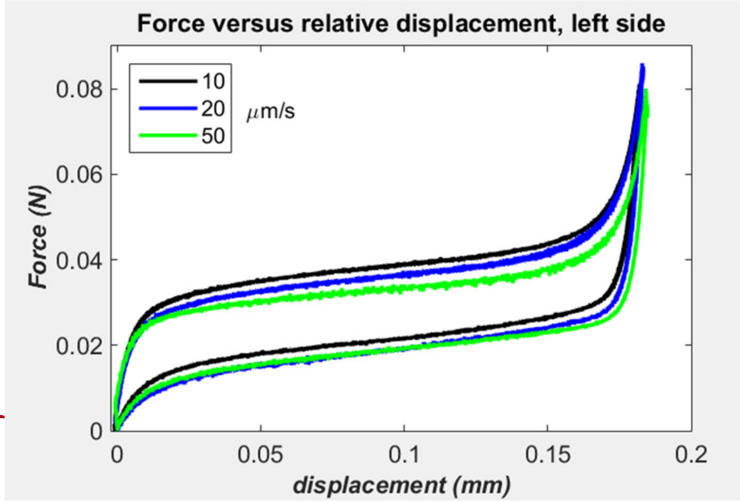


ElastoViscoPlasticity
Glidcop Al-15 at
different temperature

Shear strain:100% ~ 400%



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MEDSI 2016, Sept. 11-19, 2016, L. ZHANG

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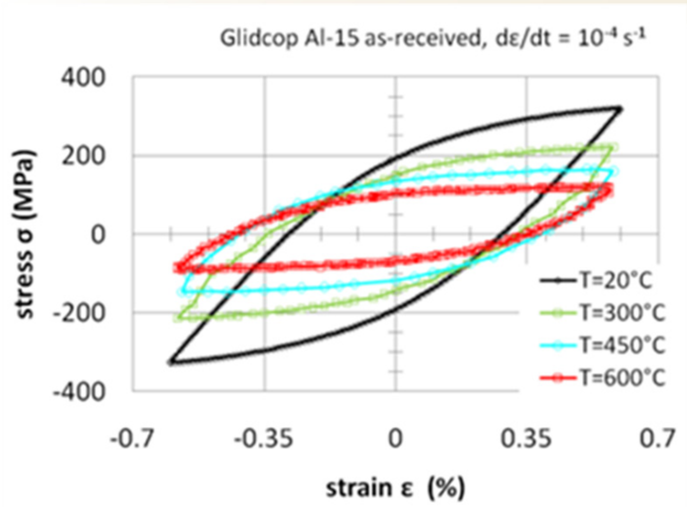

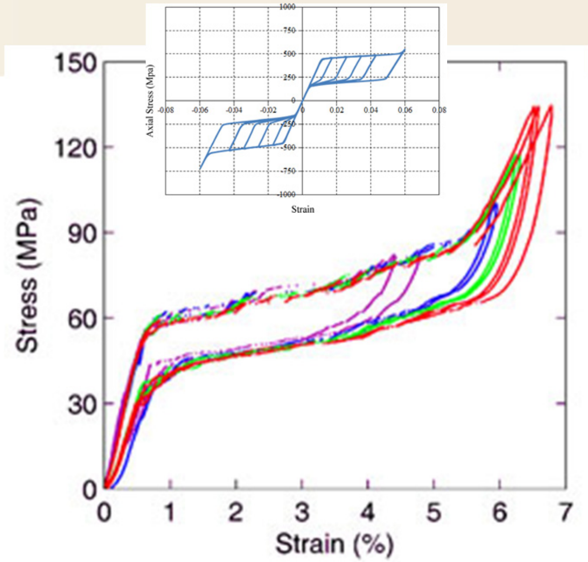

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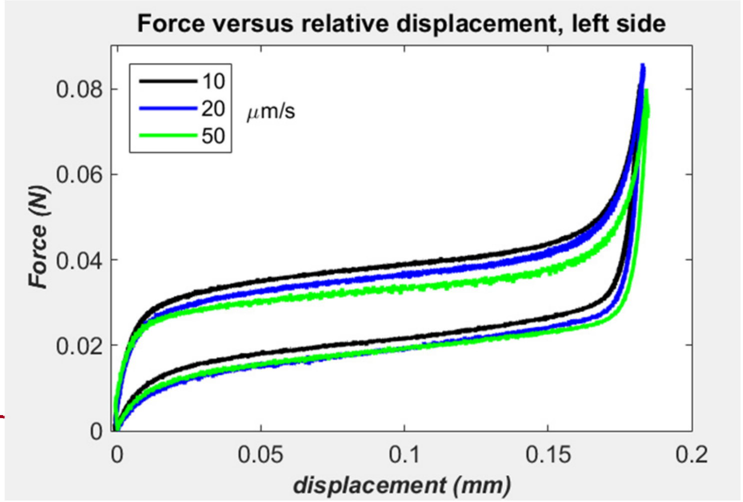
SuperElasticity
NiTi shape-memory alloys (SMAs)



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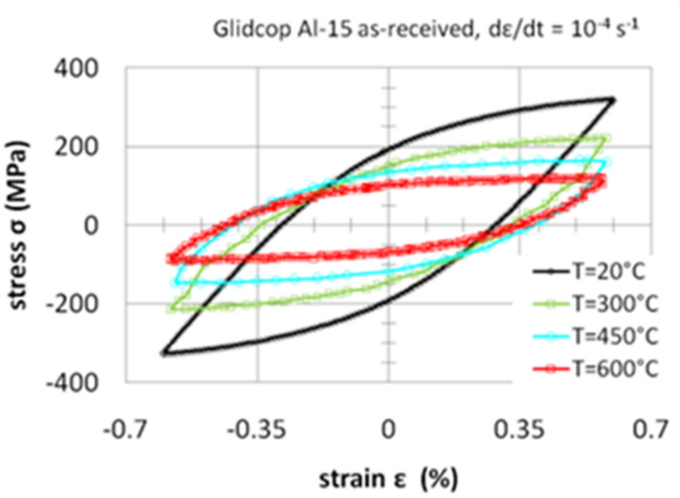

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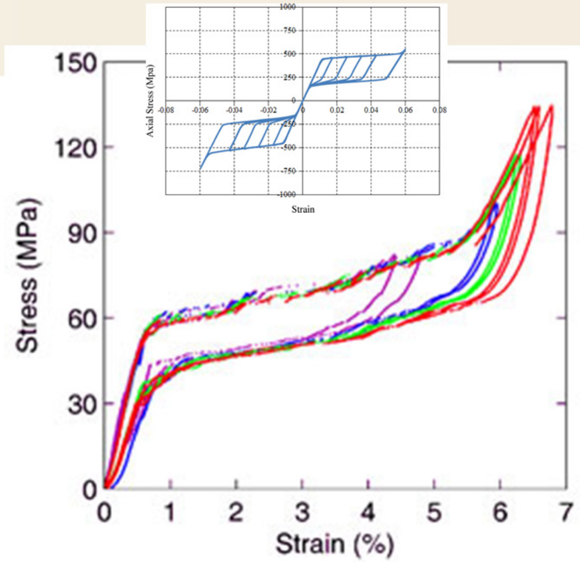

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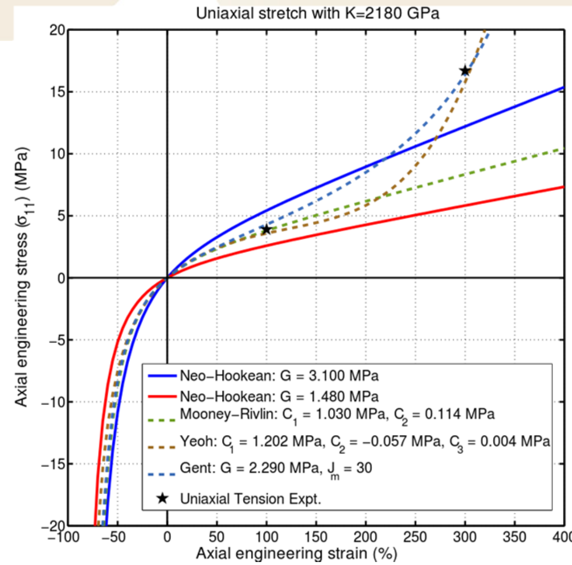
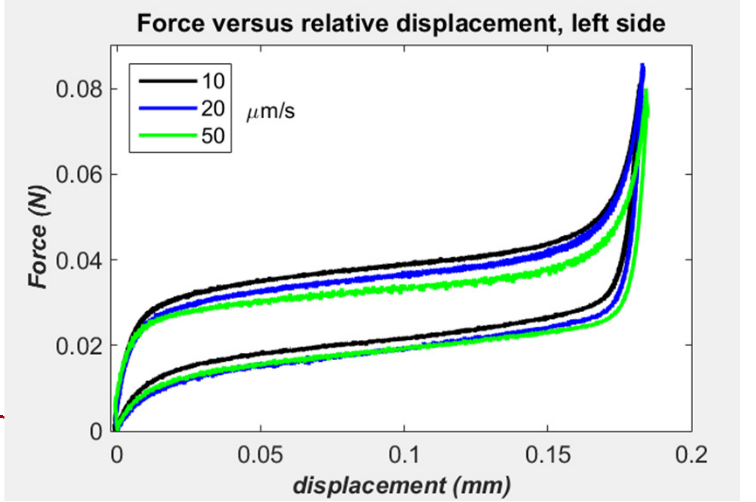


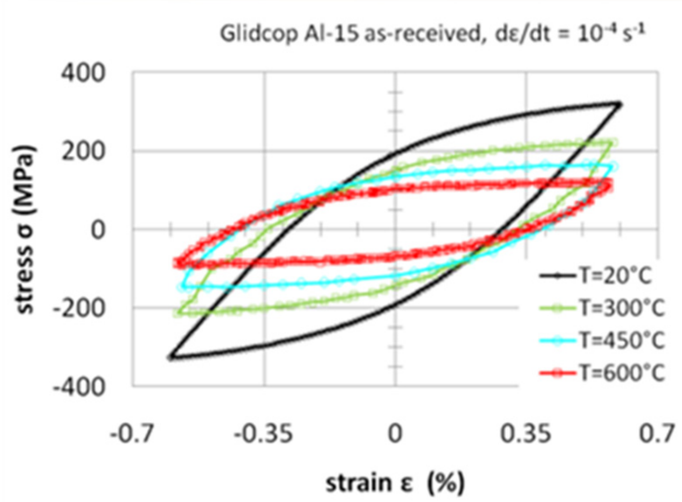
HyperElasticity
rubber

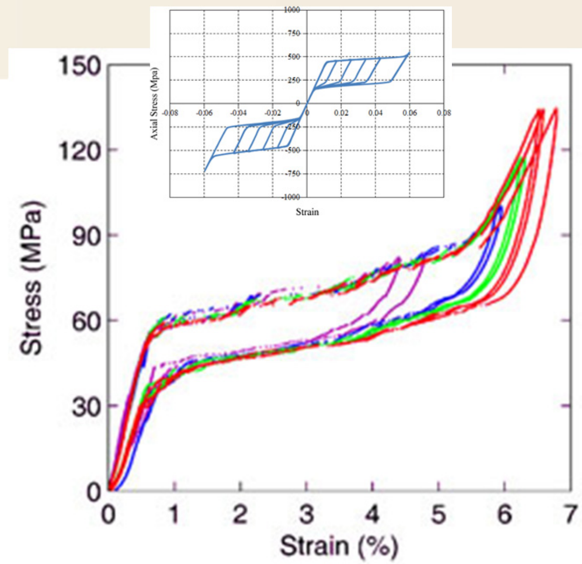
Shear strain:100% ~ 400%

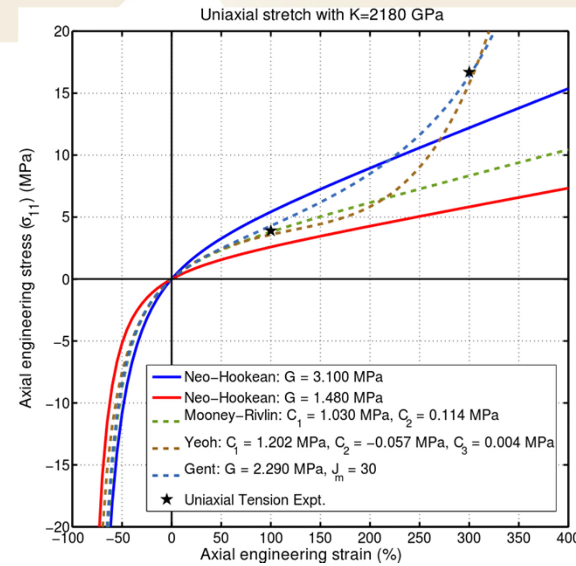


Which type of material model ?

SLAC







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Glidcop Al-15 at
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SuperElasticity
NiTi shape-memory
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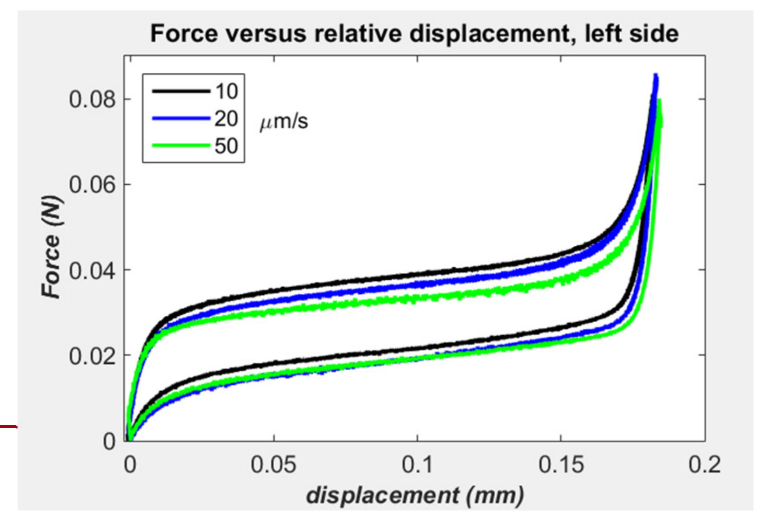
HyperElasticity
rubber

Shear strain:100% ~ 400%
→ Full range FEA impossible (non convergent) with ANSYS



Forces Analysis

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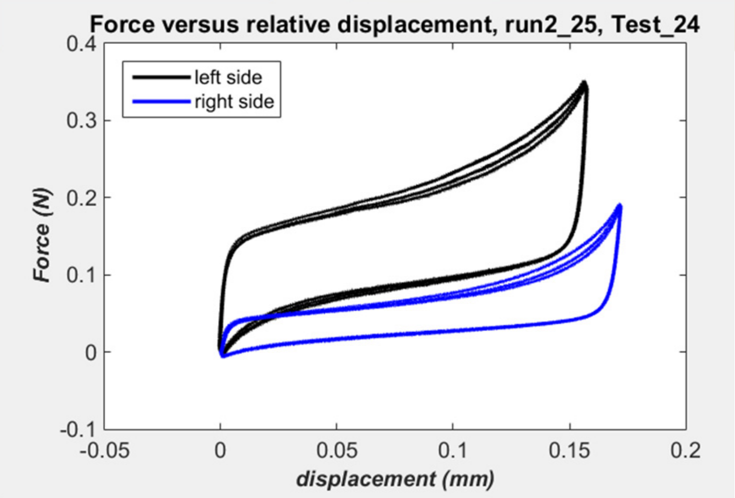
- **Mechanical constraint effects**
  - eGaIn interface induced
    - Force F_{GaIn} ~ 0.35 N/pad
    - $\mathbf{M_{GaIn}}$ ~ F_{GaIn} (2*0.35+2*0.45) = **0.56 Nm**
  - Bending moments (30-mm thick mirror)
    - $\mathbf{M_{bending}}$ ~ 0.3*90 = **27 Nm**
  - **M_{GaIn} / $M_{bending}$ ~ 2%   (very significant)**



g_{GaIn}= 50 μm

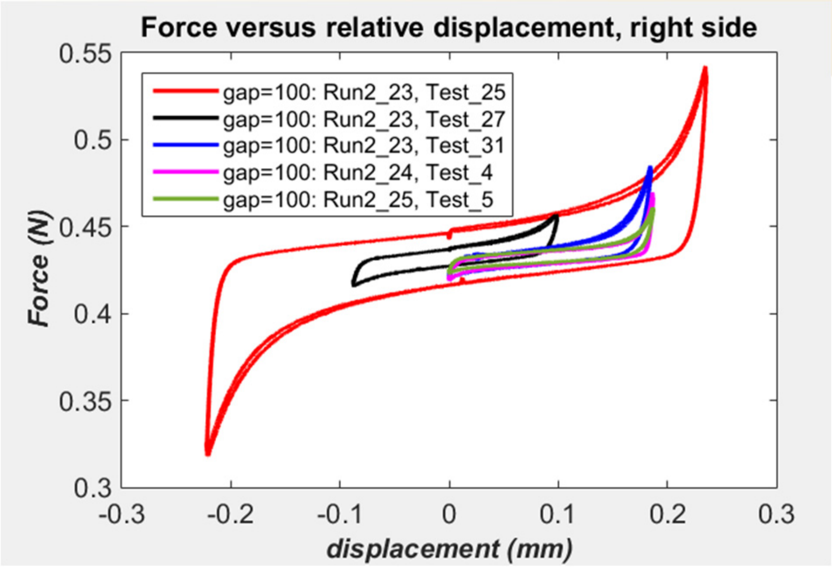
- **eGaIn Viscosity related force**

$$F_{viscosity} = A\mu \frac{\partial V}{\partial y}$$

  - $F_{viscosity}$ ~ 0.4 μN/pad
  - $F_{viscosity}$ / $F_{measured}$ ~ 10^{-6} **(negligible)**

- The mechanical constraint effects of eGaIn interface is **not negligible (at this stage), but it's not viscosity related force** (and therefore will not be treated as fluid)

GaIn Test results – Data fitting, modulus



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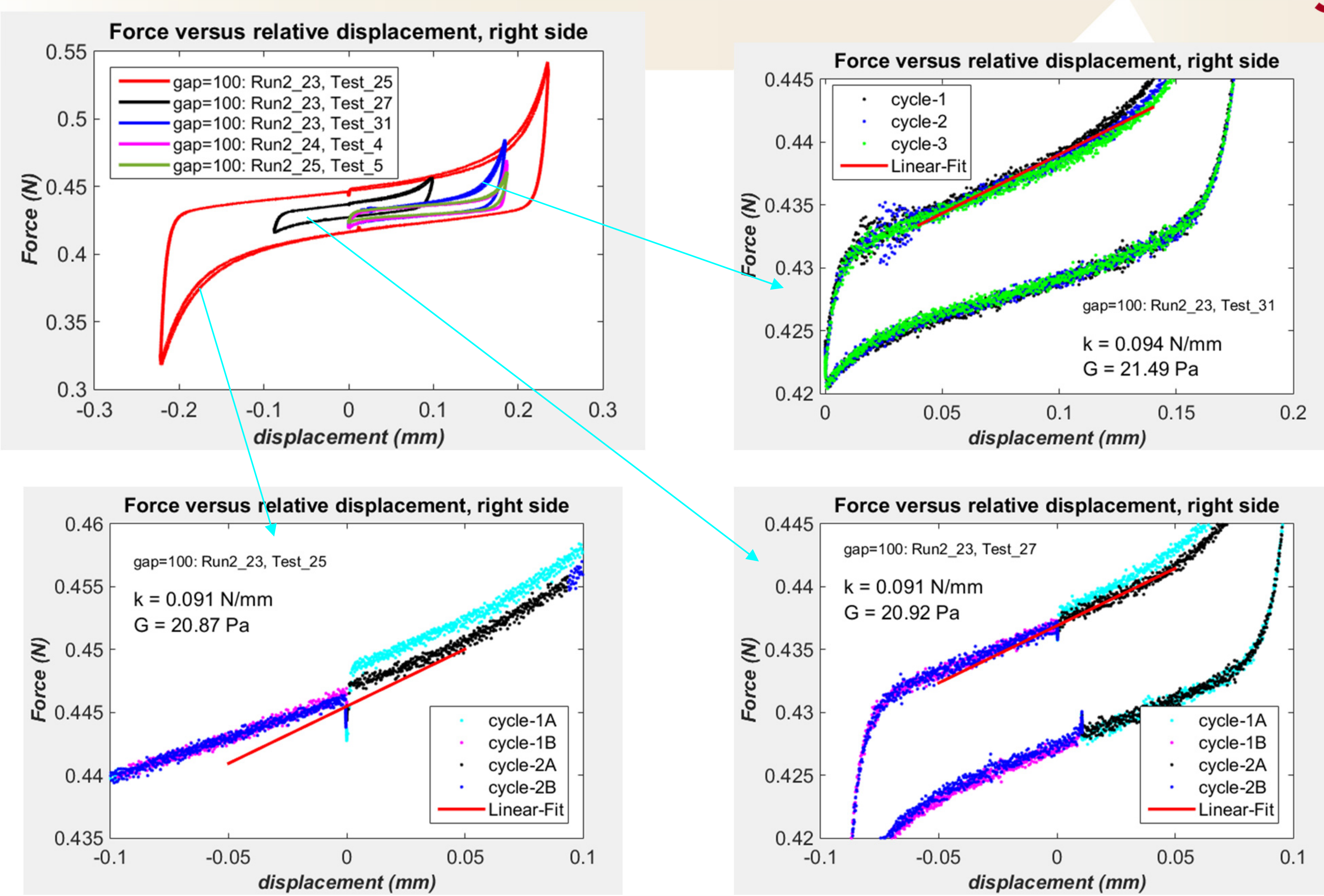

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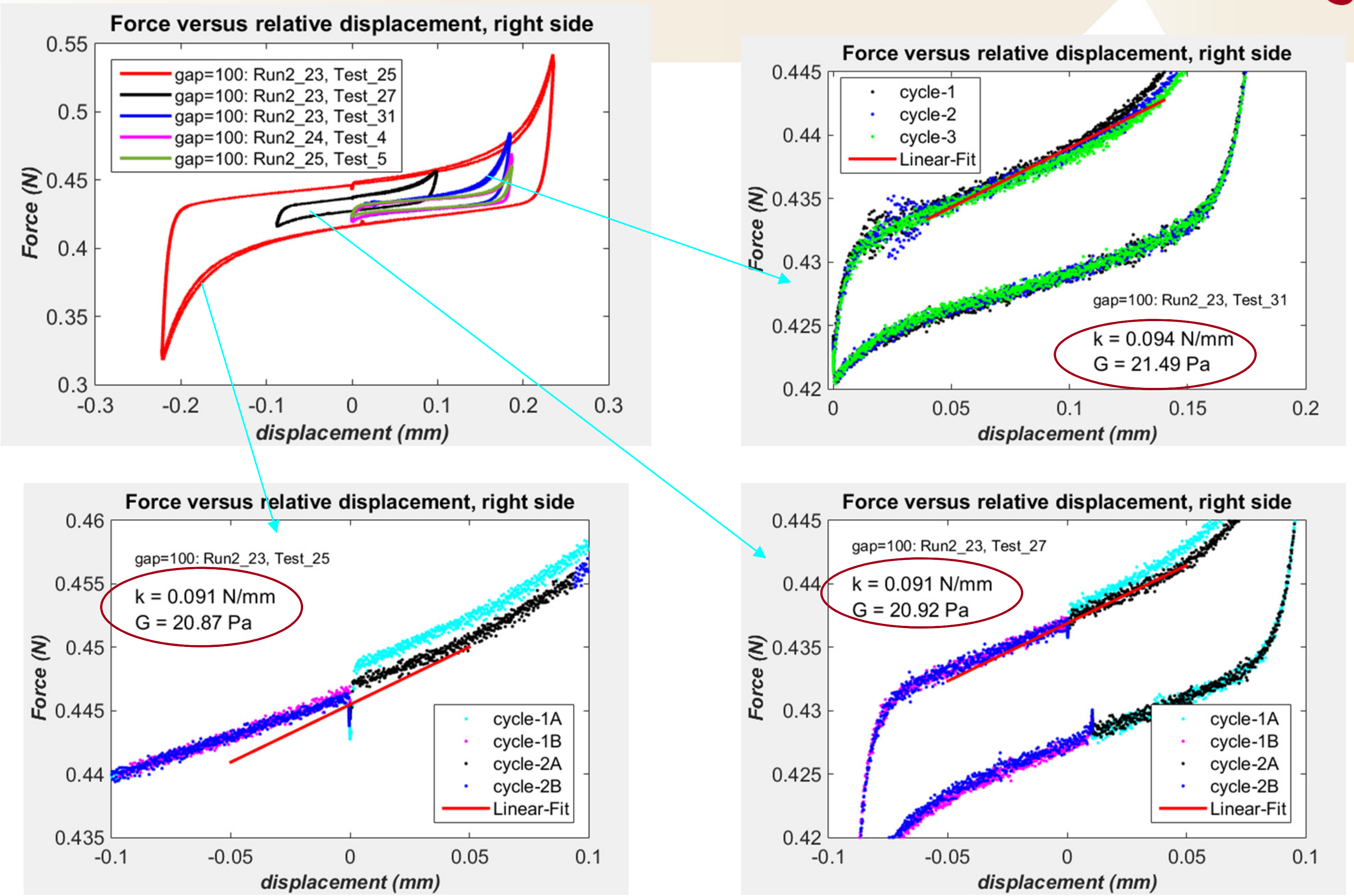

GaIn test results – gap dependant; Modulus G_1 and G_2

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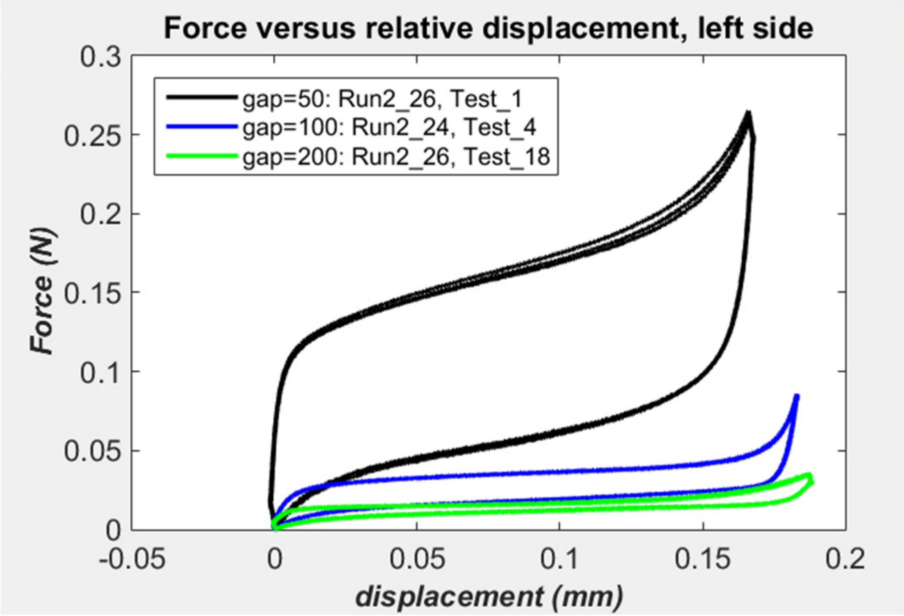

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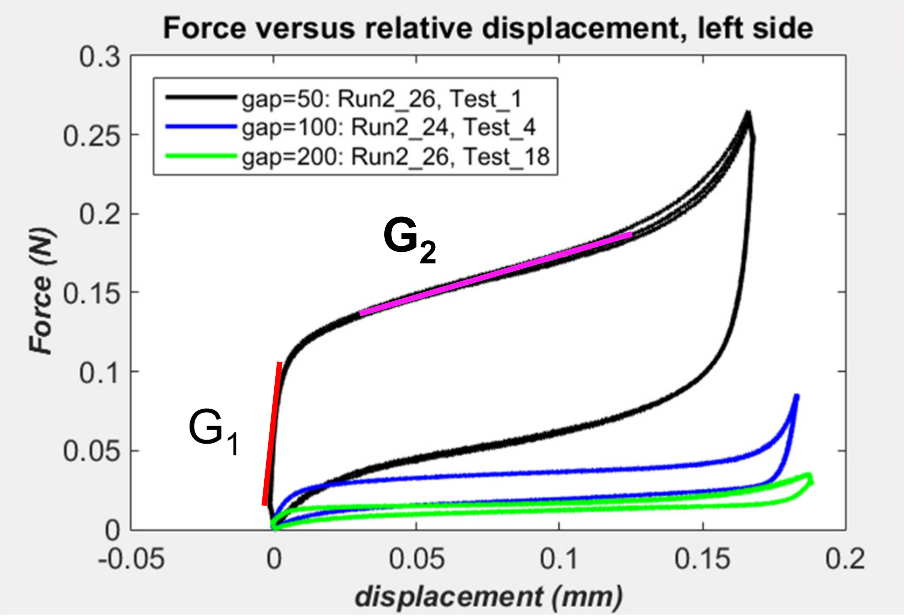

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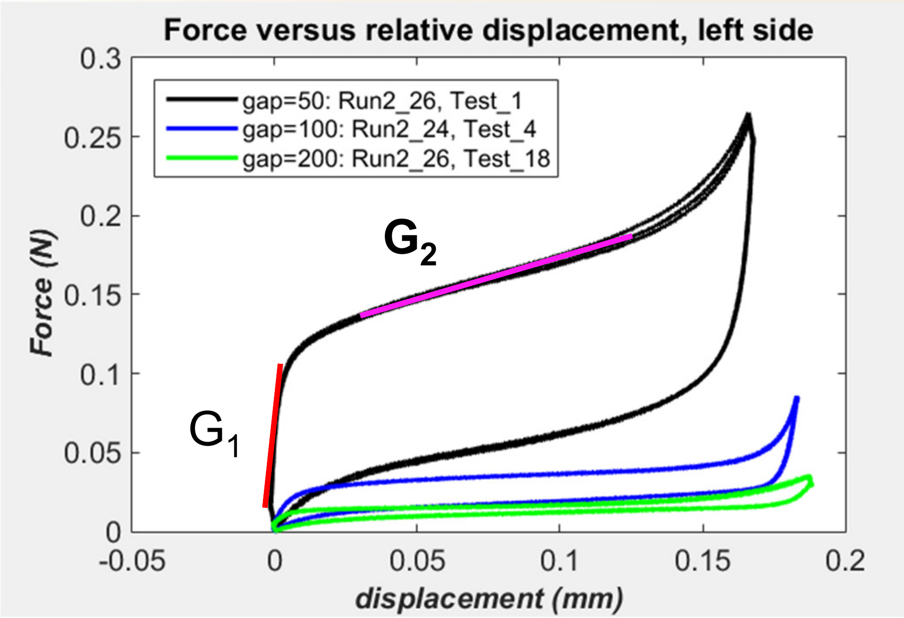

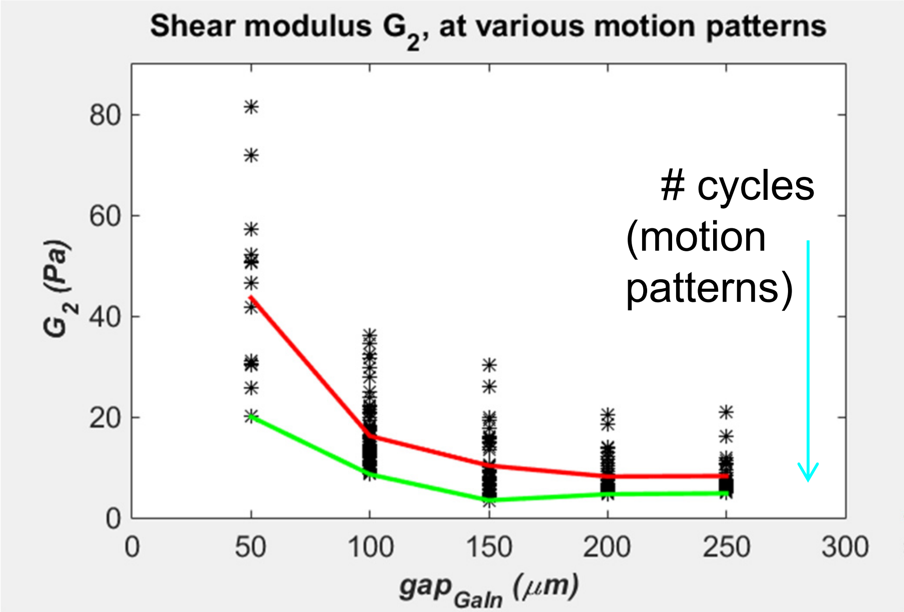

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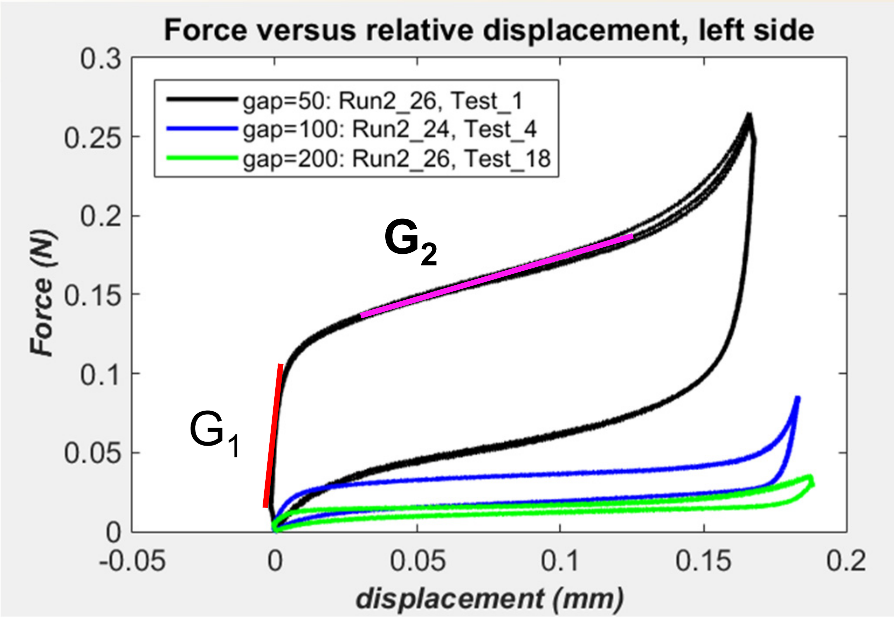
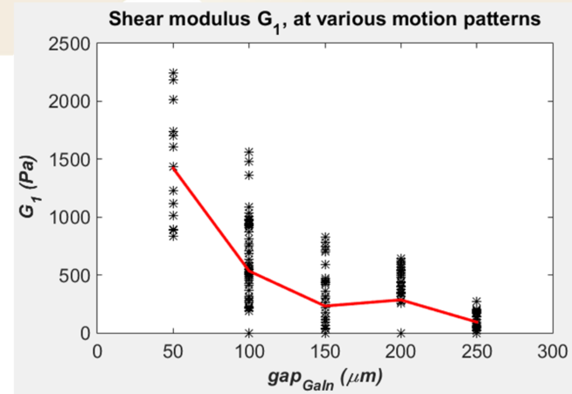
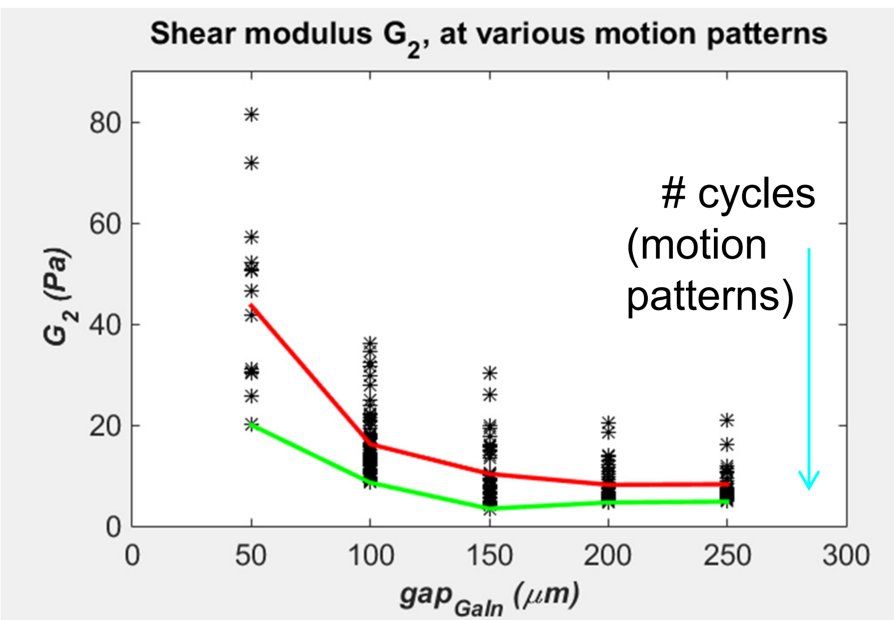


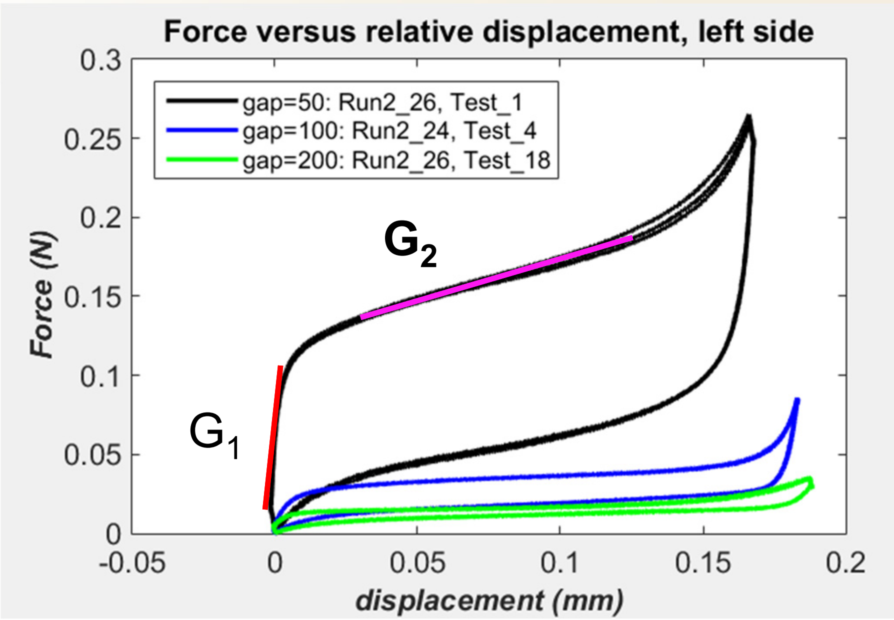


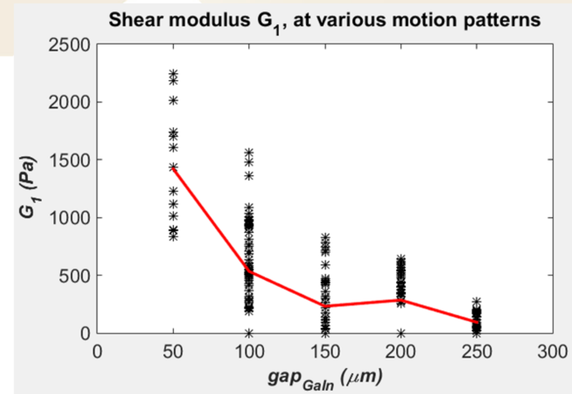


Shear modulus G of GaIn interfac

gap	G_{2_av}	G_{2_min}	G_1
μm	*Pa*	*Pa*	*Pa*
50	43.7	20.0	1421
100	16.2	8.6	534
150	10.3	**3.4**	232
200	**8.2**	**4.7**	285
250	**8.3**	**4.8**	94

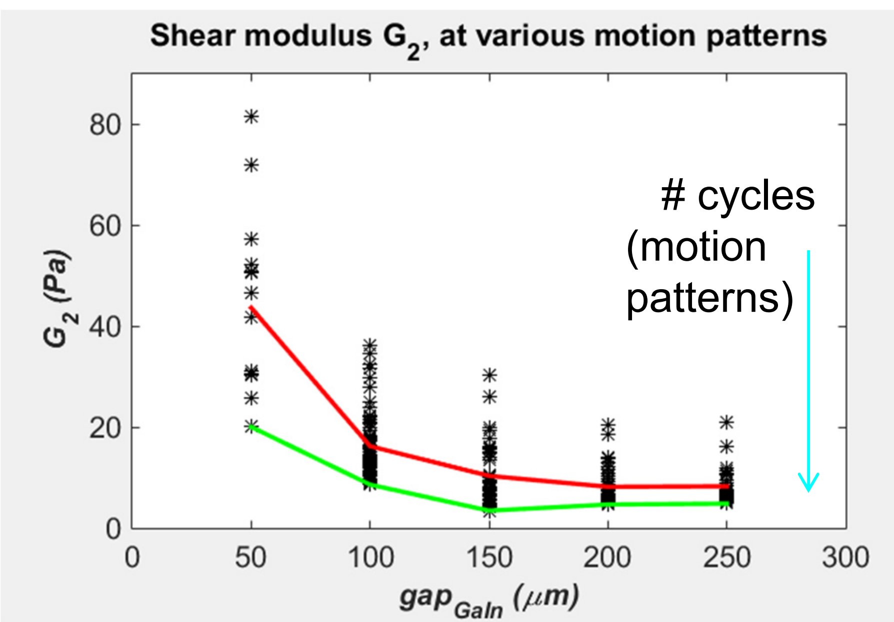
GaIn test results – gap dependant; Modulus G_1 and G_2





Shear modulus G of GaIn interfac

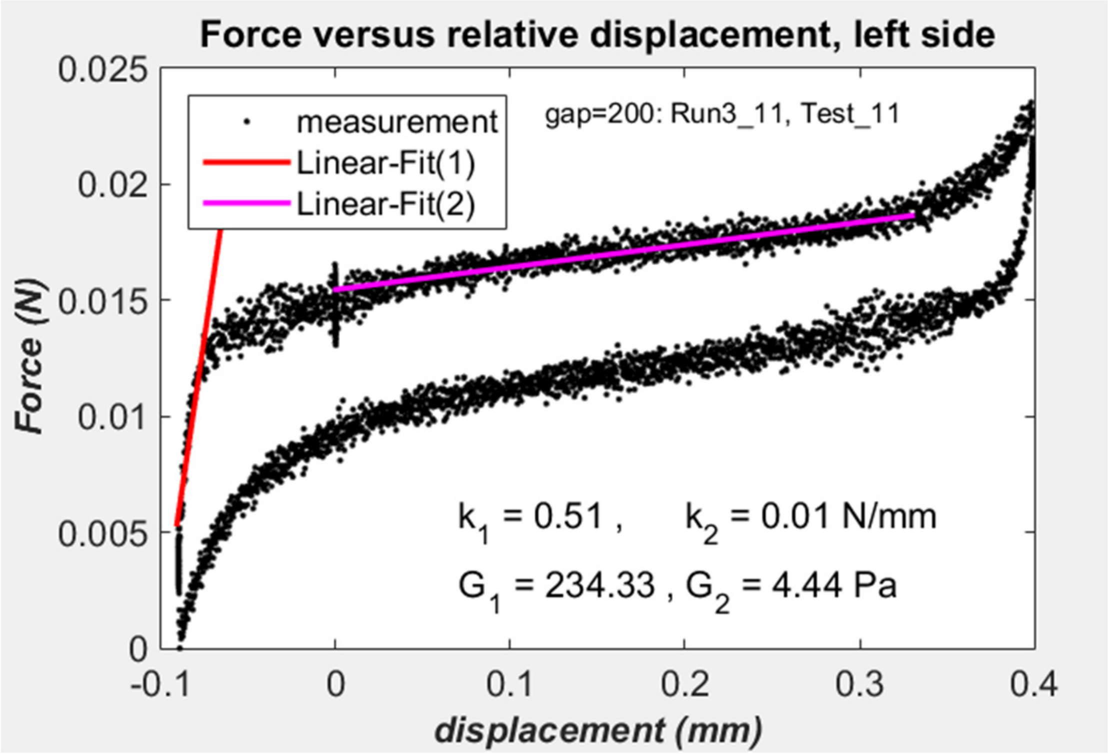
gap	G_{2_av}	G_{2_min}	G_1
μm	*Pa*	*Pa*	*Pa*
50	43.7	20.0	1421
100	16.2	8.6	534
150	10.3	**3.4**	232
200	**8.2**	**4.7**	285
250	**8.3**	**4.8**	94



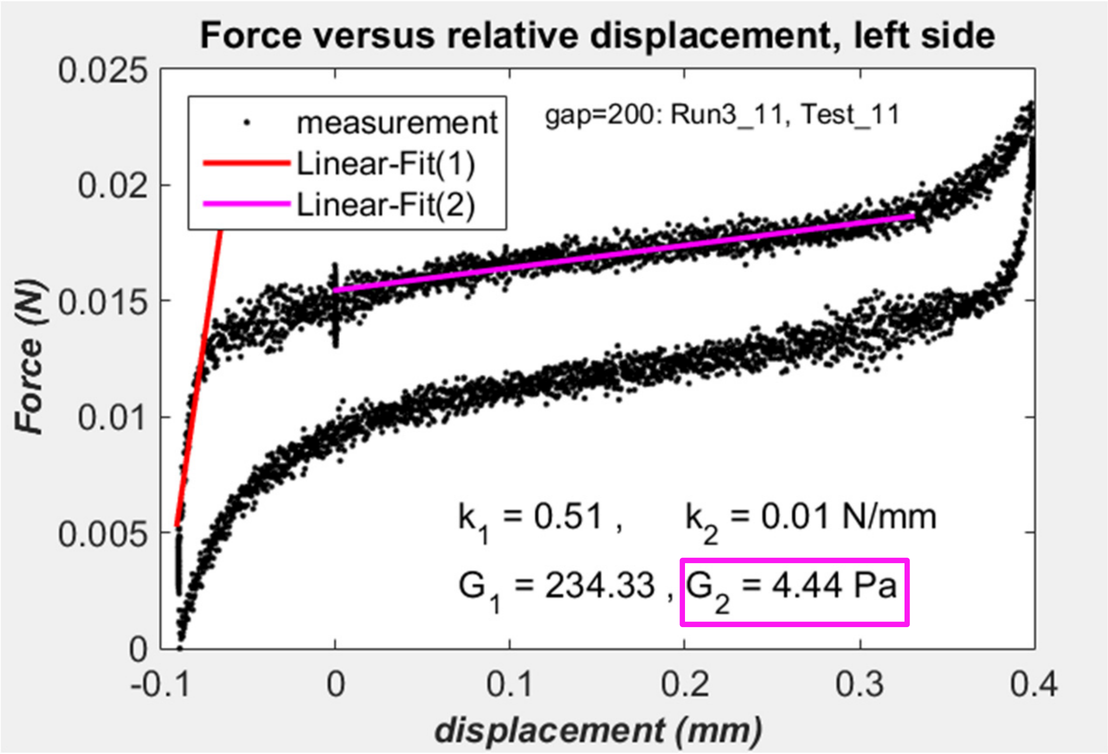
G_2 = 9 Pa

ce

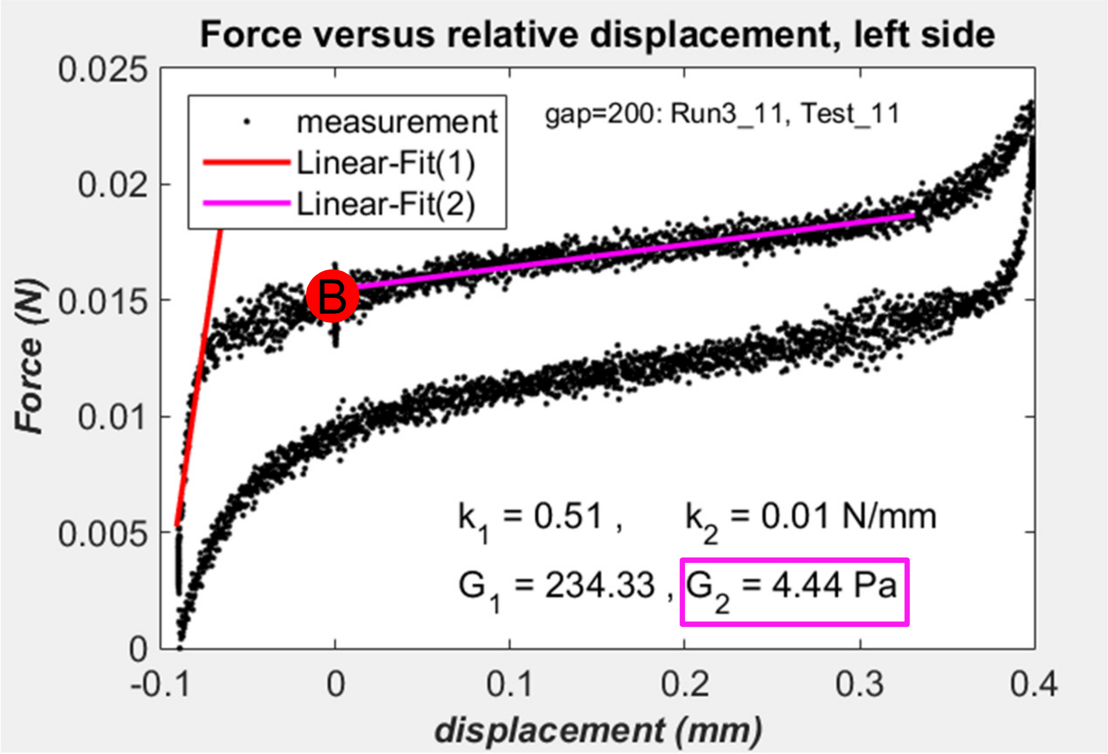
Bending Operation Optimization with GaIn Interface



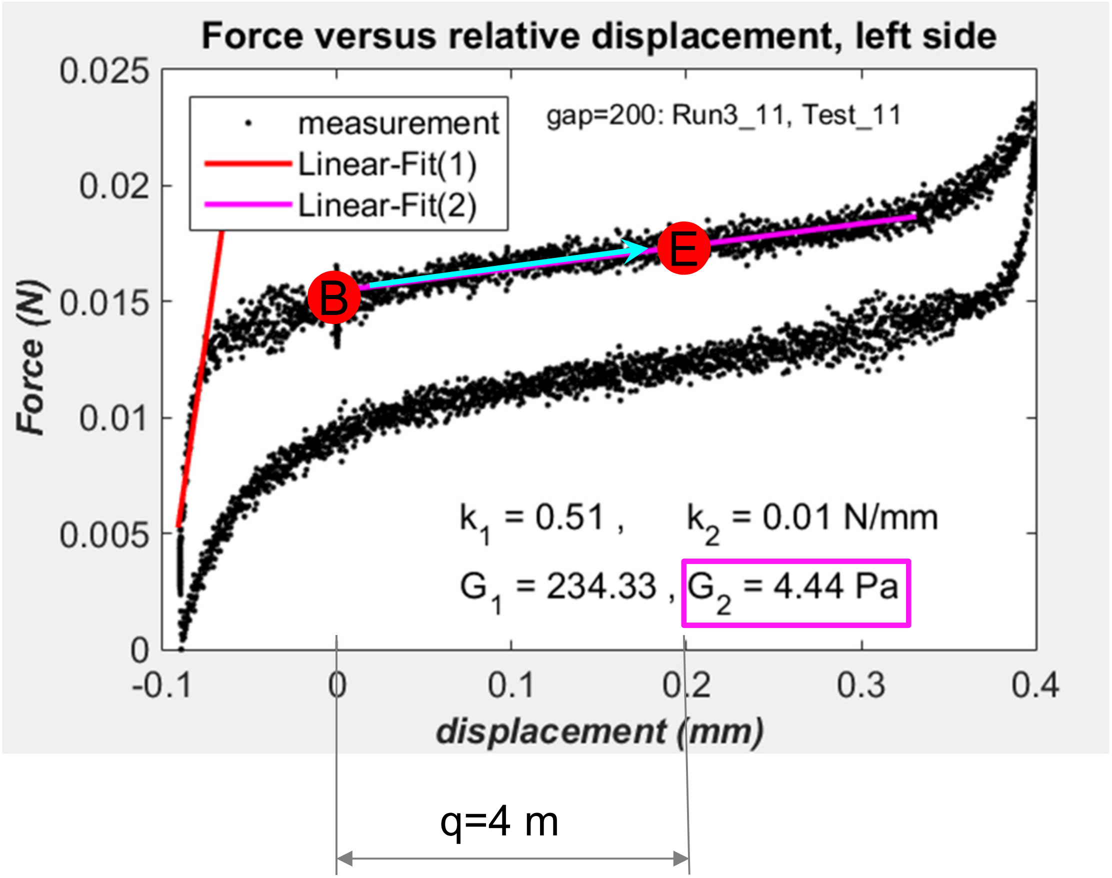
Bending Operation Optimization with GaIn Interface



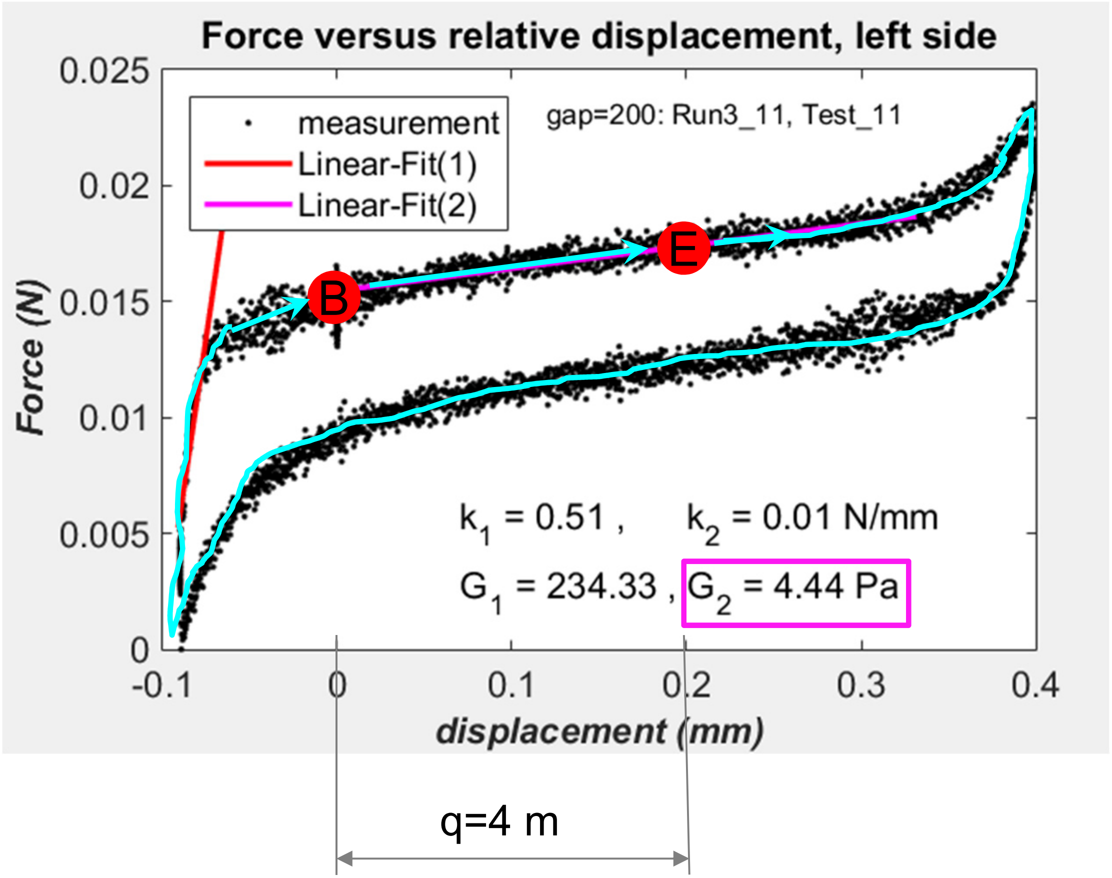
Bending Operation Optimization with GaIn Interface



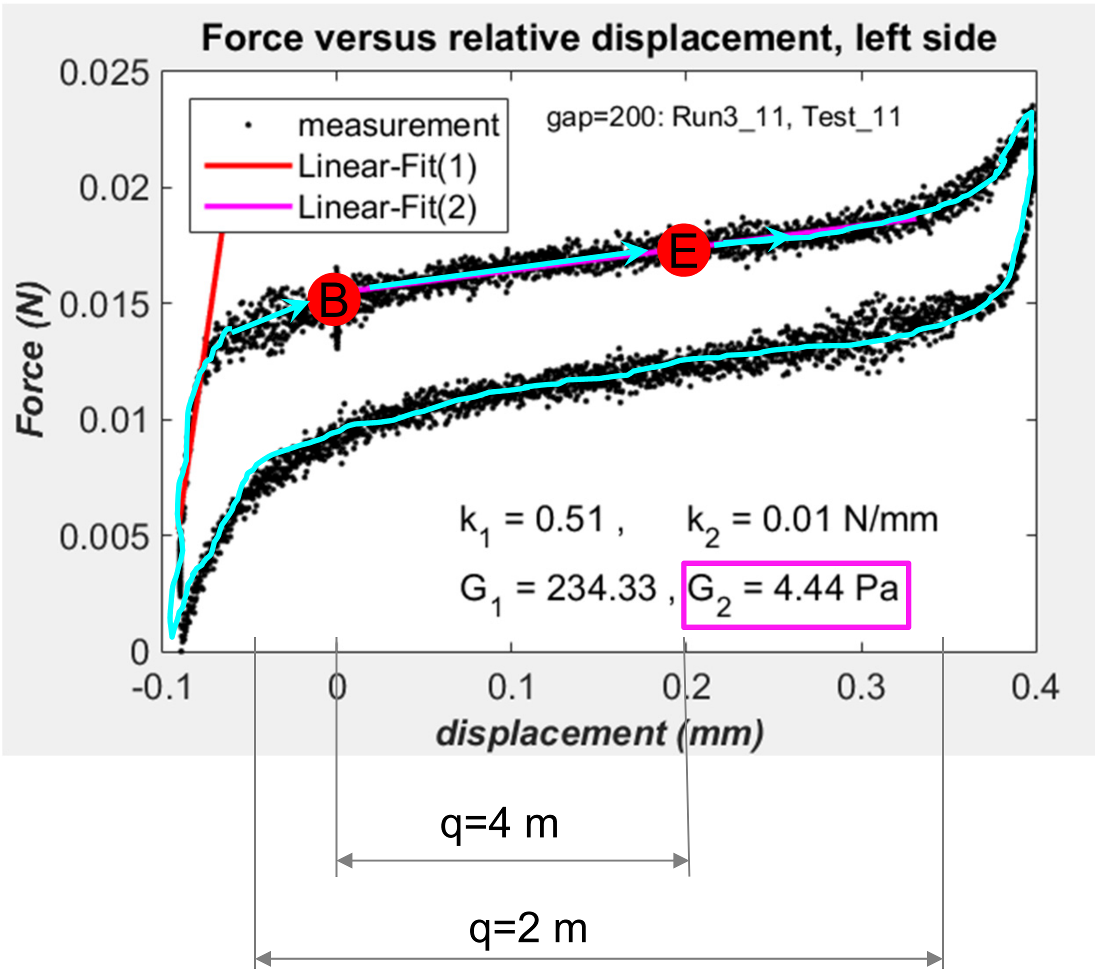
Bending Operation Optimization with GaIn Interface



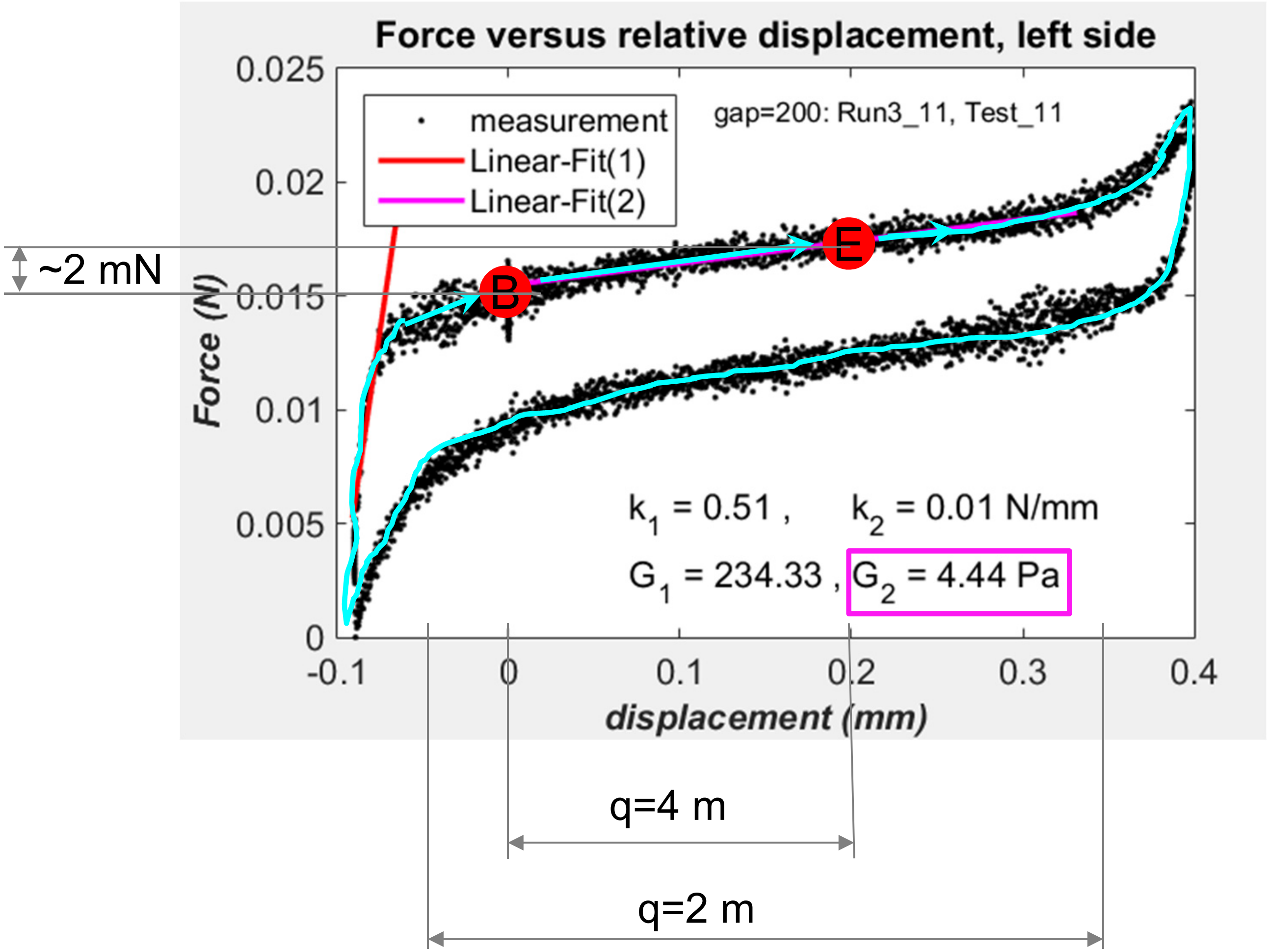
Bending Operation Optimization with GaIn Interface



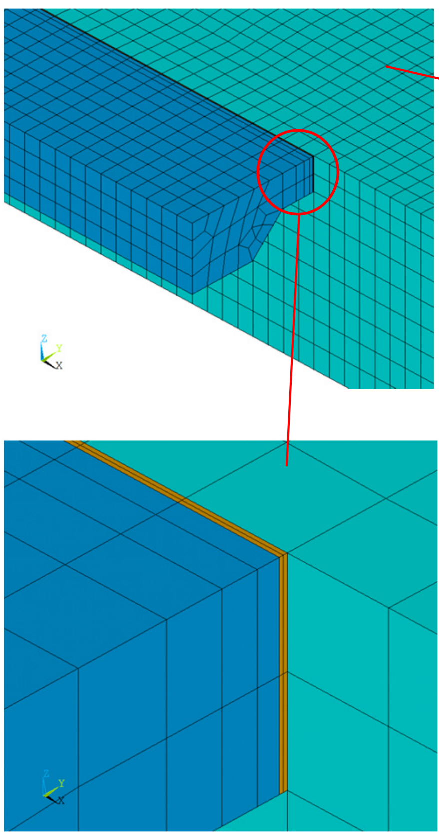
Bending Operation Optimization with GaIn Interface

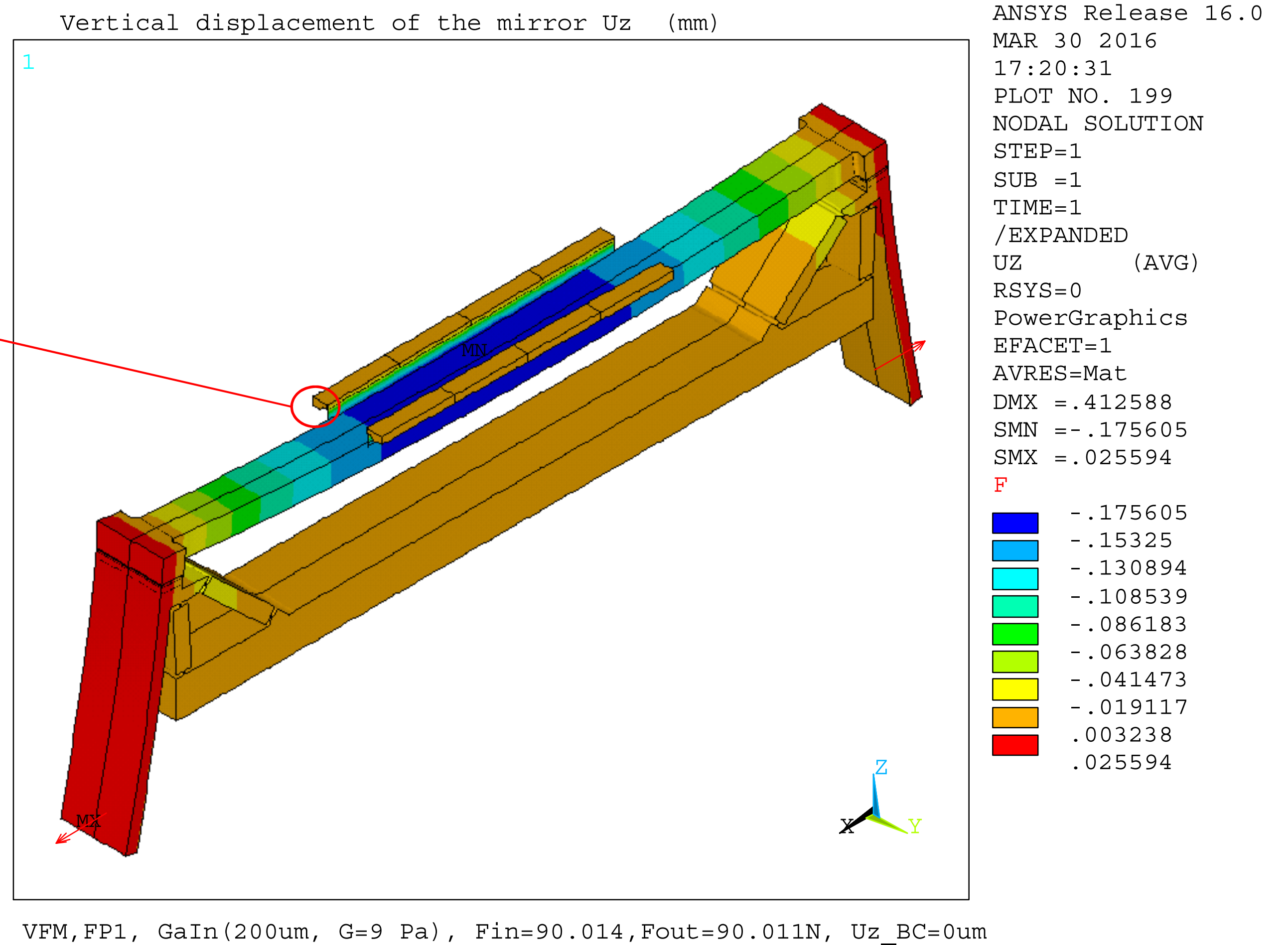


Bending Operation Optimization with GaIn Interface



FEA results with cooling blocks and GaIn interface

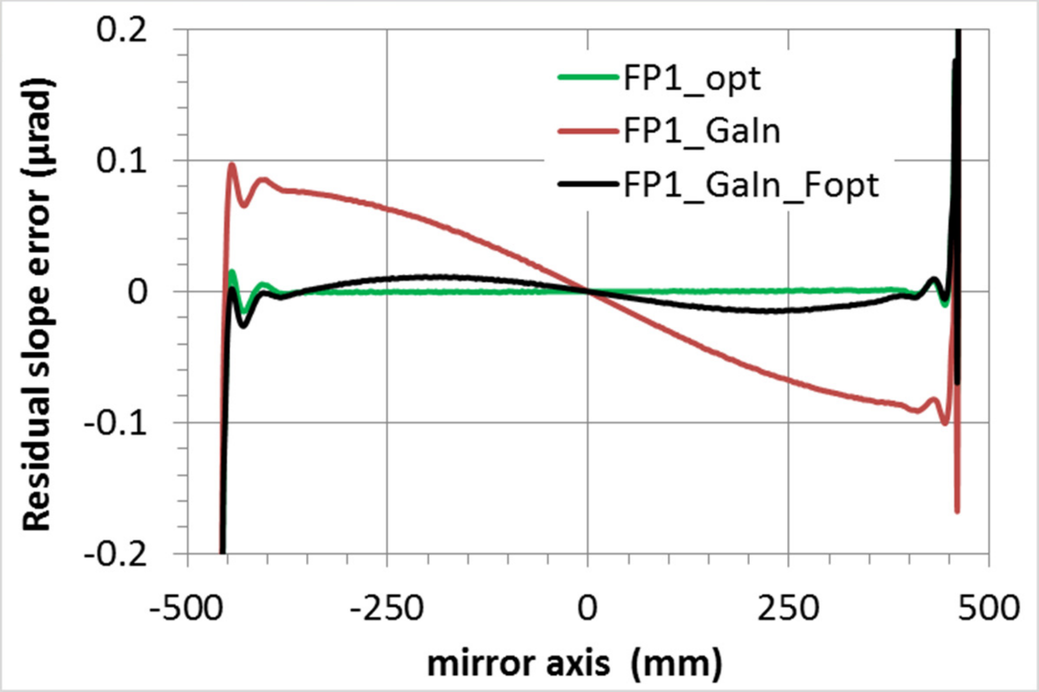




G_2=9 Pa

FEA results with cooling blocks and GaIn interface

SLAC

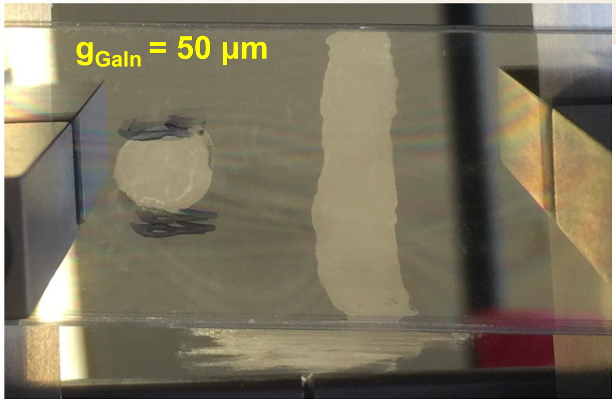


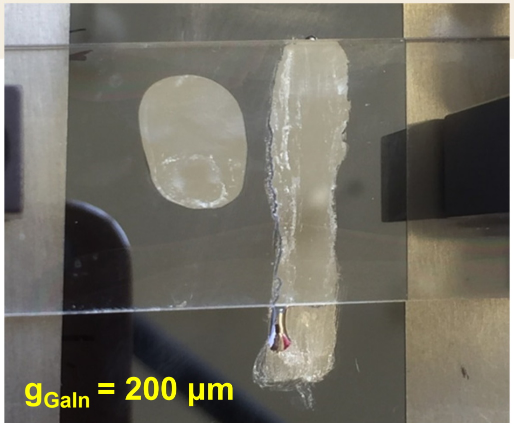
Residual Slope Error (RSE) :

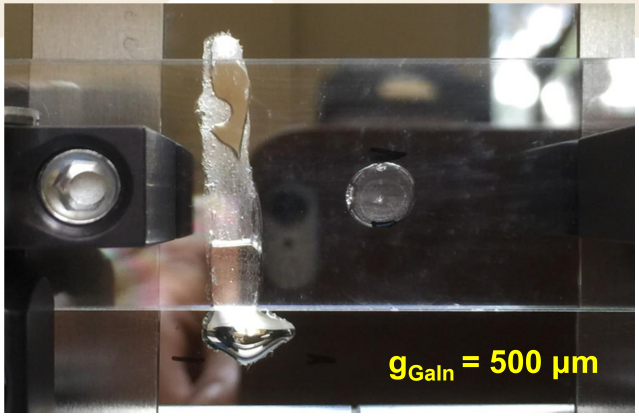
$\Delta slope = slope - slope_{ellipse}$

Uz_{BC}	F_{GaIn}	g_{GaIn}	G_2	q	F_{inp}	F_{outp}	RMS_{dUz}	RMS_{dslp}
μm	*mN*	*μm*	*Pa*	*m*	*N*	*N*	*nm*	*nrad*
		-1	-1	4.7	90	90	**0.4**	**1**
0	-13.7	200	9	4.7	90	90	**10.0**	**57**
0	-13.7	200	9	4.7	90.014	90.011	**1.8**	**9**

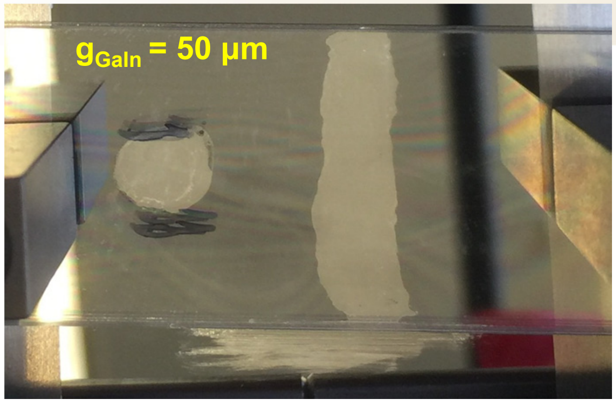
GaIn gaps

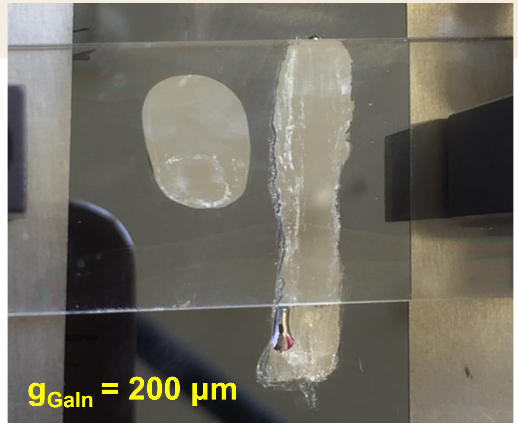


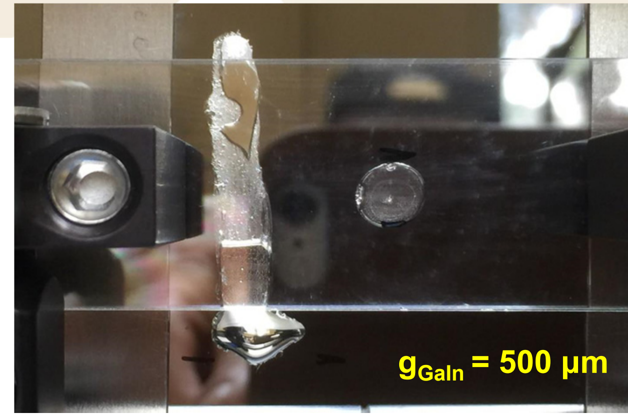


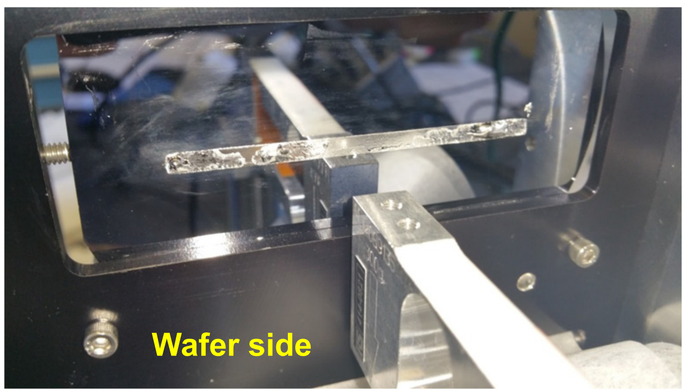


GaIn gaps

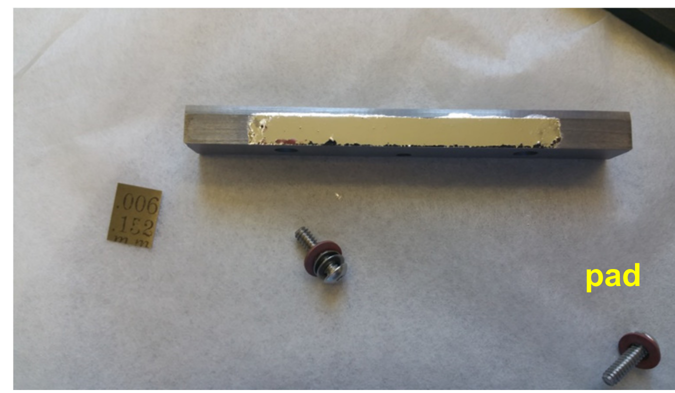


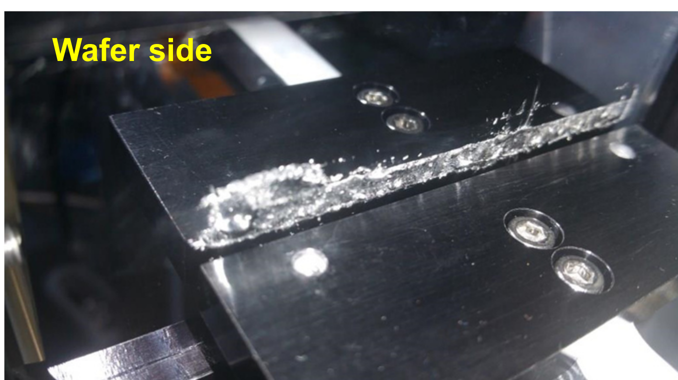






Before assembling for test at g_{GaIn}= 152 µm

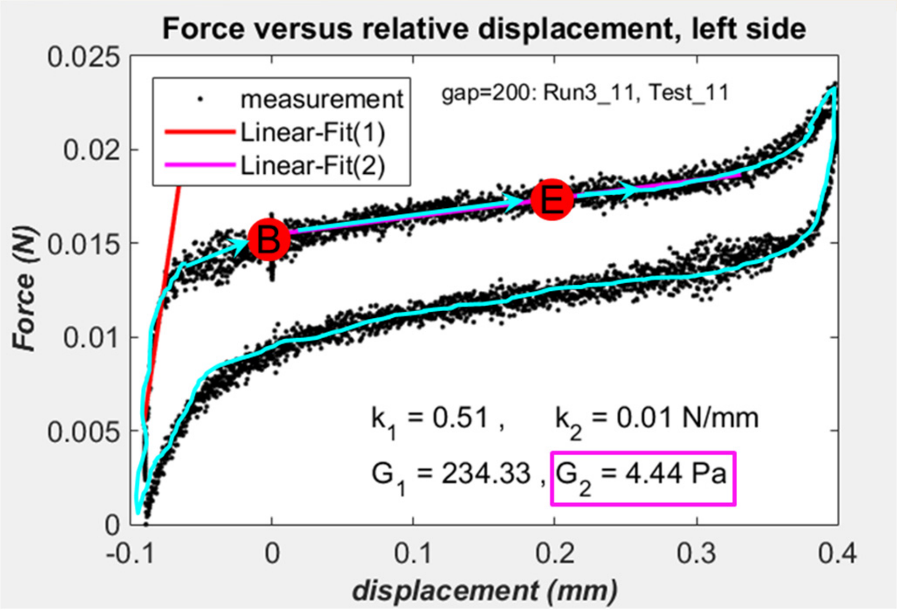


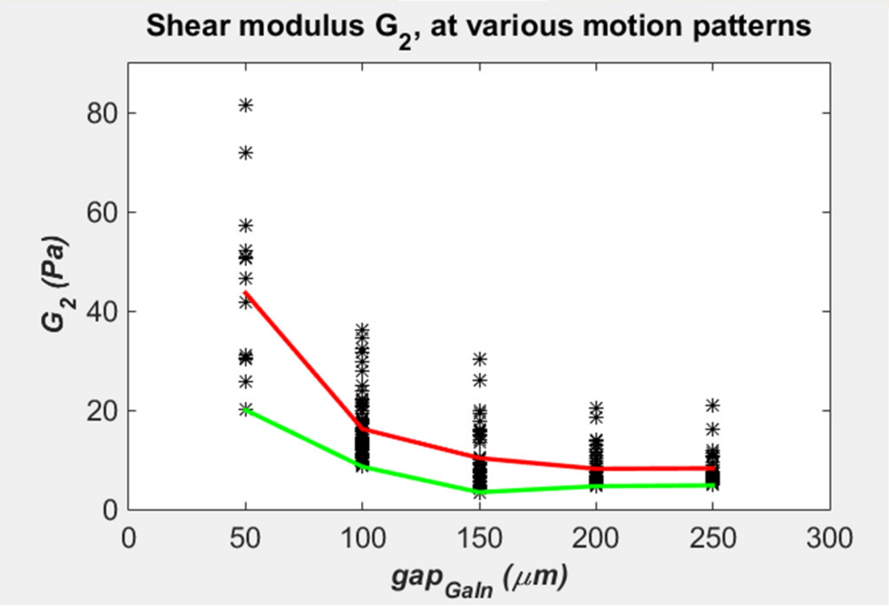


After test at g_{GaIn}= 152 µm

Summary of GaIn test results

SLAC





- **The mechanical constraint effects of GaIn contact interface can be minimized to be negligible for LCLS-II SXR KB mirrors by**
  - Setting the g_{GaIn}=150 μm. Shear modulus G_2= 9 Pa easily achievable
  - Operating between point B and E, and following the force ~ displacement curve

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