Radiation Pressure to Facilitate Measurements of High Laser Powers

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Why do we measure optical radiation?

- High-accuracy laser power measurement essential in science/metrology community
- Calibration/comparison typically done using direct substitution
- Cryogenic radiometer provides 0.02% or better
  - µW – mW regime
- How do we scale to higher powers?

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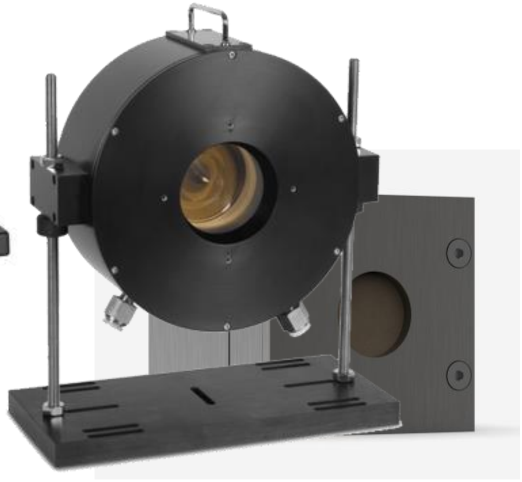

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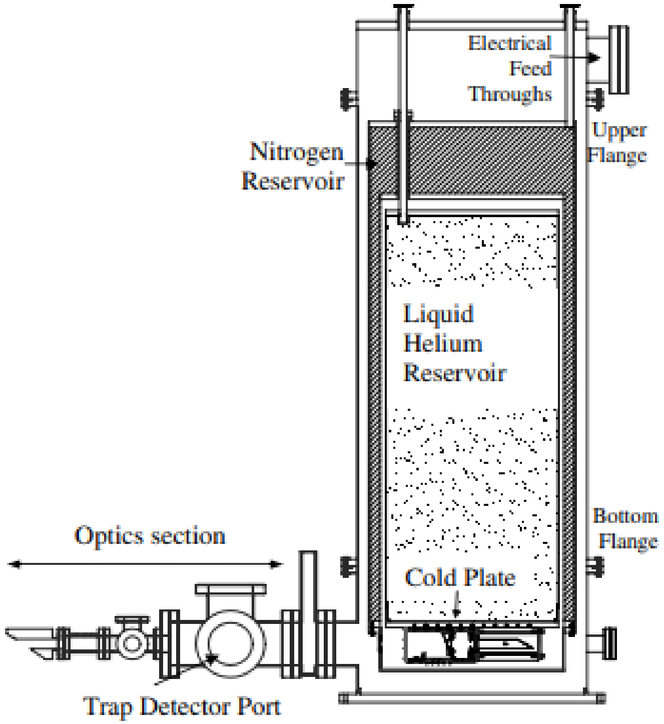
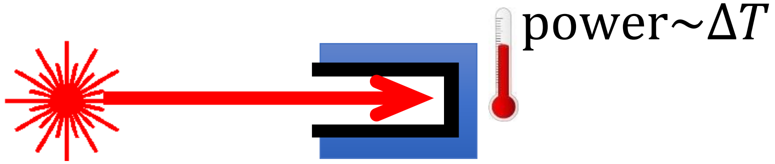
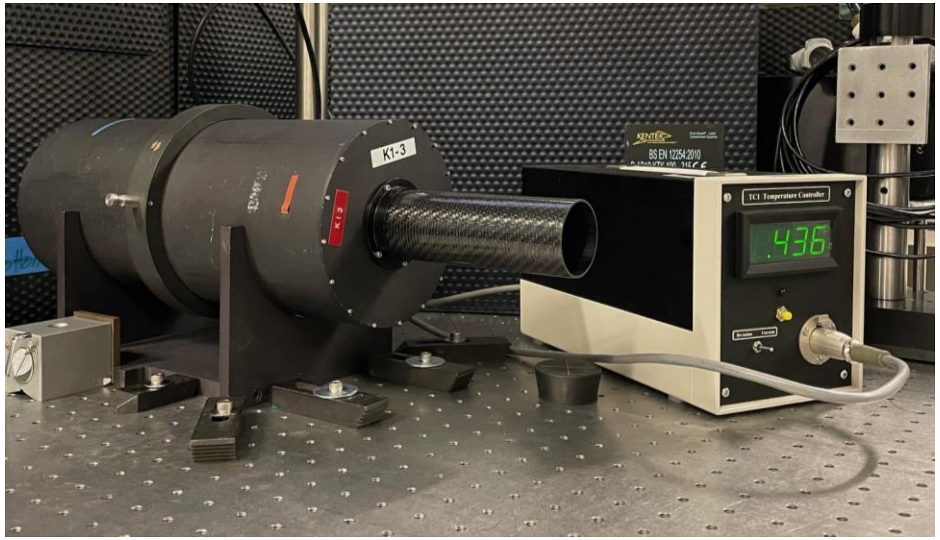


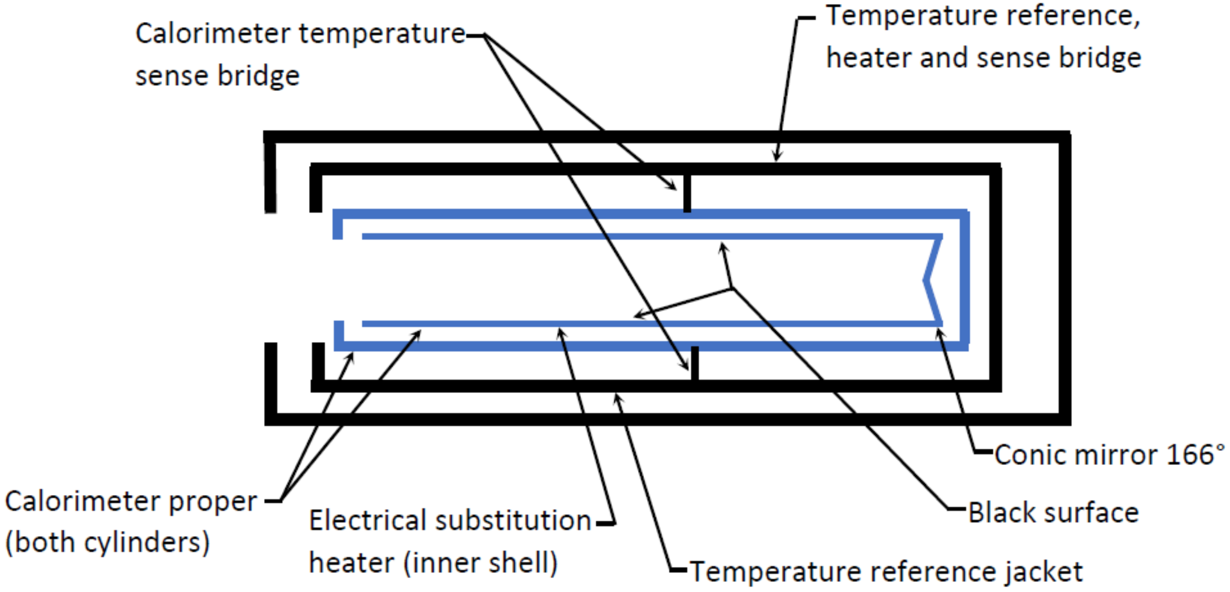
J. Houston and J. Rice, *Metrologia,* **43** S31 (2006)

How do we accurately measure high-power laser output?

Traditional calorimetry:
100 % absorption



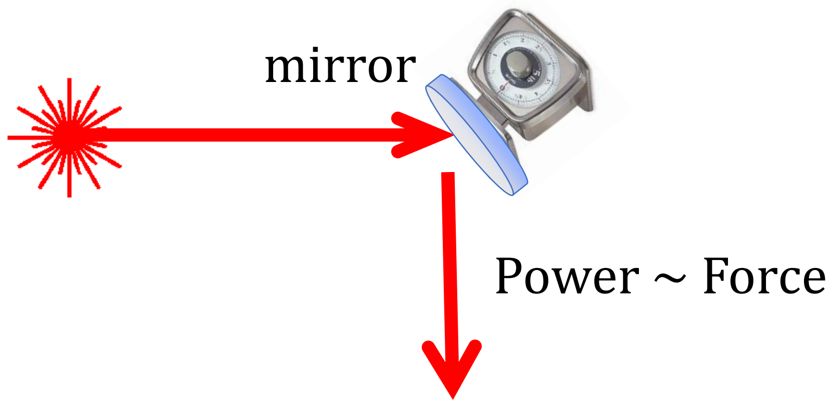




Expanded uncertainty:
1.2% (*k*=2) for 5W - 10 kW

Non-absorptive measurement

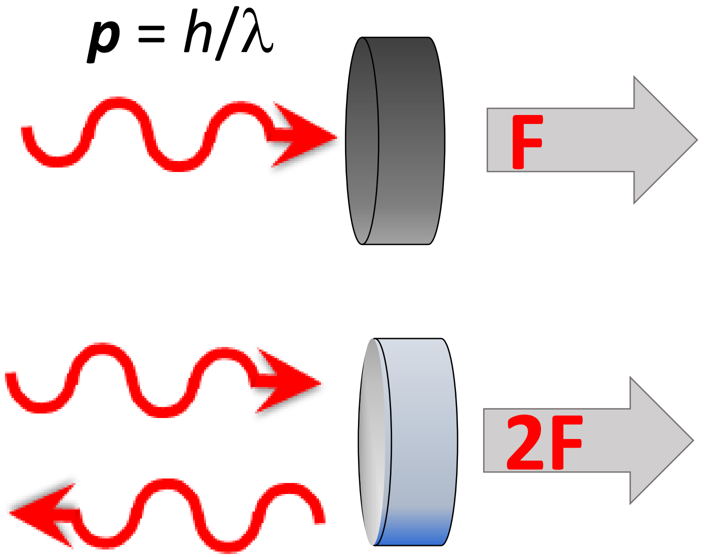
Radiation force:
0 % absorption



$$F = (2P/c) r \cos\theta$$

F = Force (Newtons)
P = optical power (Watts)
c = speed of light (m/s)
$r = R+(1-R)\alpha/2 \rightarrow$ reflectivity
θ = angle of incidence

$$P = F \cdot (c / 2r \cos\theta)$$

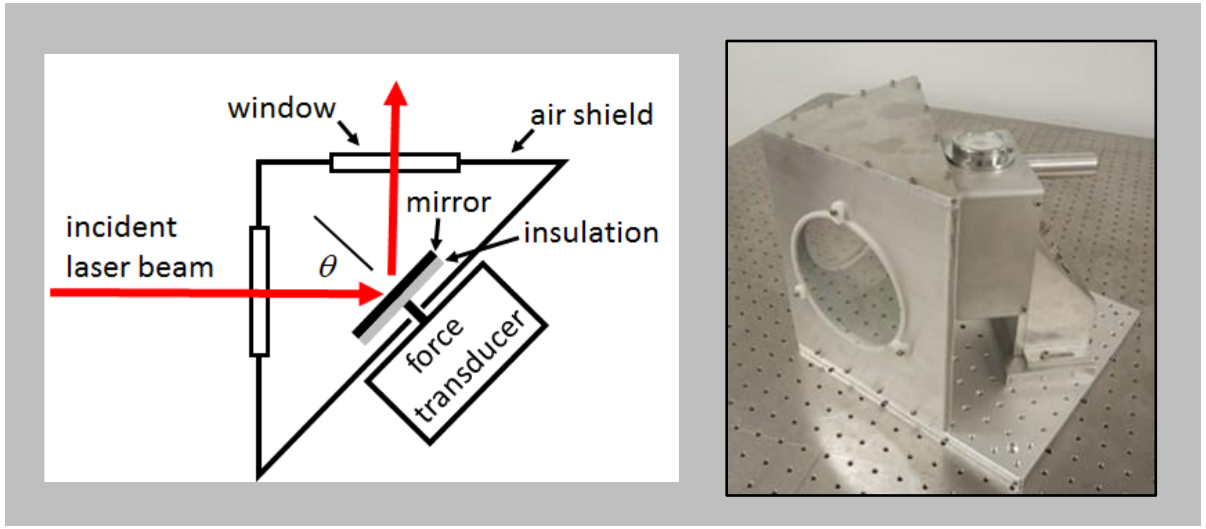


An absorbed photon imparts a force **F**

A reflected photon imparts a force **2F**

Radiation Pressure Power Meter (RPPM)

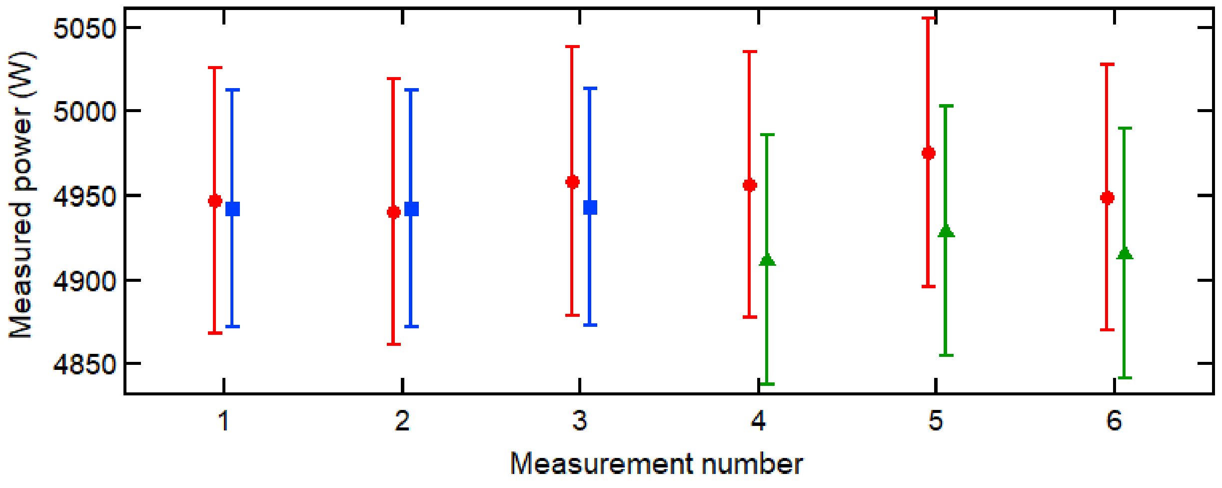
NIST



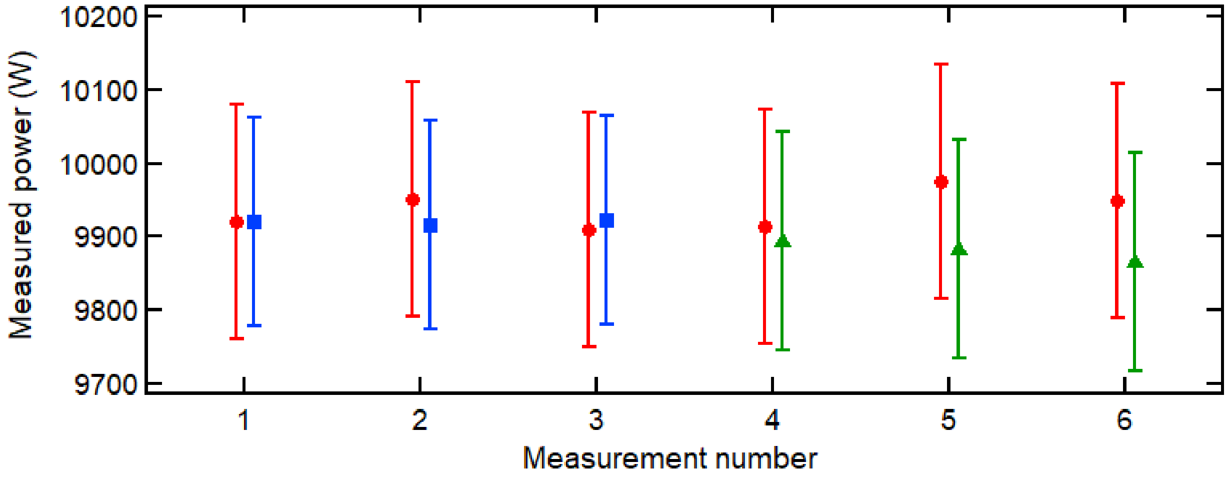
P. Williams, et al., *Optics Express*, **25**, 4382 (2017)

Expanded uncertainty:
1.6% (*k*=2) for > 1 kW

RPPM Validation at NIST

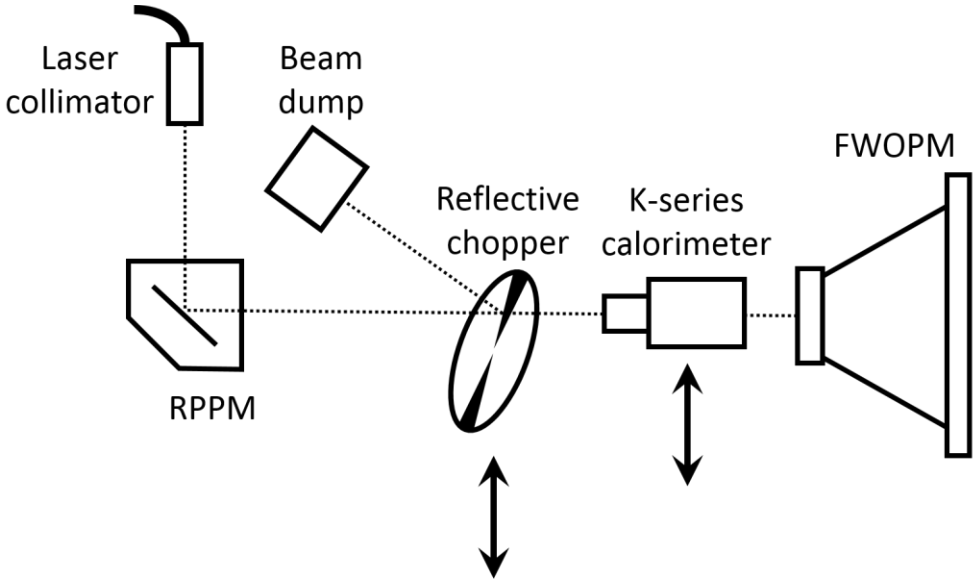


5kW



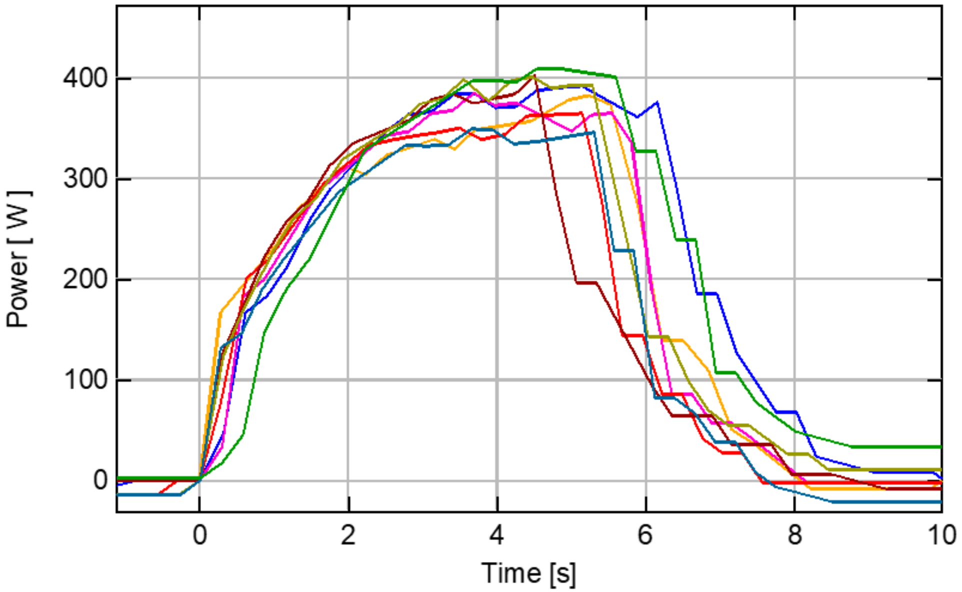
10kW

Comparison results of RPPM (Red), FWOPM (Green), and K-series Calorimeter (Blue)

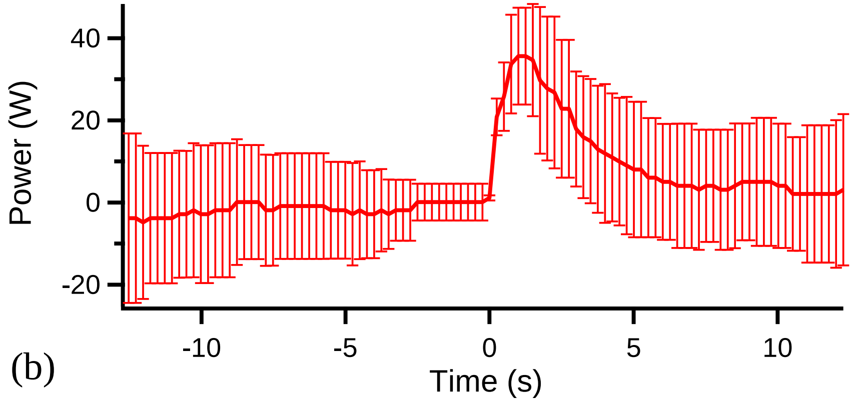


P. Williams, et al., *Metrologia*, **55**, 427 (2018)

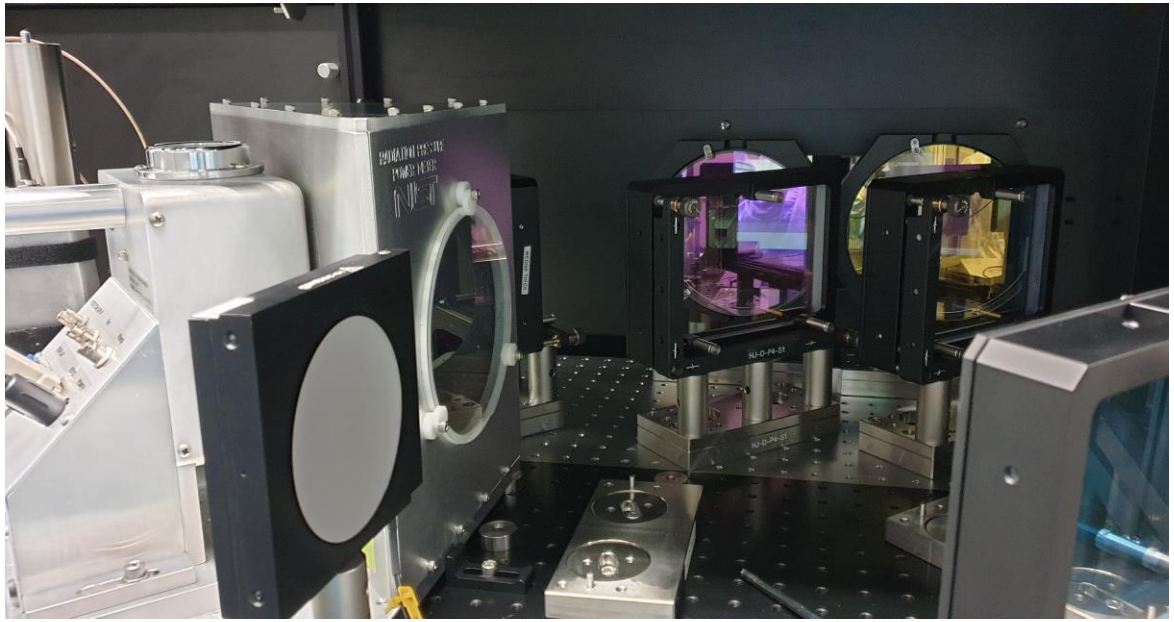
RPPM Applications



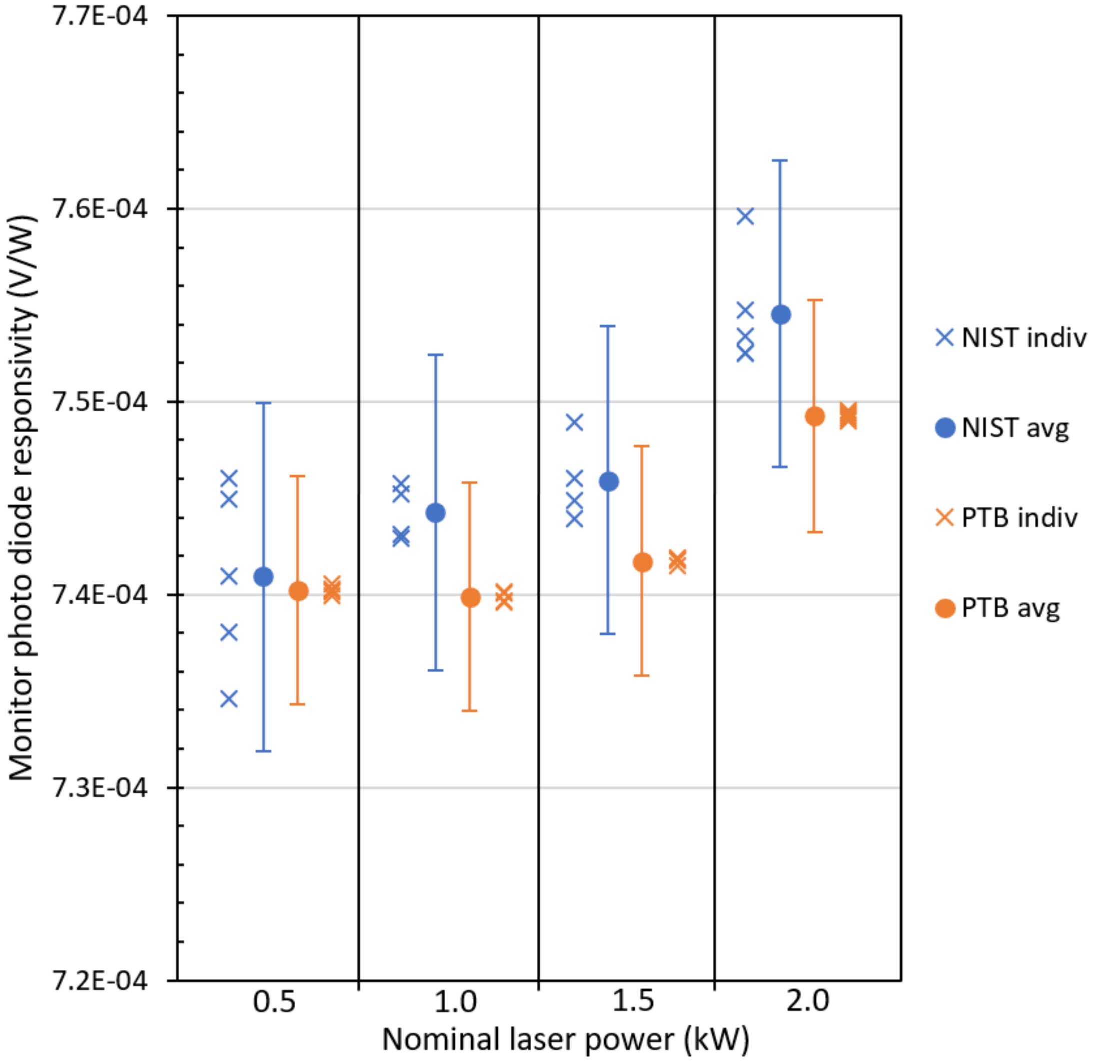
C. Holloway, et al., *Appl. Phys. Lett.*, **113**, 164102 (2018)

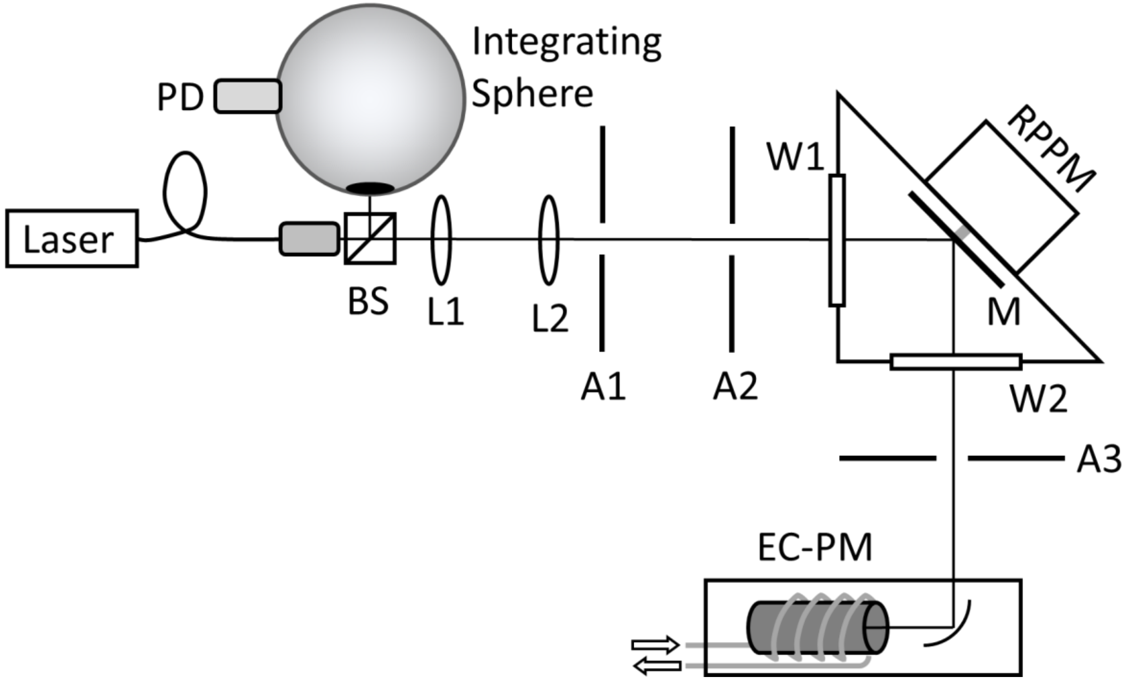


P. Williams, et al., *Optics Express*, **30**, 7383-7393 (2022)



RPPM Validation with External NMI



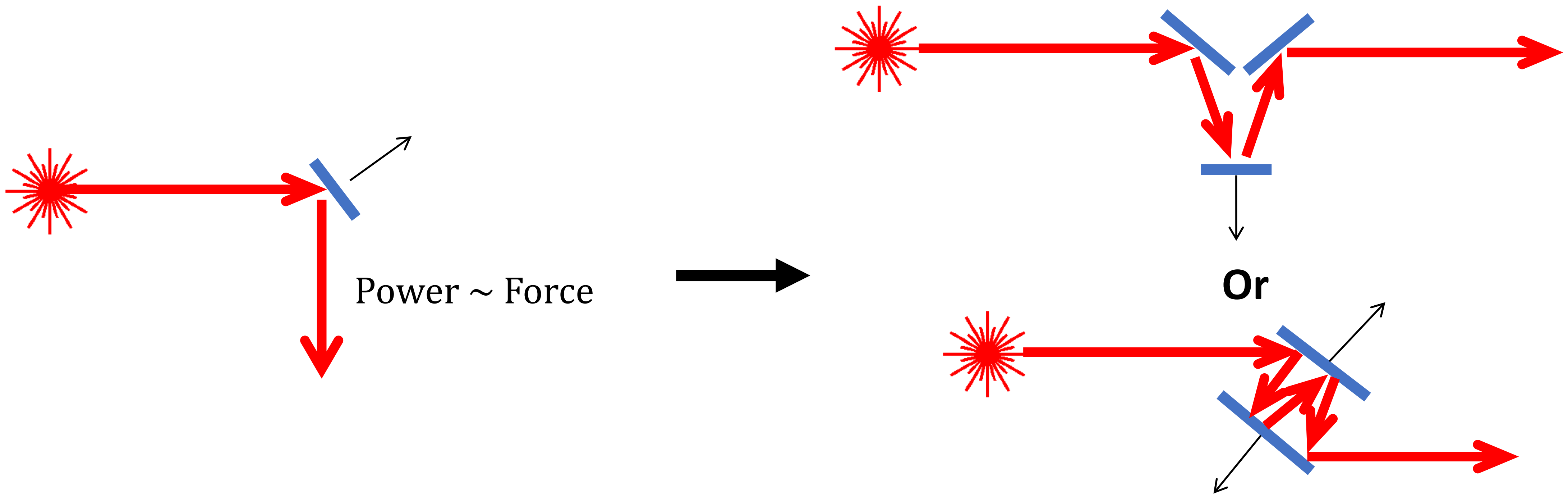


Expanded uncertainty:
1.22% to 1.05% (*k*=2)

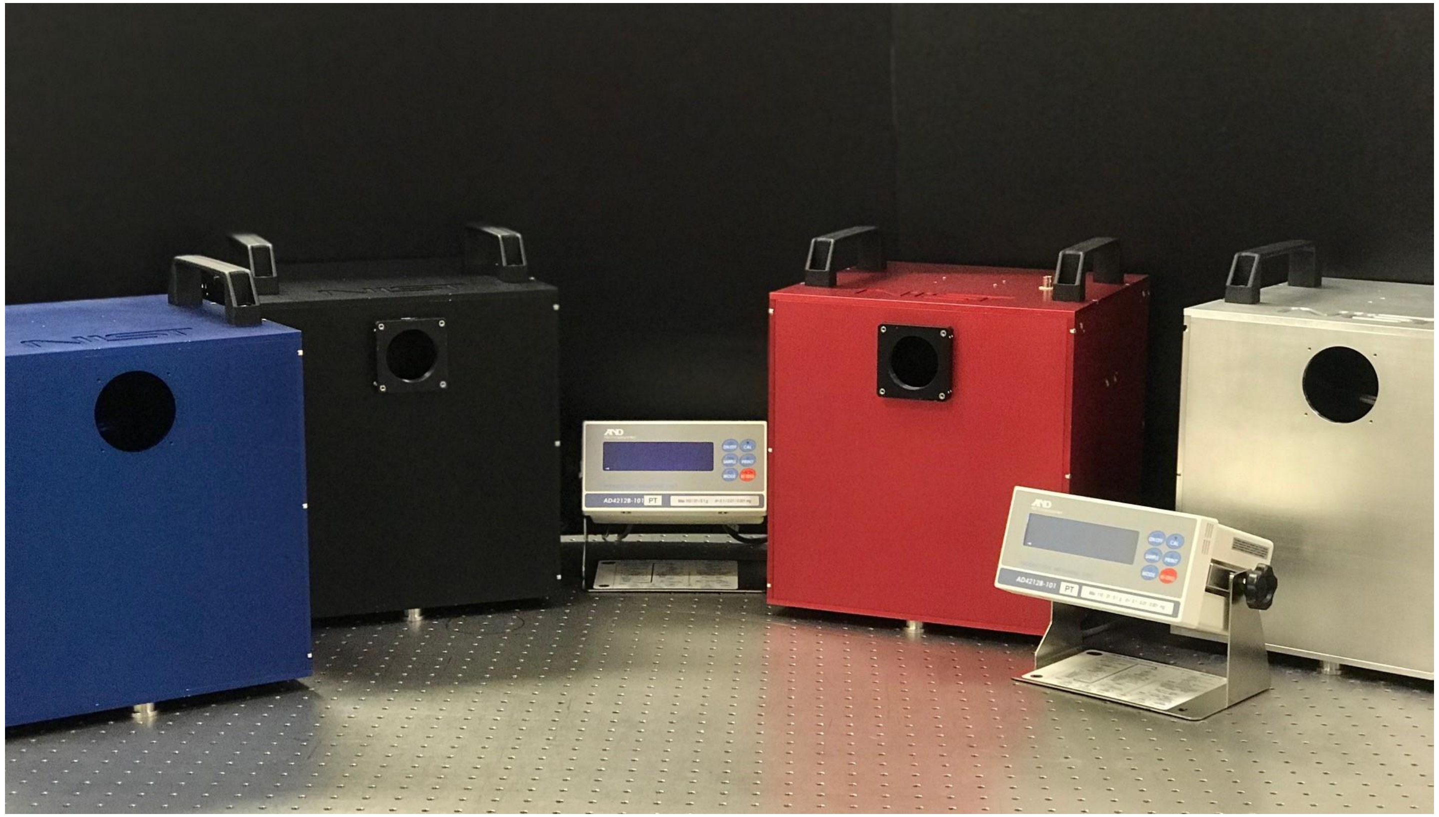
K. Rogers, et al., *Metrologia, In Review*

How can we continue to improve?

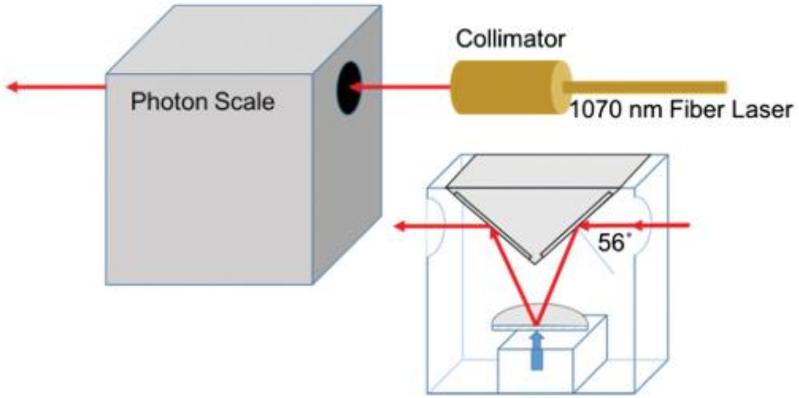
- In-line measurement
- Steeper angle of incidence for higher realized force
- Lower noise environment
  - Smaller optics
- Multiple reflections for increased signal-to-noise



Axial Force Radiometer (AFR)

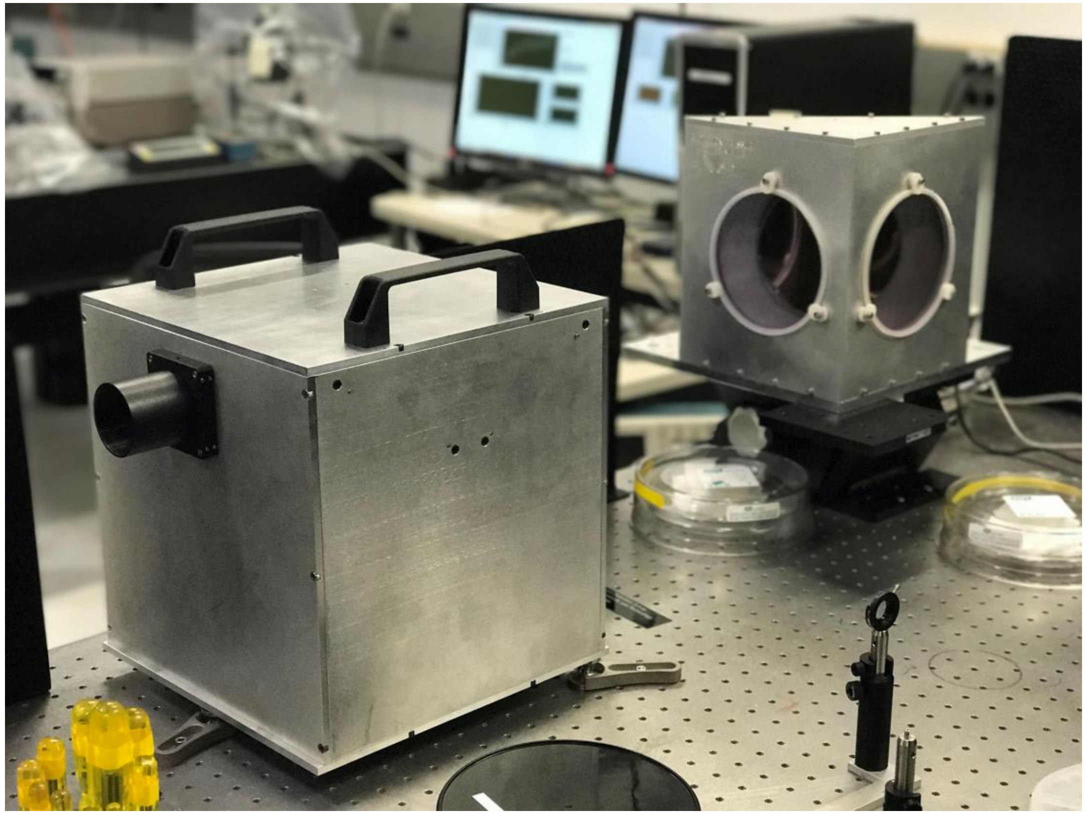


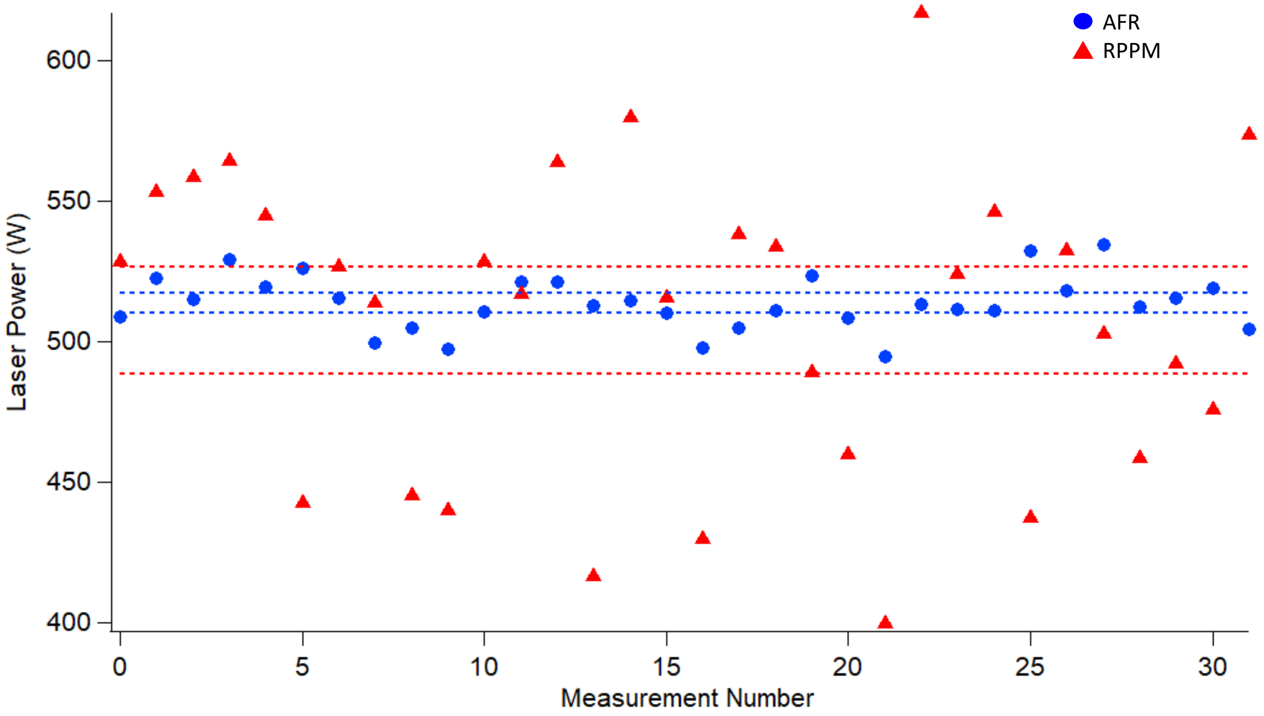
P. Williams, et al., *Metrologia*, **58**, 015010 (2021)



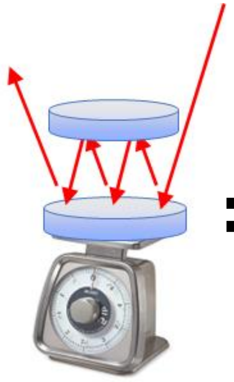
Expanded uncertainty:
2.1% (*k*=2) for 1 – 2 kW
1.2% (*k*=2) for > 2 kW

AFR Validation at NIST

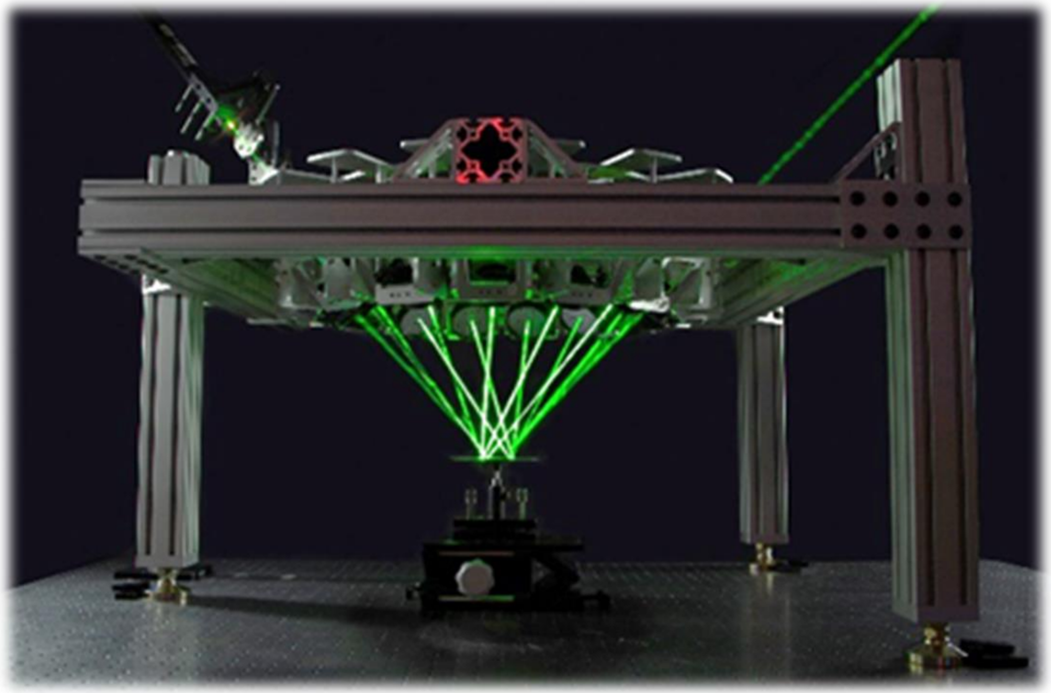


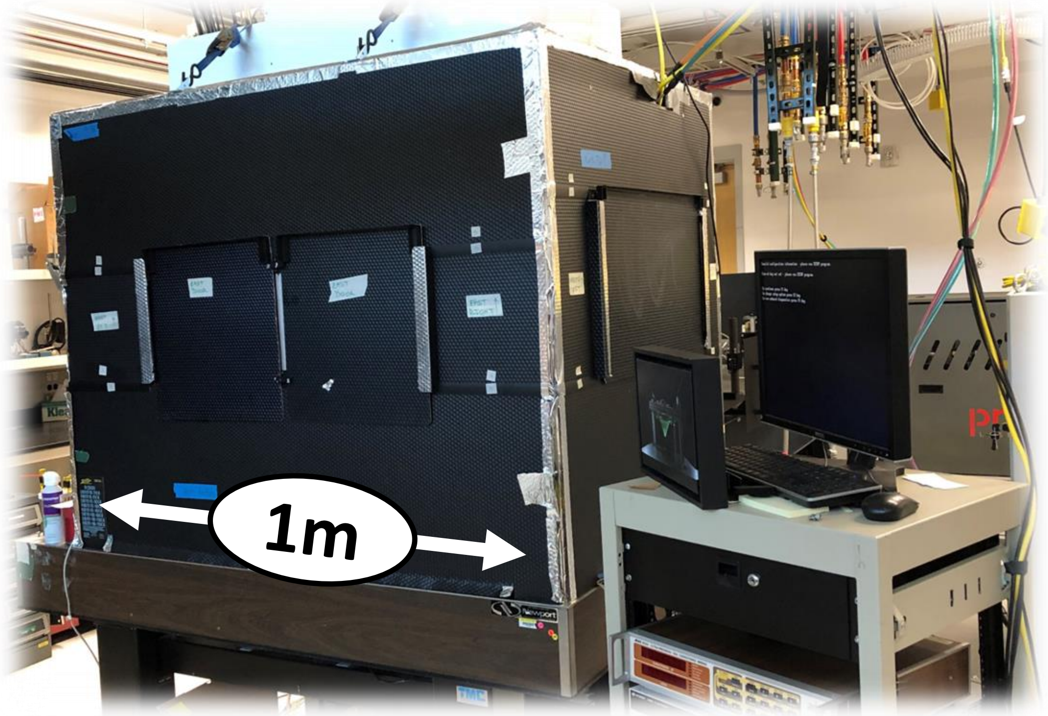


High Amplification Laser-pressure Optic (HALO)



= Improved SNR

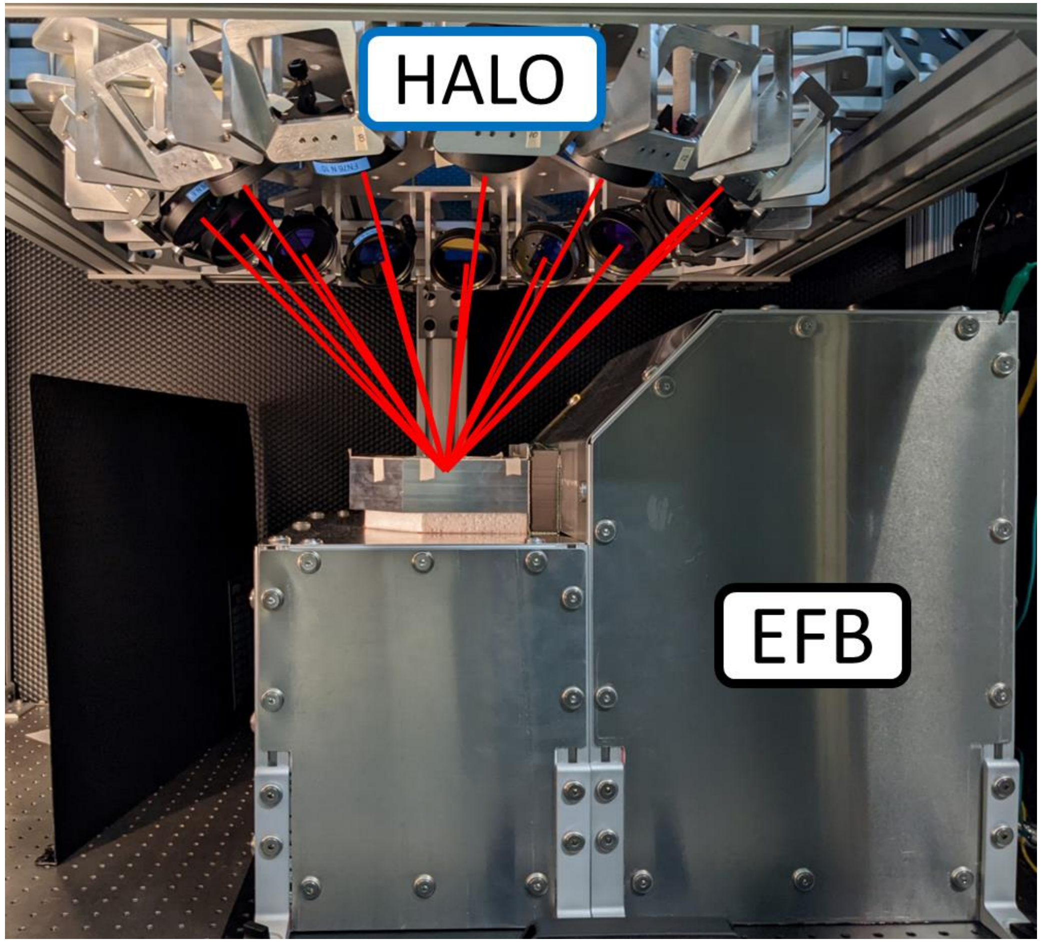


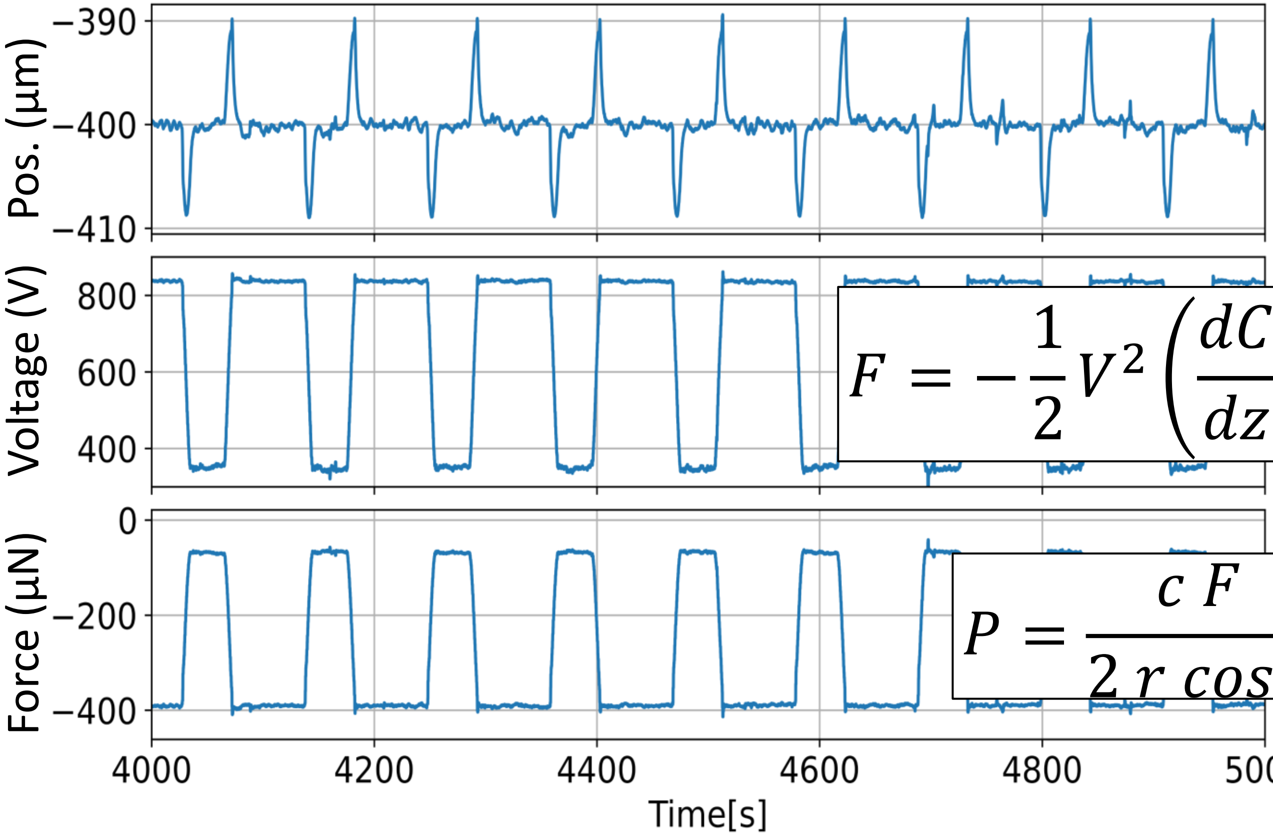


A. Artusio-Glimpse et al., *Metrologia*, **58**, p. 055010 (2021)

B. Simonds et al., *Metrologia, In Review*

Lowest uncertainty for kW-class measurement





$$F = -\frac{1}{2}V^2\left(\frac{dC}{dz}\right)$$

$$P = \frac{c\,F}{2\,r\cos\theta}$$

Expanded uncertainty:

0.17% (*k*=2) for 1 – 2 kW

0.12% (*k*=2) for 5 kW

Where to next?

NIST

- Further buy down uncertainty using HALO
  - Can we rival the cryogenic radiometer?
- Pulse measurement
  - Robust and repeatable device
  - Adaptability to experimental environments
- Redesign and implementation of updated RPPM
  - Smaller package for further capability

Thank you!

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