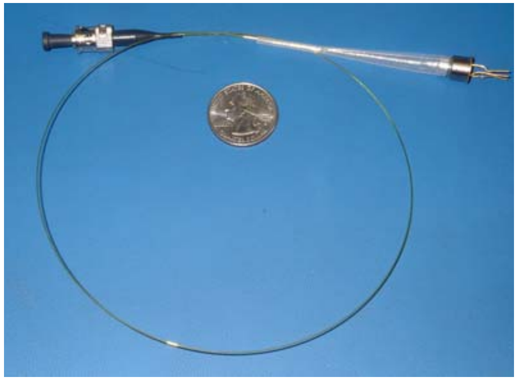
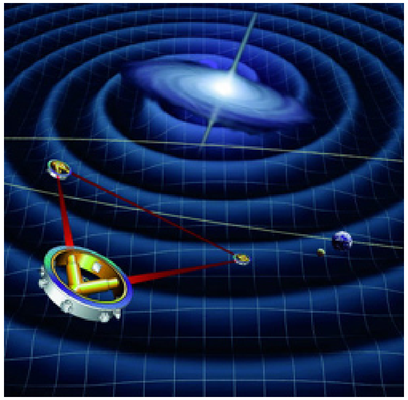
The Next Generation Charge Management Technology

UV LED AC Charge Management Systems for LISA and LIGO





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Stanford University, [§]MIT

2007 Workshop on Charging Issues in Experimental Gravity
MIT, July 26-27, 2007

Outline

- UV LED based AC charge management
  - GP-B,
  - ST7, LPF, STEP, LISA
  - LIGO (Initial, Enhanced, and Advanced LIGO)
  - UV LED characteristics
- System development
  - UV LED lifetime testing
  - Electronics development
  - UV Irradiation Tests
- Next Steps
  - UV LED
  - Kelvin Probe
- Stanford applied patent for UV LED based AC charge management technology

UV LED AC Charge Management Research Reference Selection

[1] K.-X. Sun, B. Allard, S. Williams, S. Buchman, and R. L. Byer, “LED Deep UV Source for Charge Management,” presented at Amaldi 6 Conferences on Gravitational Waves, June 2005, Classical and Quantum Gravity, 23(8):S141-S150, 2006.

[2] K.-X. Sun, S. Higuchi, A. Goh, B. Allard, D. Gill, S. Buchman, and R. L. Byer, "Spectral and Power Stability Tests of Deep UV LEDs for AC Charge Management," 6th LISA International Symposium, GSFC June 2006, AIP proceeding vol. 873, pp.215-219

[3] K.-X. Sun, S. Higuchi, B. Allard, D. Gill, S. Buchman, and R. L. Byer, “LIGO Test Mass Charging Mitigation Using Modulated LED Deep UV Light, ” LIGO Science Collaboration (LSC), OWG & SWG Joint Meeting, Hanford, Washington, March 22, 2006, LIGO Documentation G050143-00-Z

[4] Stanford University (K.-X. Sun, B. Allard, S. Buchman, and R. L. Byer), Patent Application on UV LED AC Charge Management, initial filing May 2006

[5] K.-X. Sun, G. Allen, S. Buchman, R. L. Byer, J. Conklin, D. DeBra, D. Gill, A. Goh, S. Higuchi, P. Lu, N. Robertson, and A. Swank, "Modular Gravitational Reference Sensor for High Precision Astronomical Space Missions," AAS/AAPT joint meeting 2007, Session 074.07, Seattle, Washington, January 5-10, 2007.

Ke-Xun Sun visited University of Washington by invitation from Scott Pollack, provided further information on UV LED AC charge management, and discussed collaboration in this area.

[6] K.-X. Sun, N. Leindecker, S. Higuchi, A. Markosyan, R. Route, S. Buchman, R. L. Byer, G. Harry, J. Hines, J. Goebel, and E. Agasid, “Development of UV LED Based AC Charge Management Systems For Gravitational Wave Detectors”, The 7th Edoardo Amaldi Conferences on Gravitational Waves, Sydney, Australia, 8-14 July 2007.

LISA Charge Management Requirements May Become More Stringent Due to GP-B Experience

Category	Limit (C)	Assumptions
Lorentz Noise	$4x10^{-11}$	$\eta = 0.01, f = 10^{-4}$ Hz
Displacement and voltage noise	$4x10^{-11}$	$\Delta d = 10\ \mu m, \delta V = 10 \mu V / Hz^{1/2}$
Charge noise	$1.4x10^{-11}$	$f = 10^{-4}$ Hz
Stiffness	$4x10^{-13}$	$\Delta d = 10\ \mu m$
Dynamic Range (GP-B Experiences)	10^2 Normal 10^5 Decaging	Charging rate: 100 protons/s Decaging 1 nC/hour

First four requirements: Sumner et al, Class. Quantum Grav. **21** (2004) S597–S602
Dynamic range requirement: GP-B communication

UV Photon Source Requirements for LIGO Test Mass Charge Management

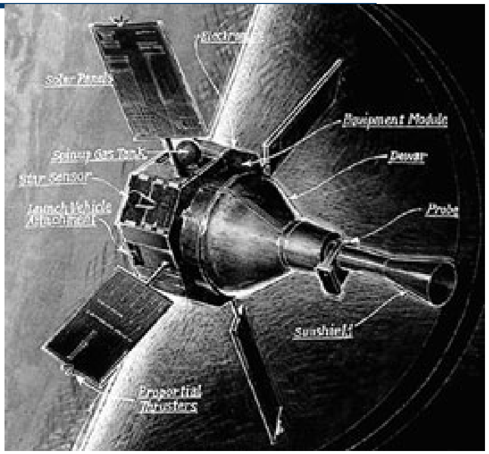
- Q_c~10^{-7} C/m^2
- Charging rate Q_c~10^{-7}C/day
- N_e~10^{12} electrons/day
- Photoelectric "Q. E.": η~10^{-5}
- UV photons required: N=10^{17}
- $P_{UV} = Nhc/\lambda T = 8.9\text{x}10^{-7}$ W
- P_{UV} ~ 1 μW (average power over a day)
- Dynamic Range ~ 1000,

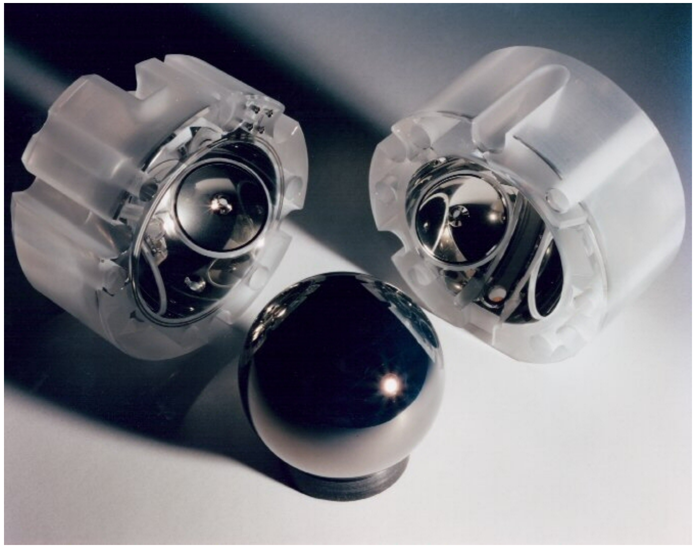
  P_{UV} ~ 1 mW (Peak power)

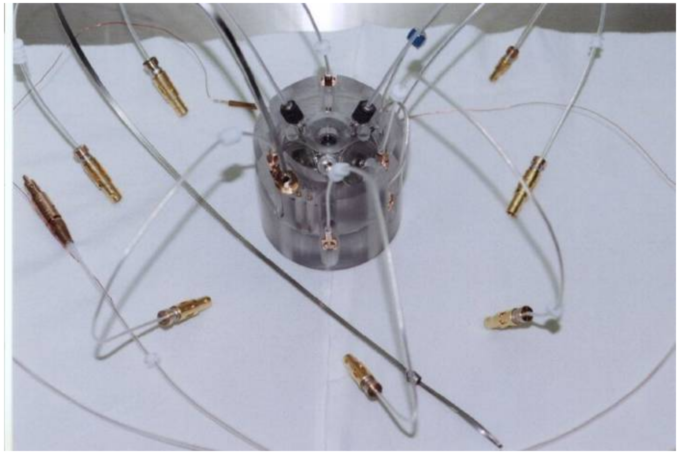
GP-B Charge Management R&D at Stanford

GP-B charge management (Buchman 1993)

- R&D since 1990’s
- Non-contact charge transfer by UV light
- Critical to GP-B mission success
  > Initial gyro lifting-off
  > Continuous charge management during science measurement





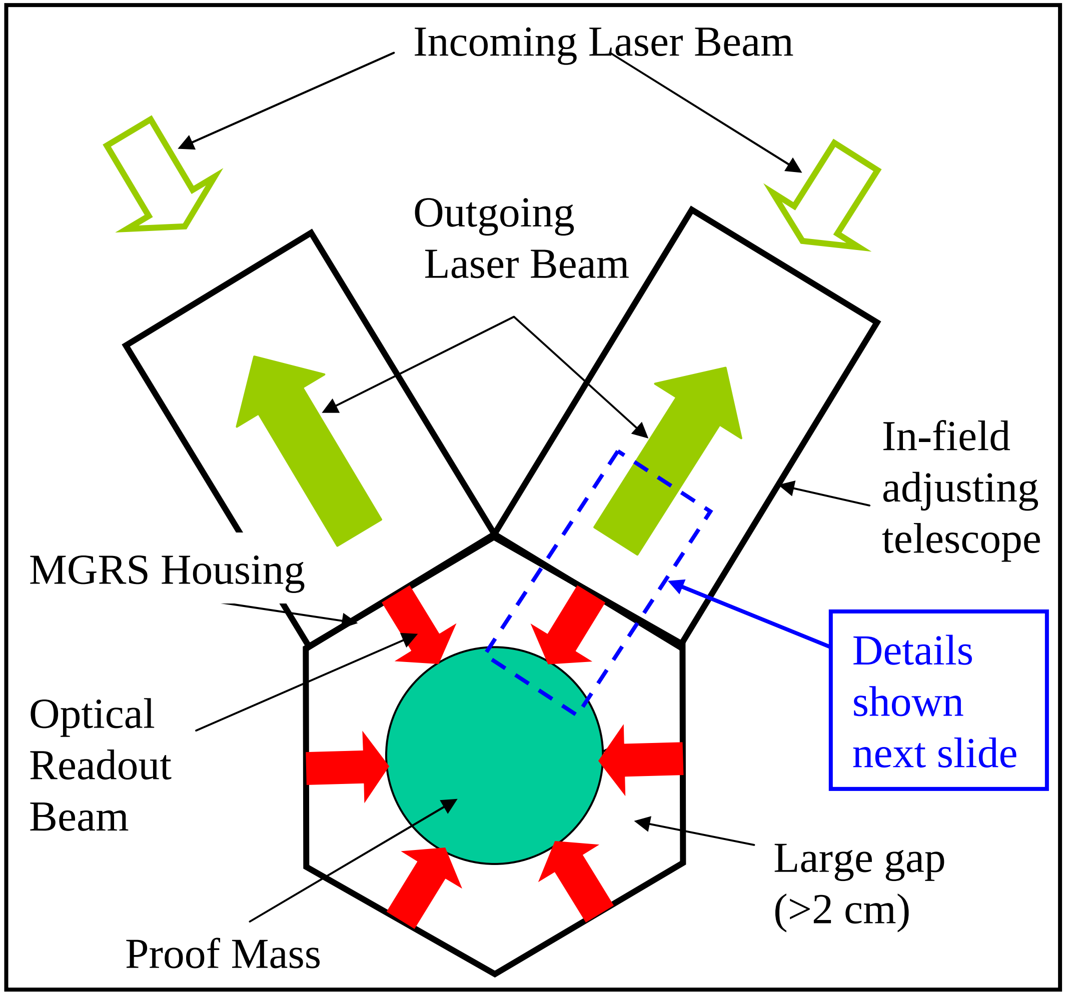


[Buchman 1993] Saps Buchman, Theodore Quinn, G. M. Keiser, and Dale Gill, *“Gravity Probe B Gyroscope charge control using field-emission cathodes,”* J. Vac. Sci. Technol. B **11** (2) 407-411 (1993)

Modular GRS Architecture

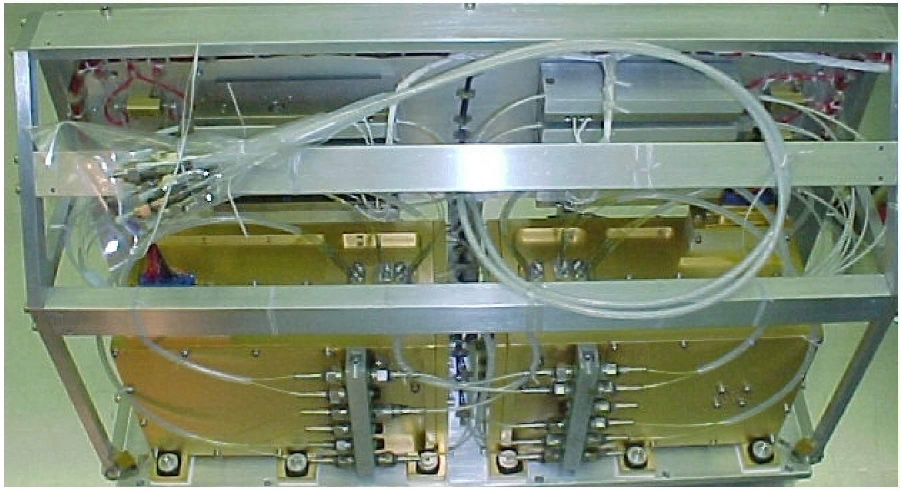
Presented at LISA 5th Symposium July 2004

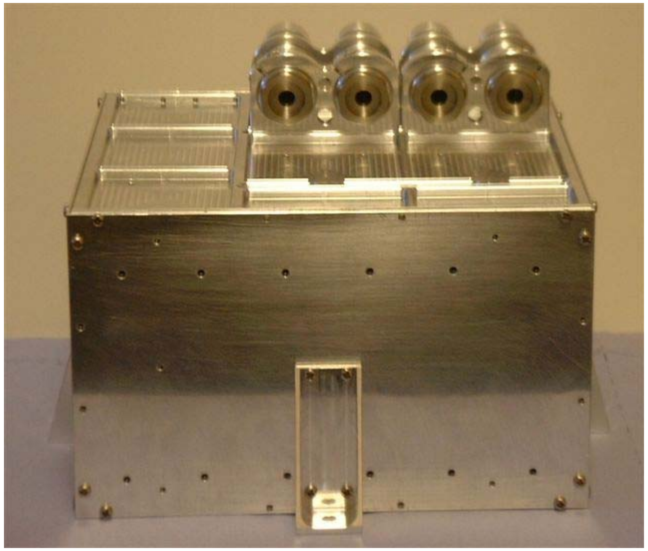
- Designed to achieve higher performance for Advanced LISA and BBO class space GW detectors
- Single proof mass
- Modularized, stand-alone GRS
- GW detection optics external to GRS
- External laser beam not directly shining on test mass
- Internal optical sensing for higher precision
- Large gap (> 2cm) for better disturbance reduction
- 3-dim sensing & true drag-free
- Determine the geometric center and **center of mass**



Sun, Allen, Buchman, DeBra, Byer, CQG ***(22)*** *2005 S287-S296*

Mercury Lamp Based Charge Management System





GP-B CMS in Flight

- **2 Hg Lamps**
- **Weight: 3.5 kg**
- **Electrical Power 7~12 W**

  (1 lamp on, 5 W for lamp, 5 W TEC cooler)

LTP CMS in Development

– 8 Hg Lamps
– Weight: ~5 kg
– Electrical power 12~15 W

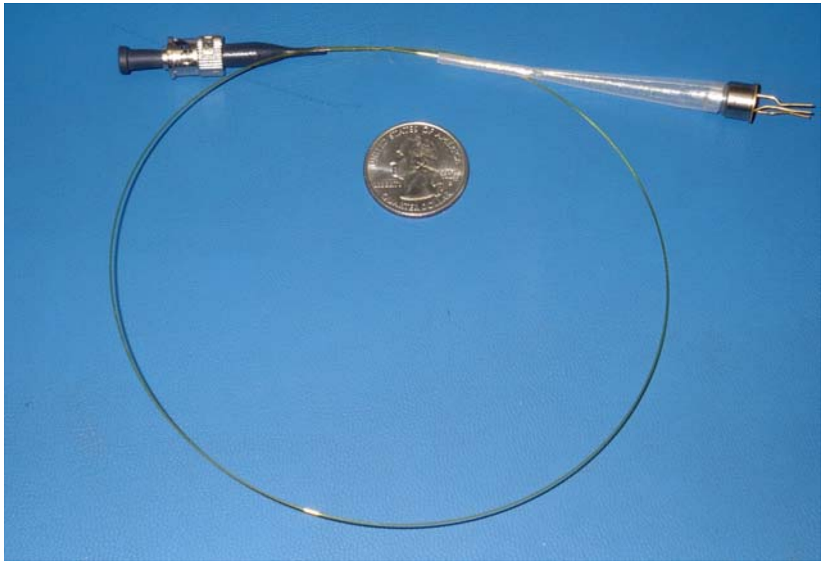
  (for 2 lamps on, ~4 W for lamp, ~4 W for control electronics)

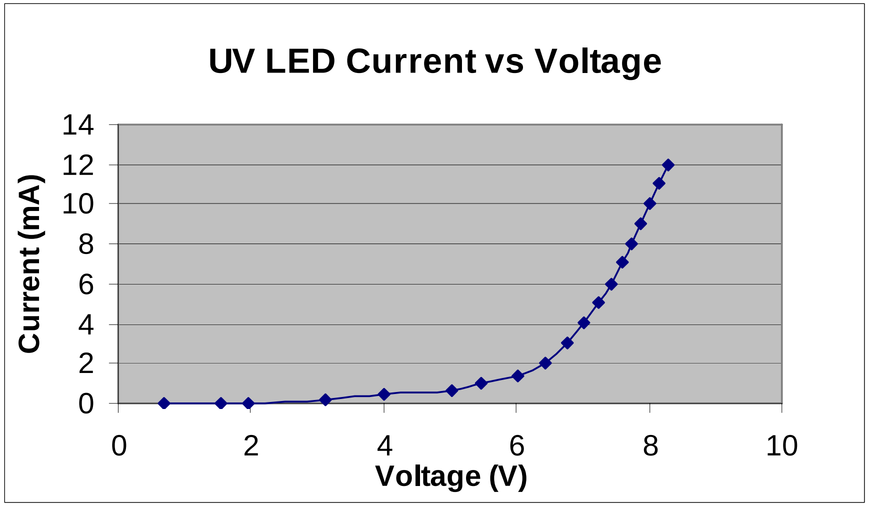
Deep UV LED Key Characteristics

"LED"--- Light Emission Diode

UV LED Charge Management System

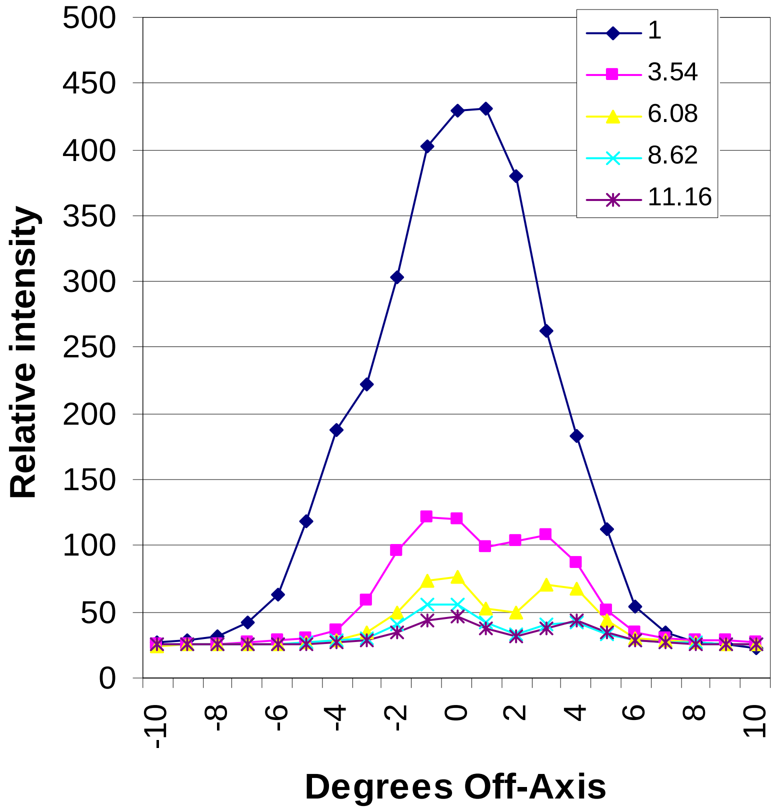
- Weight: 0.3 kg (including electronics)
- Electrical power ~1.5 W (0.1 W/LED. Est. power for control electronics ~1.2 W)
- Fast switching (<0.1 μS), wide selection of modulation frequency and duty ratio
- AC charge management at frequencies *out-of signal band* (e.g. at cap bridge freq.)
- Various AC charge management techniques for better performance



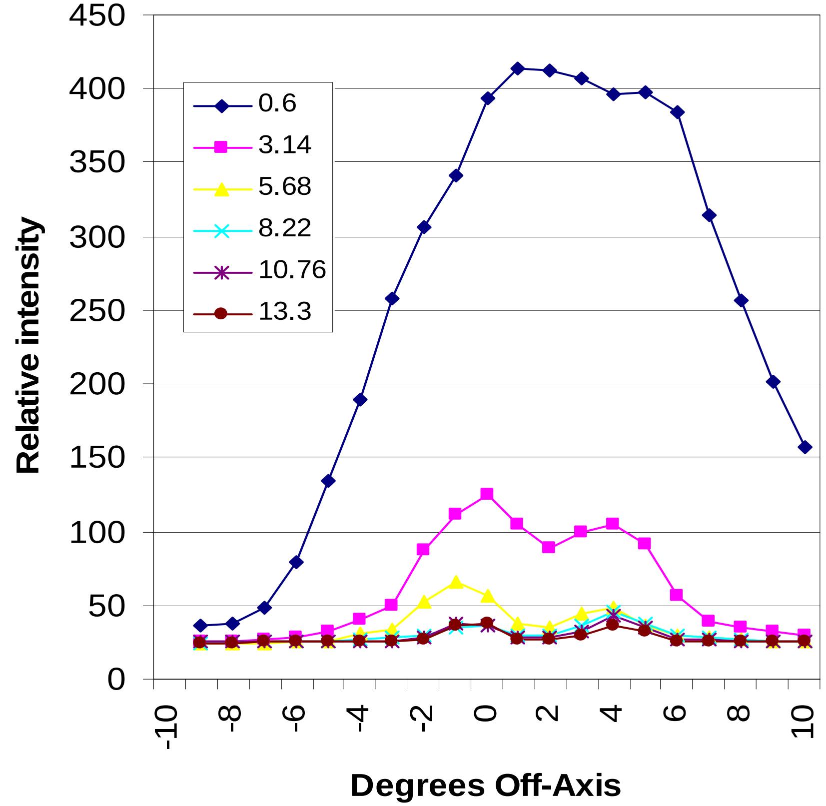


UV LED Beam Profile

UVLED Spatial Power (Horizontal Dimension) (Series: distance from source in cm)

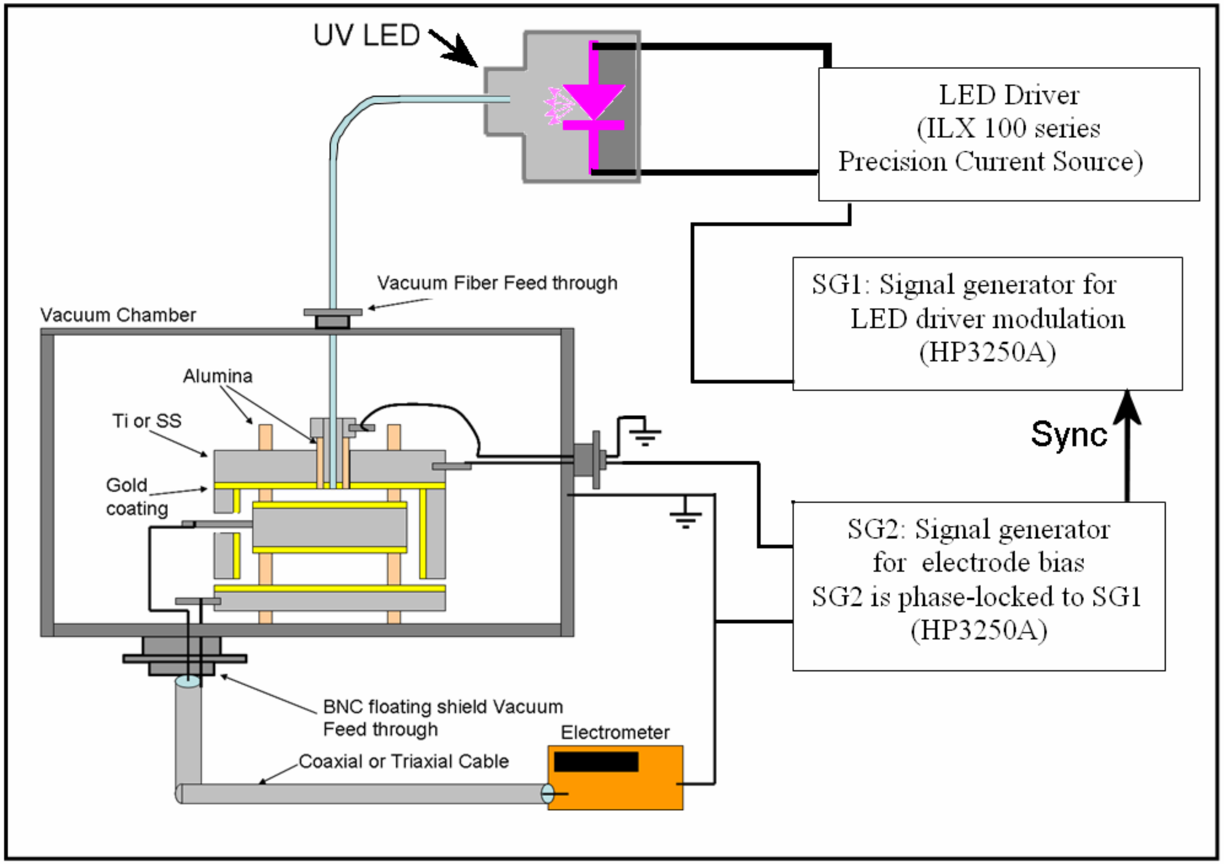


UVLED Spatial Power Distribution (Vertical Dimension) (Series: distance from source in cm)



UV LED AC Charge Management

Experimental Setup



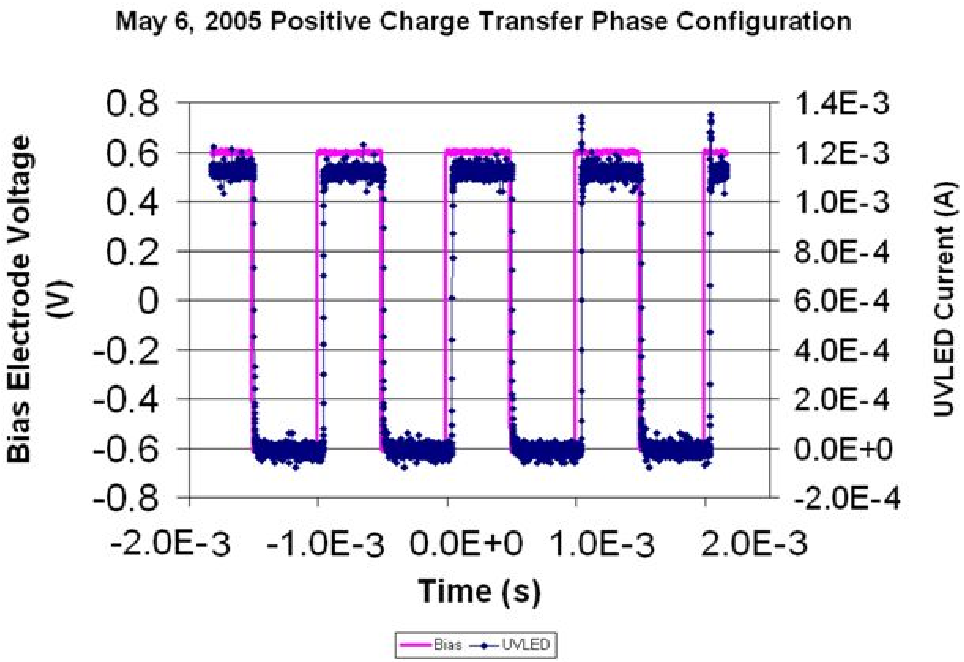
- GP-B heritage
- Au coating on proof mass and housing to simulate LISA GRS
- Fiber connected UV LED driven by modulated current source
- Housing electrode modulation phase-locked to UV modulation
- UV light shining on proof mass and reflected onto housing electrode
- Sensitive electrometer to measure the proof mass potential

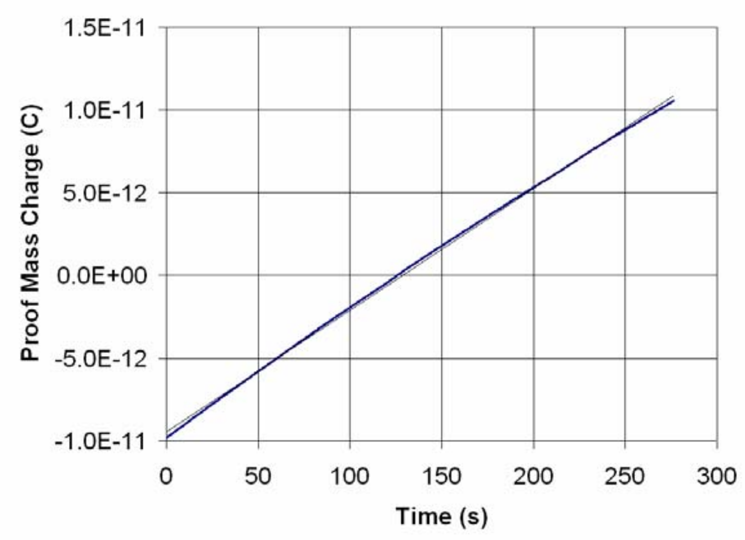
UV LED vs. Mercury Lamp Based Charge Management System

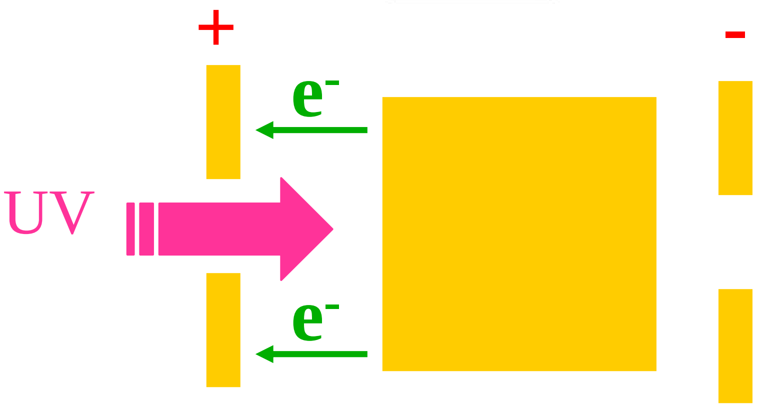
Category	*UV LED CMS*	*Mercury Lamp CMS*
Electrical Power Consumption	0.5 W	15 W
EMI	Minimal	Large due to RF excitation
Weight	0.3 kg	3.5 kg
Dimension of the CMS system	10 cm x 8 cm x 3 cm	17 cm x 13 cm x 17 cm
UV emission power	~120 μW	~100 μW
UV Power at the fiber tip	~16 μW	~11 μW
UV Wavelength, central	257 nm	194 nm & 254 nm
UV Wavelength, spread	12.5 nm	Doppler Broadening
Fast modulation capability	Easy – Intensity, pulse train frequency and phase, etc.	Difficult
Charge management method	AC & DC	DC only
Charge management frequency	Out-of signal band	In signal band
Equivalent dynamic range	100,000	100
Charge management resolution	high	low
Charge management speed	high	low

Positive Charge Transfer

UV LED and bias voltage modulated at 1 kHz







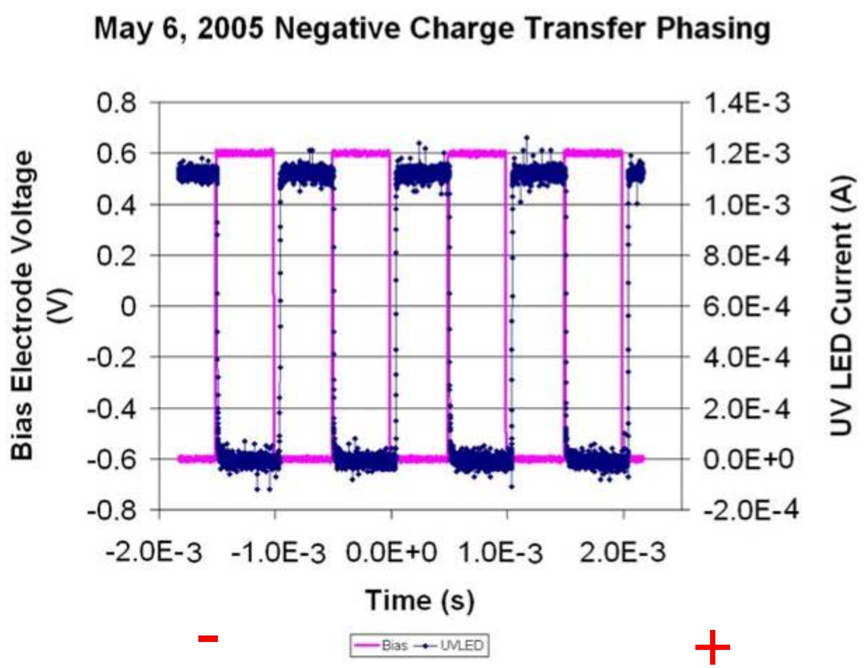
UV phased to positive AC ½ cycle

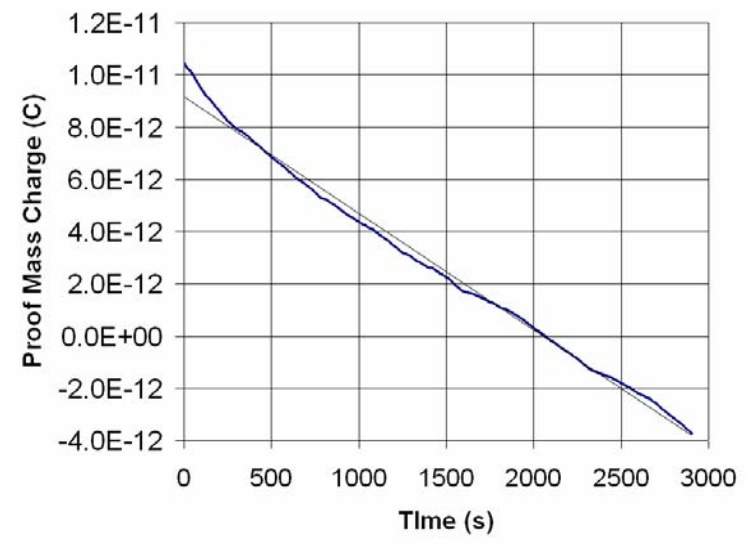
Electrons fly to housing electrode

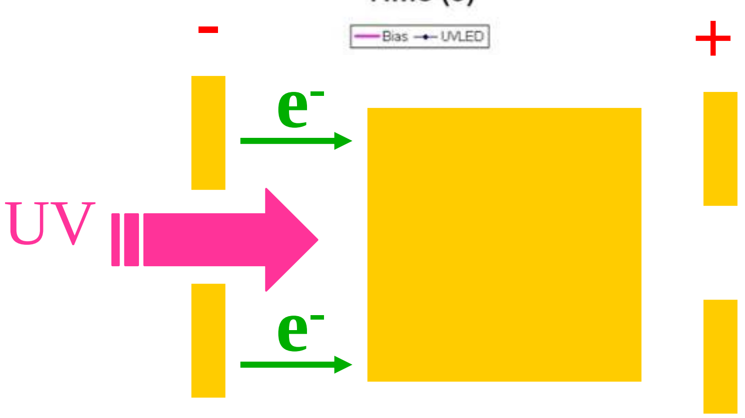
Proof mass potential increase

Negative Charge Transfer

UV LED and bias voltage modulated at 1 kHz







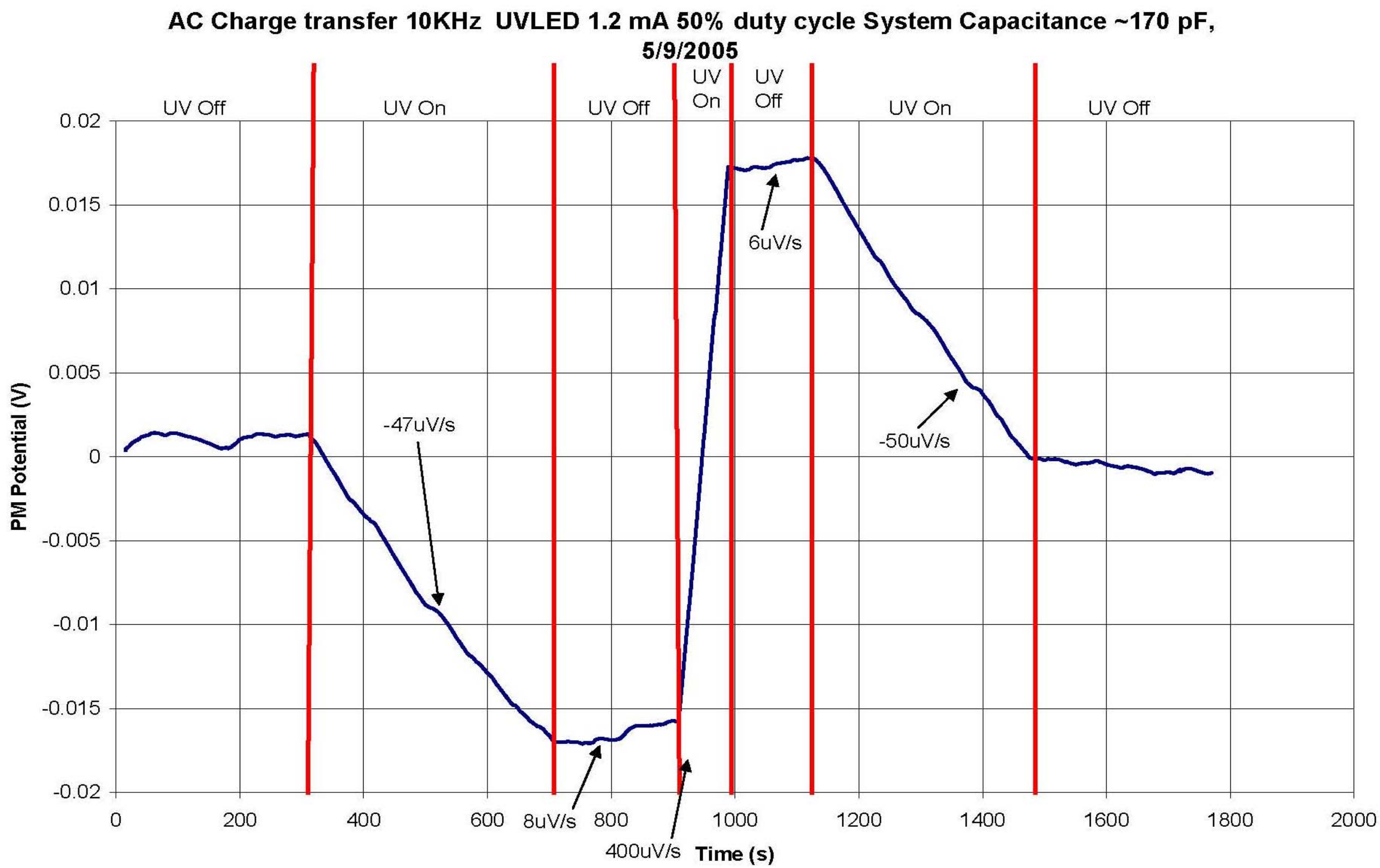
UV phased to negative AC ½ cycle

Electrons fly to proof mass

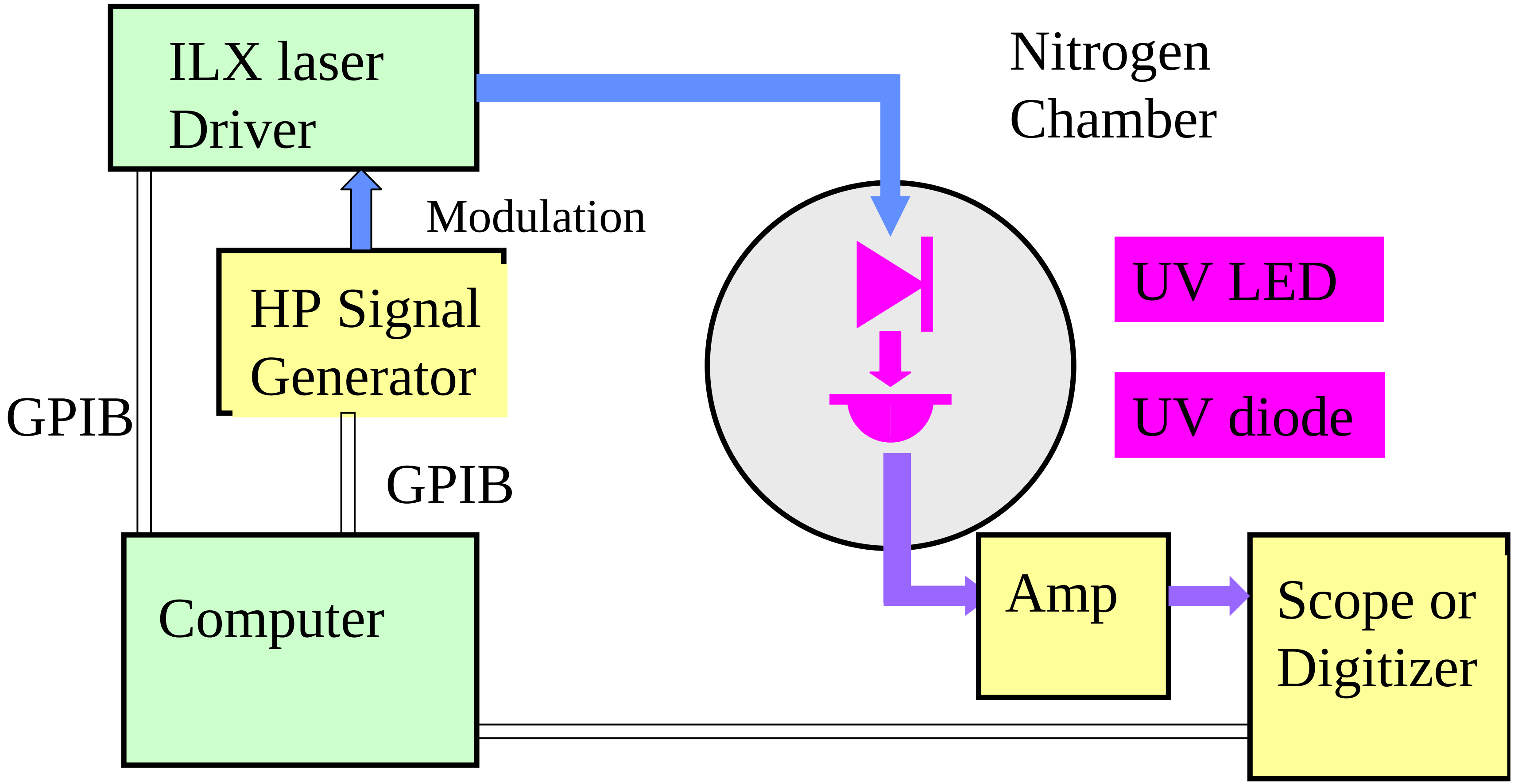
Proof mass potential decreases

AC Charge Management Shows Promising Characteristics

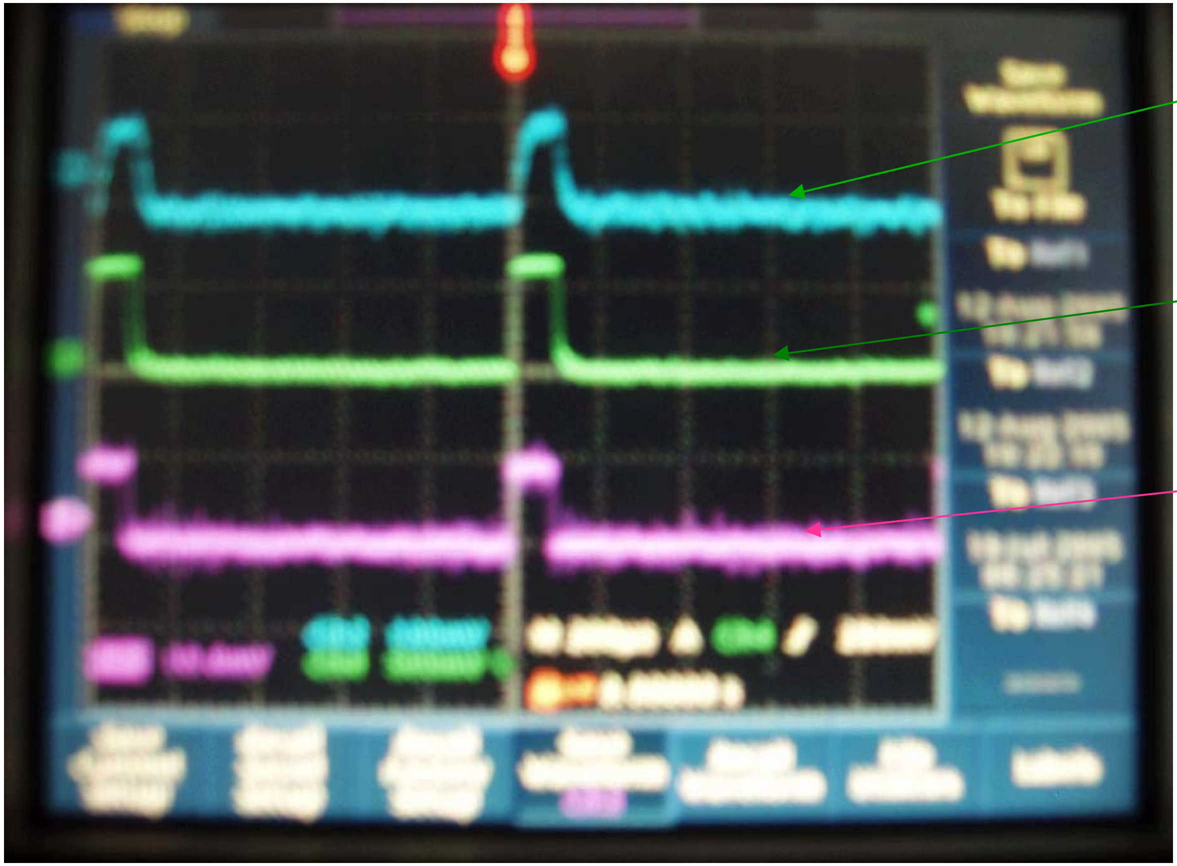
UV LED and bias voltage modulated at 10 kHz



UV LED Lifetime Experiment



UV LED Modulation Direct Readout

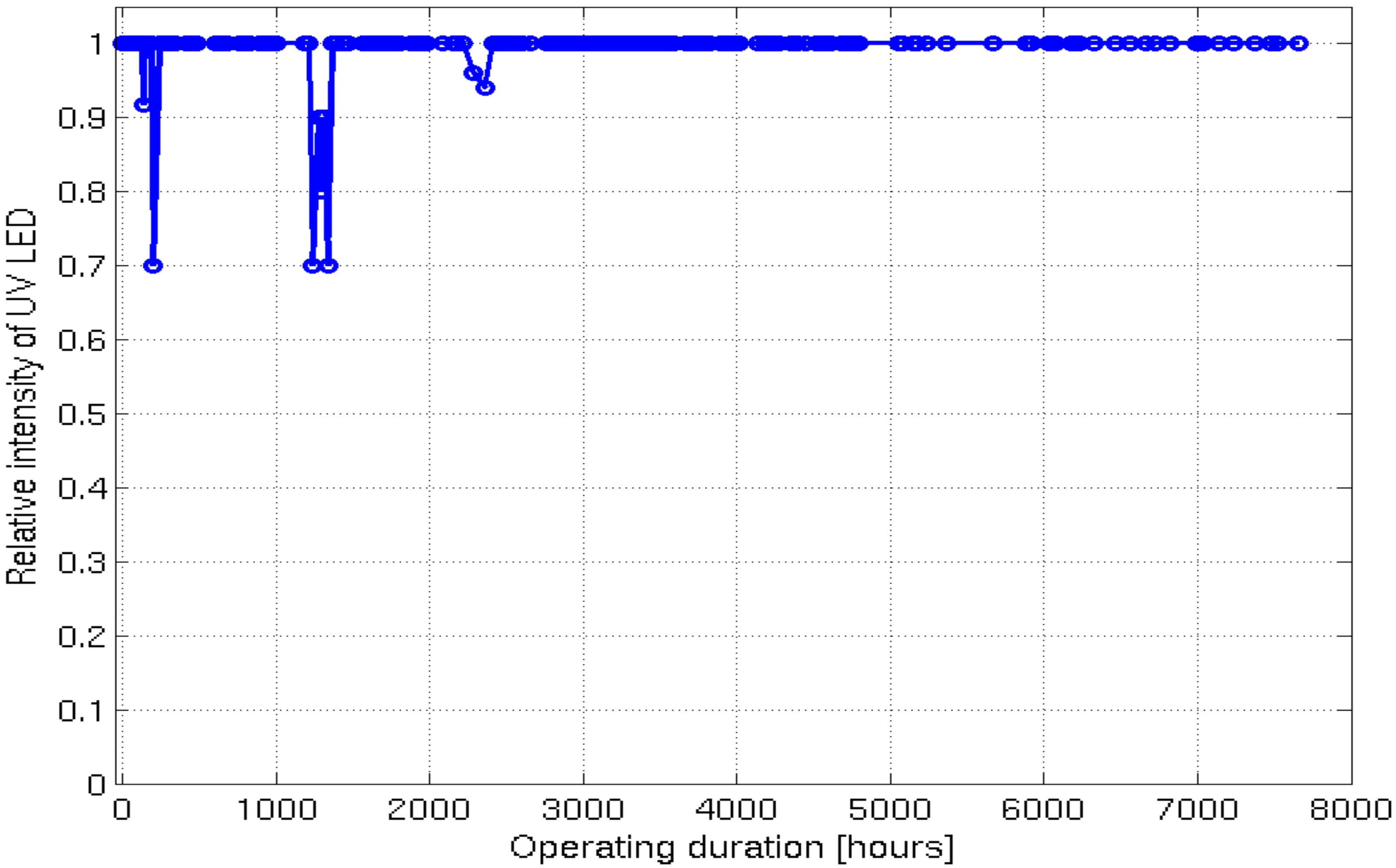


Signal from UV Photodiode

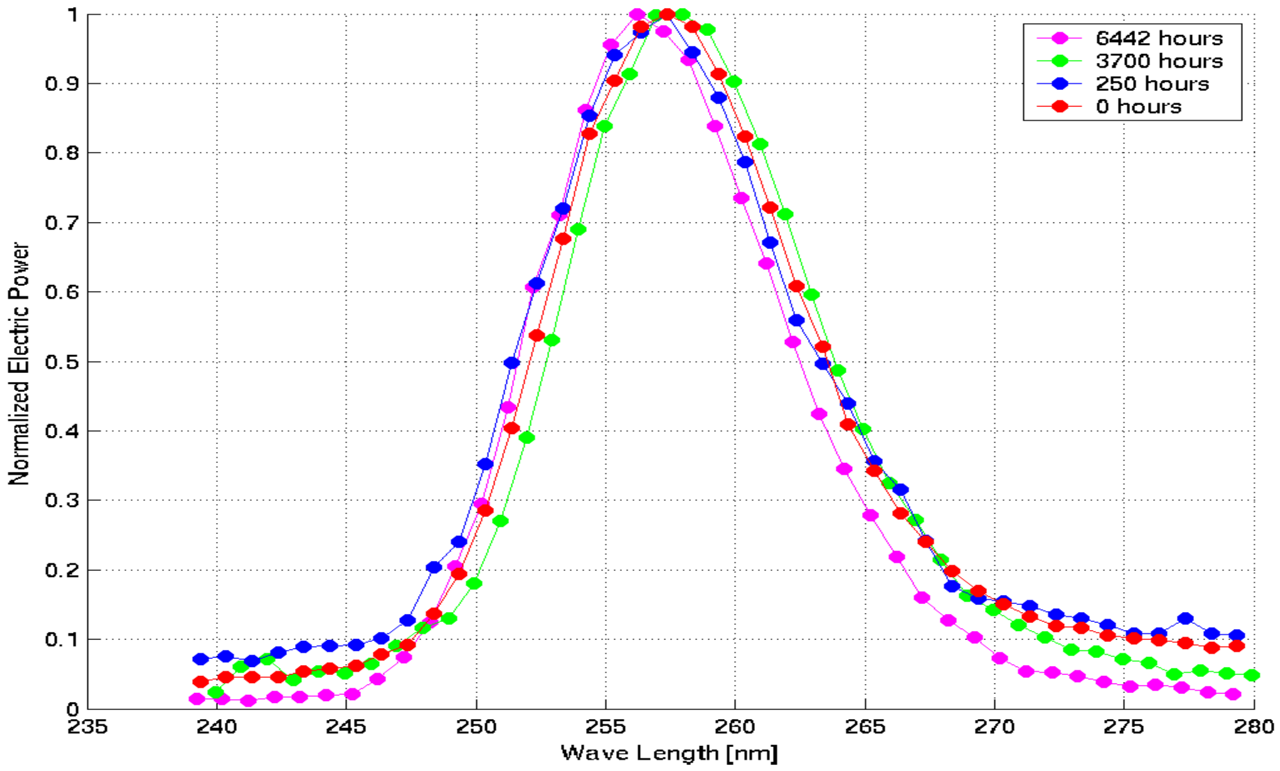
UV LED driver voltage

Driving signal

UV LED Lifetime Exceeds 8,200 Hours (Over a Year)

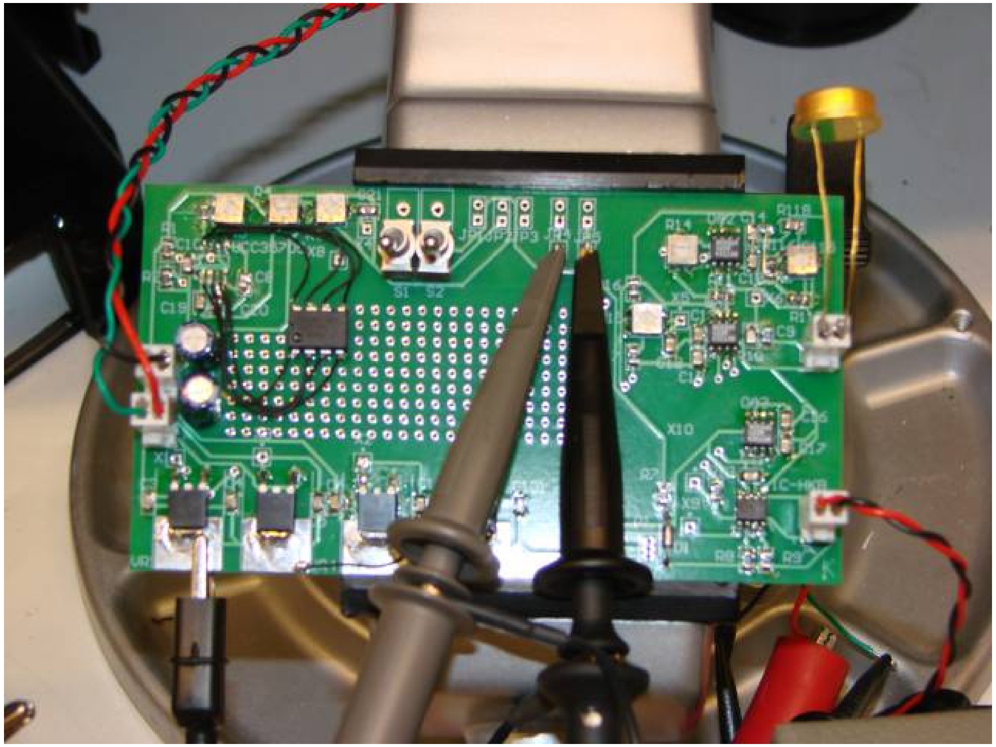


UV LED Spectral Stability Demonstrated



- Wavelength shift readout less than +/- 1 nm
- Measurement variance within spectrometer error

UV LED AC Charge Management System Development

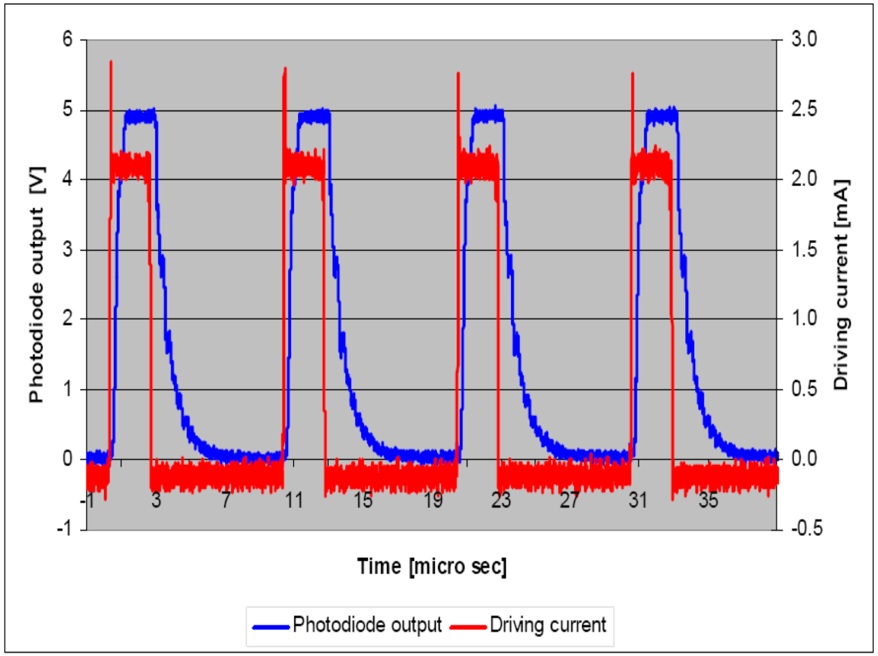


- PCB form factor fits into LIGO wavefront sensor box
- Circuit design allow modulation faster than commercial instrumentation sets
- Now operated above 100 kHz
- UV LED driver
- Photodetection circuit on board
- Electronics configuration allows easy interface with LIGO electronics structure
- Easy interface with LTP/LISA capacitive sensing mechanism

The New Electronics Design for All GW Detector Needs

- Apply AC charge management technique to LIGO
- New UV LED electronics driver enable faster modulation beyond LIGO detection band

System	Frequency
LISA GW Band	**30 µHz ~ 1 Hz**
LIGO GW Band	**10 Hz ~ 1kHz**
LIGO GW High Frequency	**37.5 kHz**
LTP/LISA Capacitive Bridge	**100 kHz**
UV LED Driving Electronics	100 kHz (with adjustable duty ratio)



Next Steps

- **UV charge management works**
  - The good news --- UV worked for GEO, easily
  - UV is *the* non-contact charge management tool
- **Development LIGO-targeted UV system**
  - More sophisticated UV LED system rivaling that for what we did for LISA
    - > UV LED sources with flexibility
    - > Modulation optimization
    - > Wavelength selections beyond 253.7 nm Hg line
    - > Full spectrum LED available from 248 nm and longer wavelength
  - Customization for eLIGO and advLIGO

Ongoing

- **Voltage probe development**
  - GSFC Kelvin probe will be commissioned after accelerated moving request. (It is a PZT driven buzzer)
  - LIGO needs an independent, vibration-less voltage probe for test mass charging concerns
  - Some possible schemes
    - > Differential electrometer
    - > Lower the cost using commercial alterations
    - > EO crystals
  - Will use a second chamber for technology development

Ongoing

- **UV Irradiation Tests:**
  - Continued UV irradiation tests on LIGO mirrors AND coatings
    - > The doubt from coaters --- increased absorption loss by UV illumination
    - > Are there any damaging effects on oxide coatings?
    - > What is the UV power threshold beyond safe charging management?
    - > What is the wavelength dependence/threshold?
    - > What is the modulation dependence?
  - Alternative UV scheme
    - > Wavelengths that fill in the gap between effectiveness and damage (such as 355 nm etc)
    - > Hidden UV source as an electron control device

Ongoing

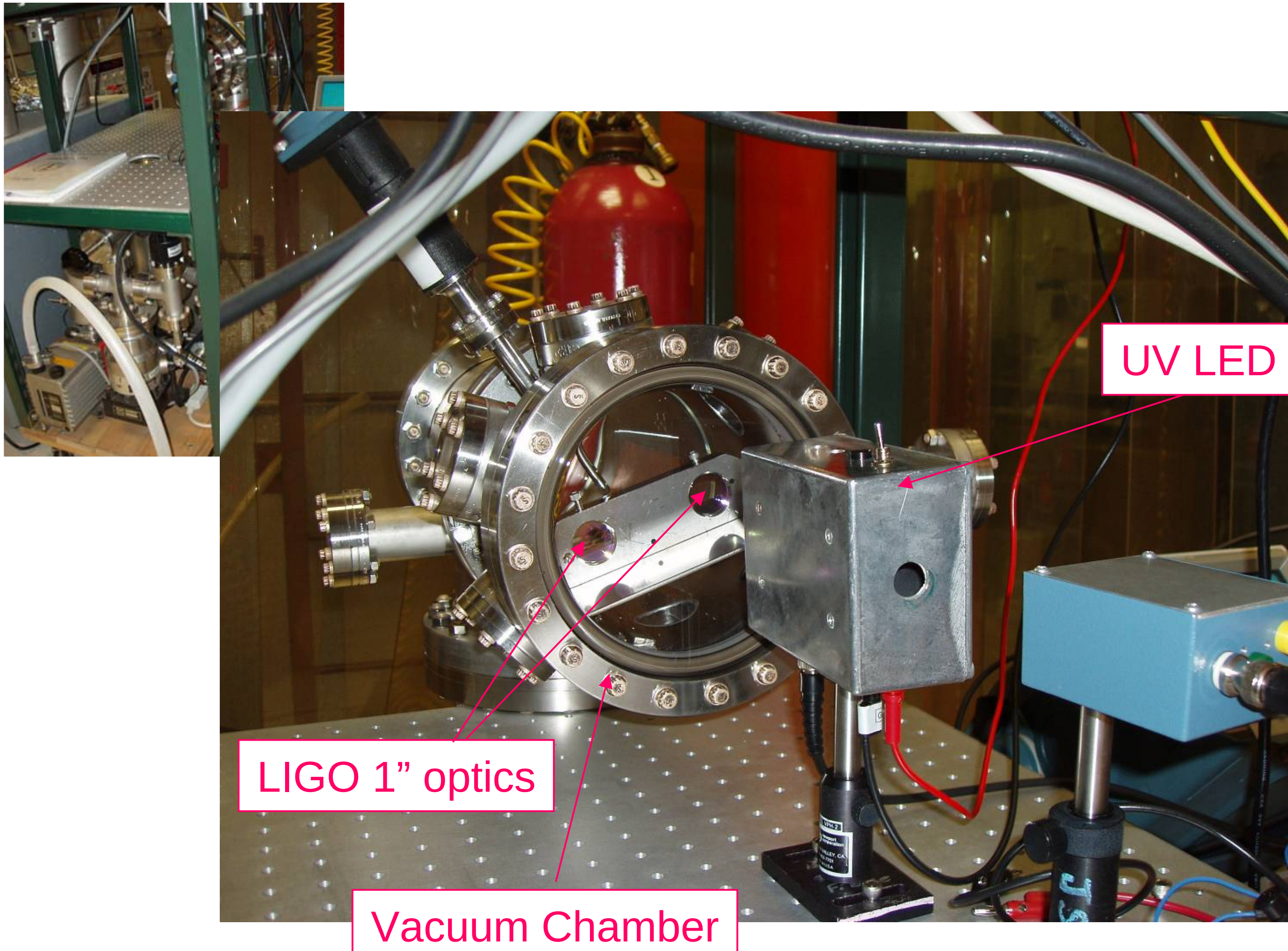
- **Modified UV scheme to mitigate additional risks**
  - UV illumination from side or the back of the mirrors
  - UV light box to contain UV radiation
  - Other wavelengths
- **Alternative charge management schemes**
  - Sharp pin discharge
  - No UV or combined with UV: Whatever is good for LIGO
  - Fluoride coating (CaF_2 etc.)
- **Collaboration with other LIGO efforts**
  - In-situ UV illumination for cavity ring down
  - In-situ UV illumination for *Q*-measurement
  - Etc…

Ongoing

The Experimental Setup

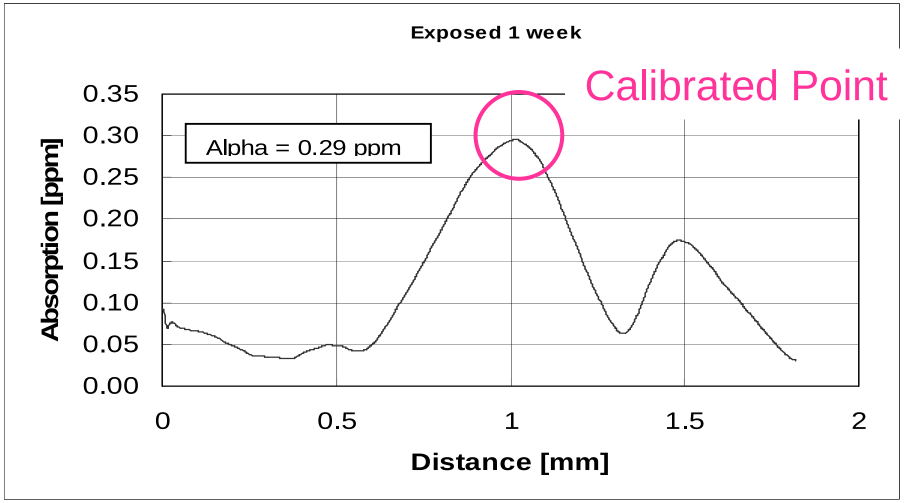
Vacuum Cart

Experimental Setup for UV Irradiation Tests

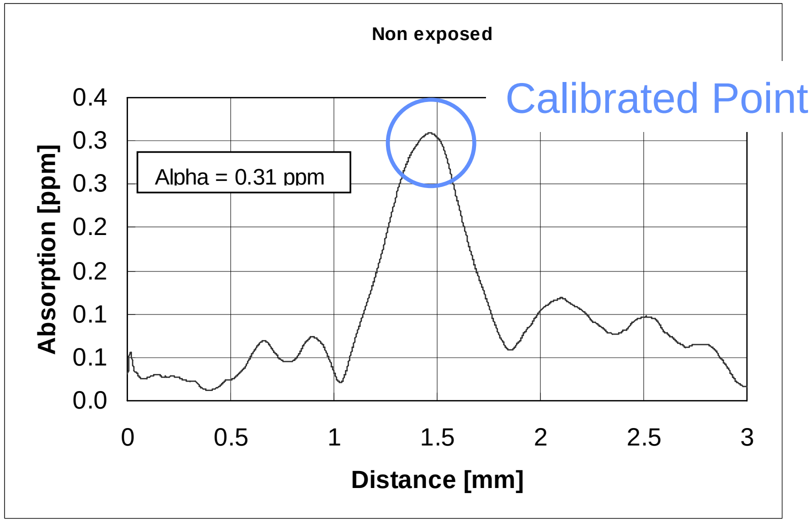


Initial LIGO Mirror Loss Measurements after One Week UV Irradiation

Left Side Mirror, Non Exposed

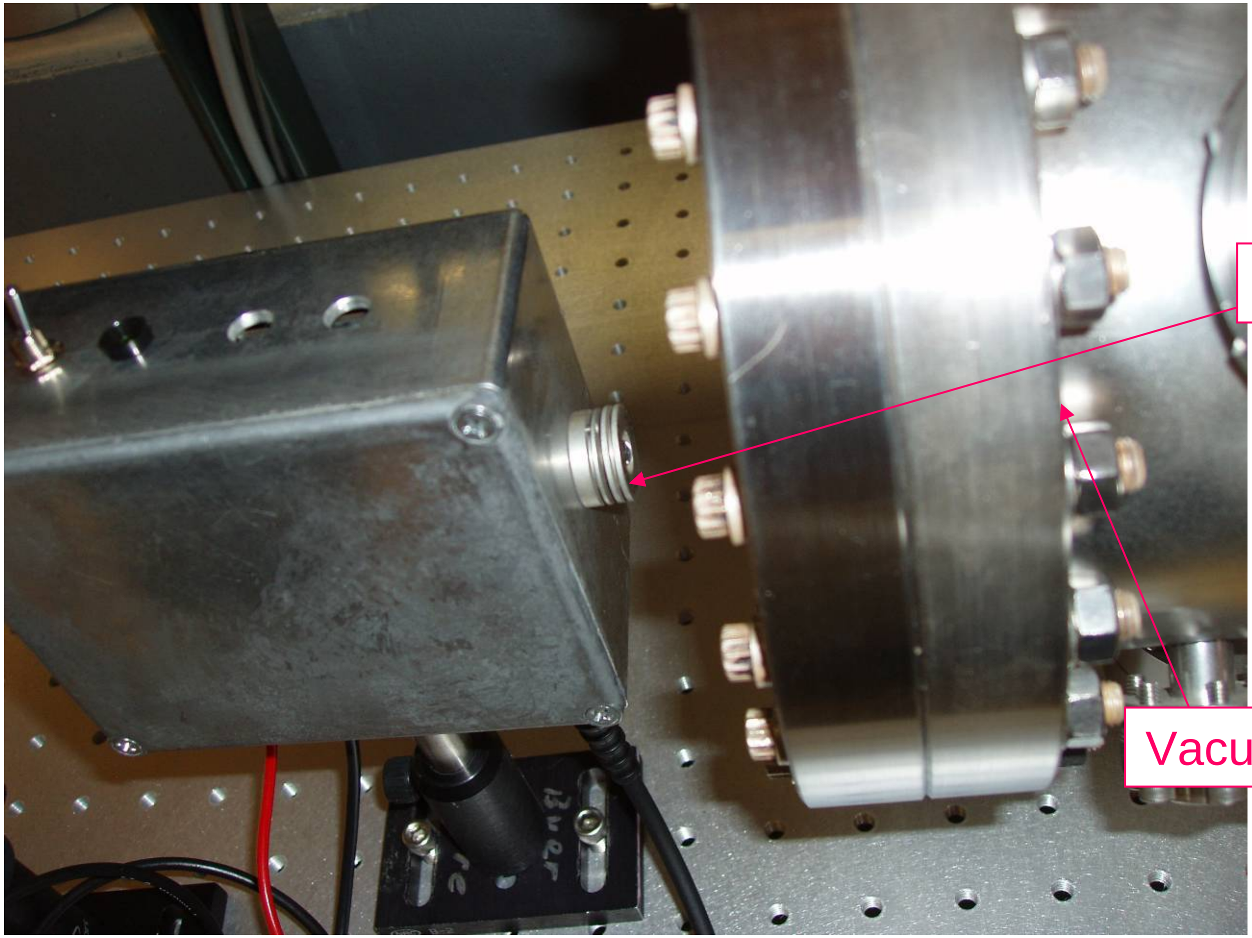


Right Side Mirror, Exposed

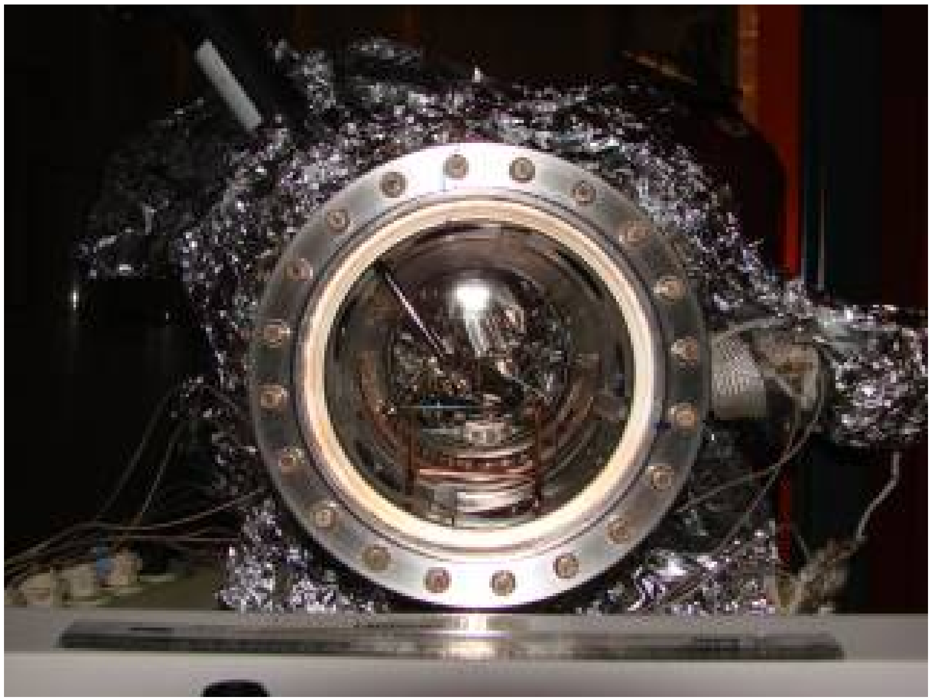


Loss Measurement Before and After UV Irradiation	Before [ppm]	After [ppm]	Change [ppm]
Non Irradiated Mirror	0.19	0.31	+0.12
Irradiated Mirror	0.23	0.29	+0.06

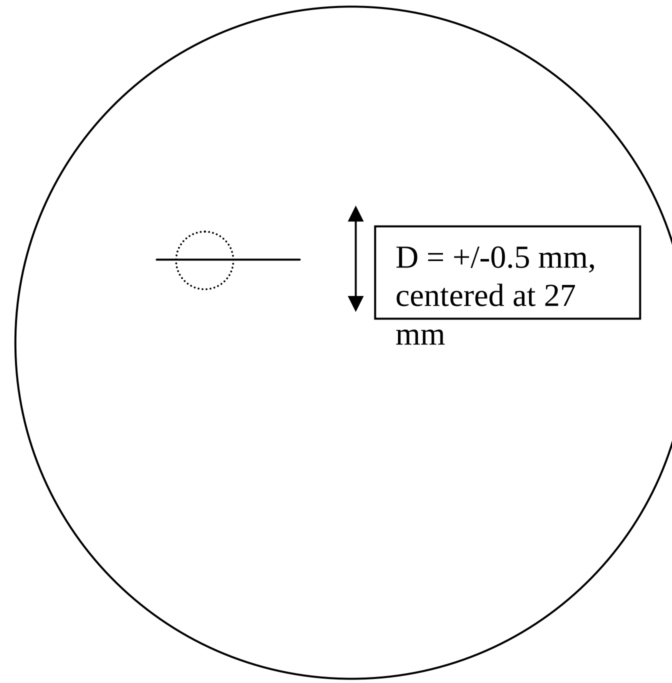
The Experimental Setup (II)



Measurement Positioning on the Adv. LIGO Mirror

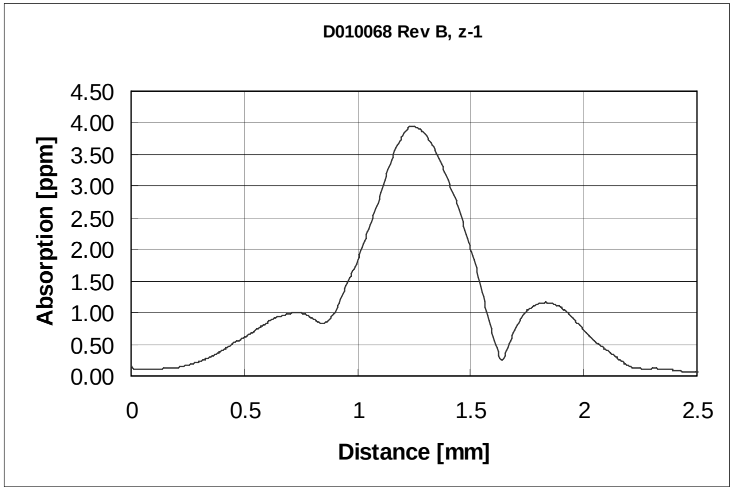


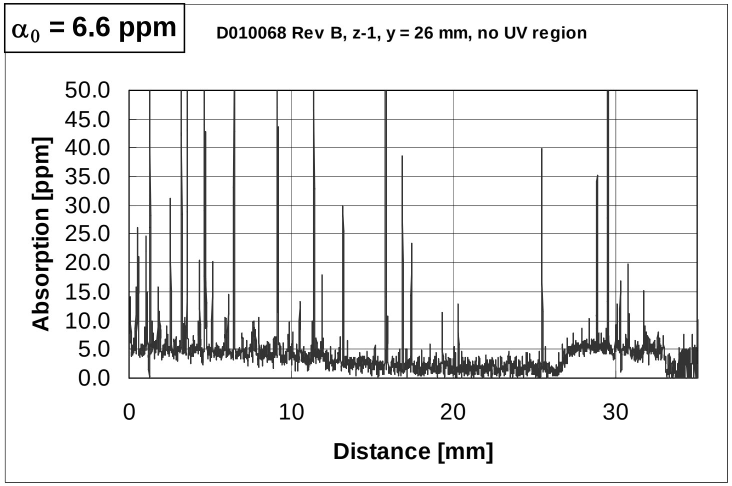
- Mirror Inside
- Mirror holder: Stainless steel wire



Exact position measurement was difficult

Adv. LIGO Laser Loss Measurement Before UV Illumination



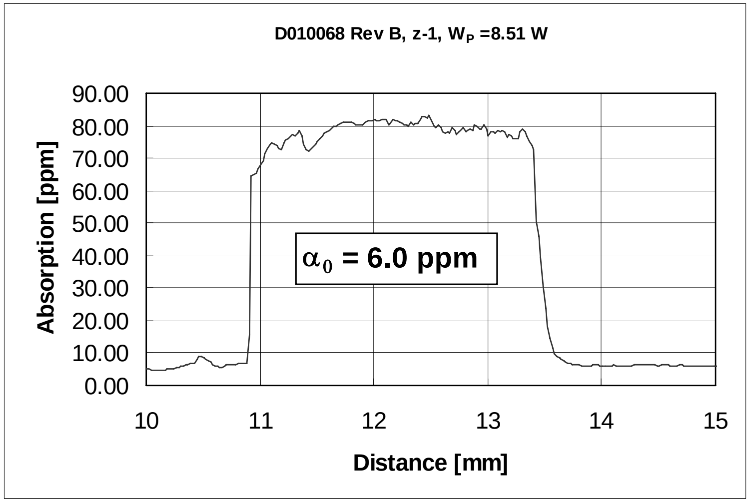


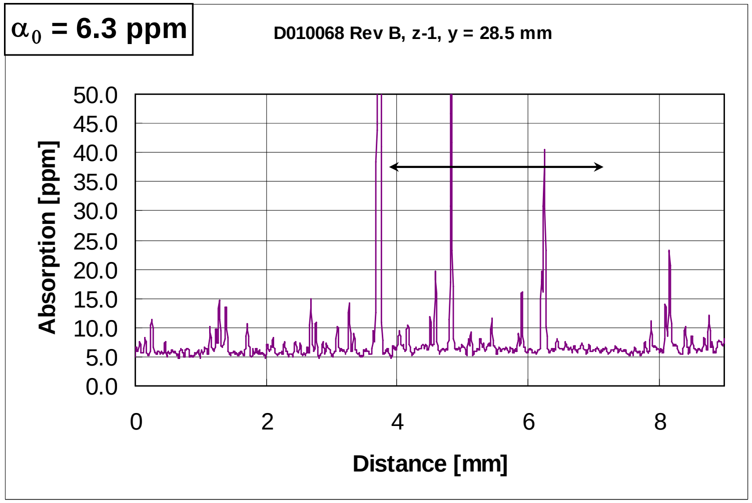
Loss in normal region: 4~6 ppm
(Only peak value is calibrated)

Long scan: 1 ~ >50 ppm
Base line hump
Large number of scatters

Advanced LIGO Mirror Loss Measurement

Laser Damage in an Area, But Uncertain if it is the UV Illuminated Area





- Laser power ~9.7 W, Spot size 75 μm
- Laser intensity ~2-4 kW/mm^2
- Laser burn over 2 mm length
  - Uncertain if it is UV illuminated area
  - Laser power is too high
  - The sample has defects packed in the region
  - Calibration needs to be checked: the non-transmitted region should have higher losses

- Scan with lowered laser power ~1W, no laser burn is observed
- Shows high loss points across the region
- Similar defect distribution observed for non-illuminated region
  - The point defects may trigger laser burn

Laser loss measurement needs improvement

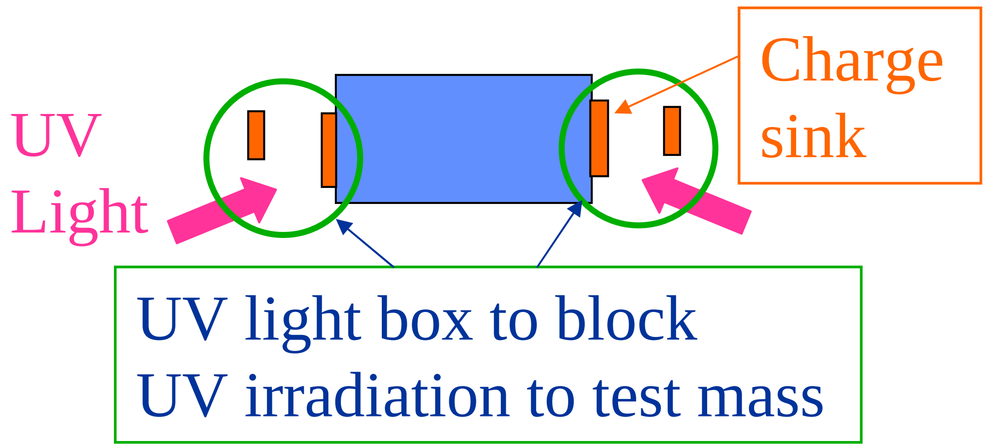
What We Learned So Far

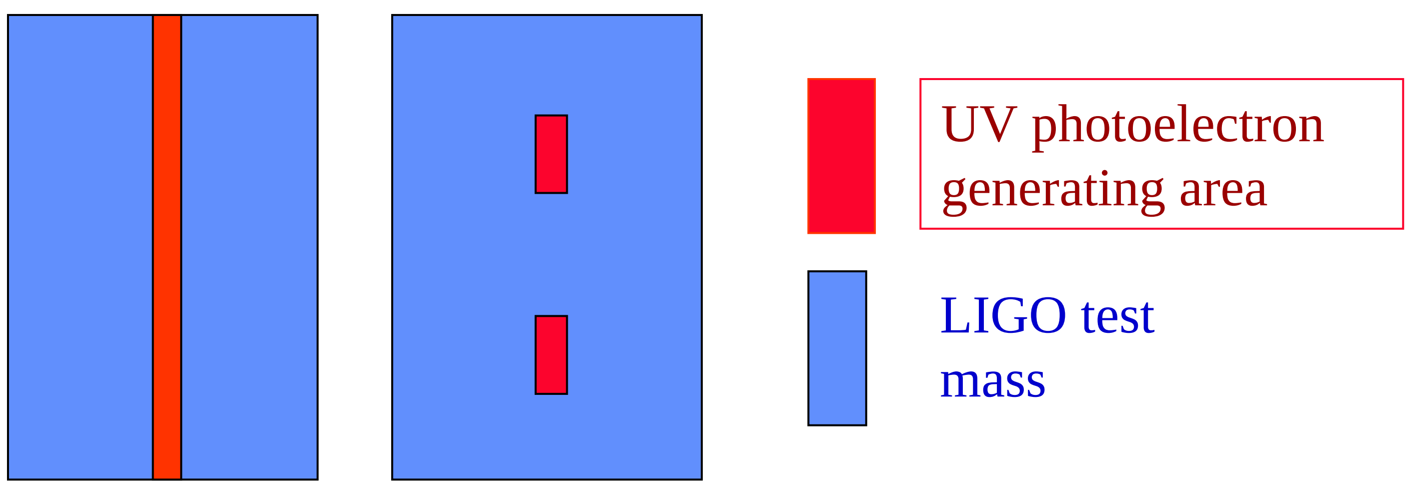
- **Deep UV irradiation effects**
  - Fused silica substrate so far so good
  - Inconclusive on LMA Adv. LIGO coating
  - GEO optics were fine with UV irradiation by an 800mW Mercury lamp
  - Prudent recommendation: Do not use high flux UV on Adv. LIGO mirrors
  - Devise indirect UV illumination scheme
- **High intensity, pulsed laser beam at 355 nm wavelength will:**
  - Damage oxide coatings in vacuum
  - Not damage oxide coatings in oxygen rich environment
  - Damage threshold is being investigated
- **Damage threshold investigations at different wavelengths are of long term interest to Adv. LIGO**
  - Deep UV (~254 nm, good for Au photoelectric effect)
  - UV, but not deep UV (photoelectric effect wavelength for other metals)

Conductive Coating

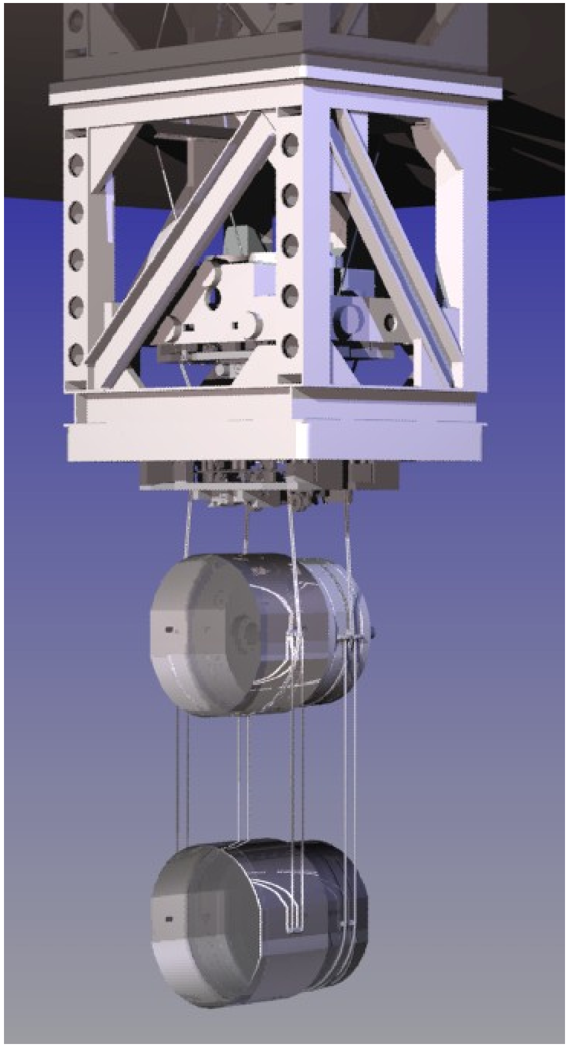
- **CaF_2 Fluoride Coating**
  - Often used in UV optics for lithography at 193 nm, high UV damage threshold
  - Electrically conductive
  - Reasonable Q
  - Thin layer CaF_2 may help charge management
- **Gold coating**
  - Help both thermal and charge control
  - 100 nm (needed by thermal control) Au coating will be opaque to UV, eliminating UV damage problem
- **Other coating**
  - Aluminum coating (work function 4.2 eV vs. 5.3 eV for Au) allows softer UV

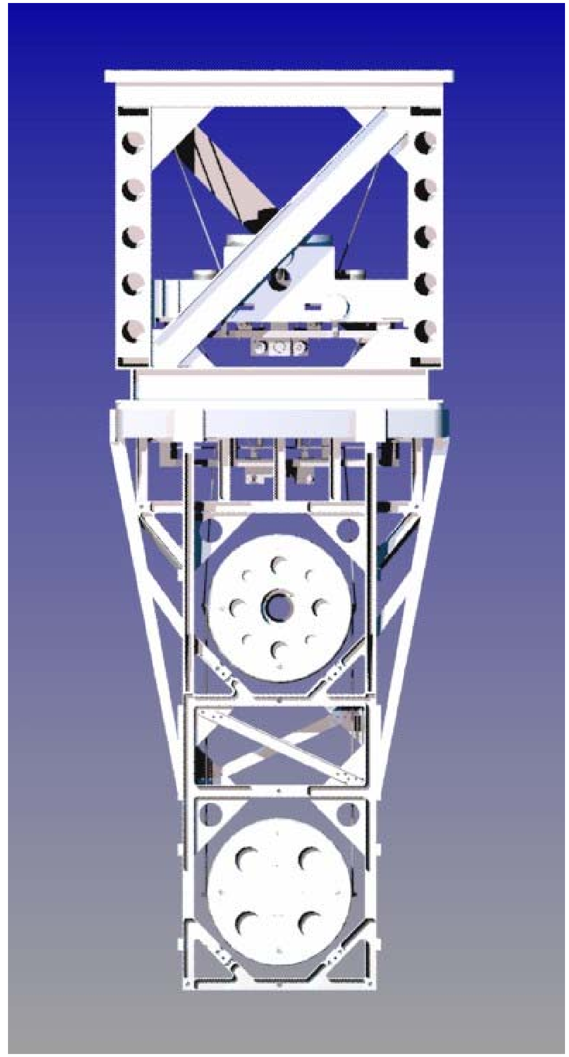
Local Conductive Coating Pattern May Help





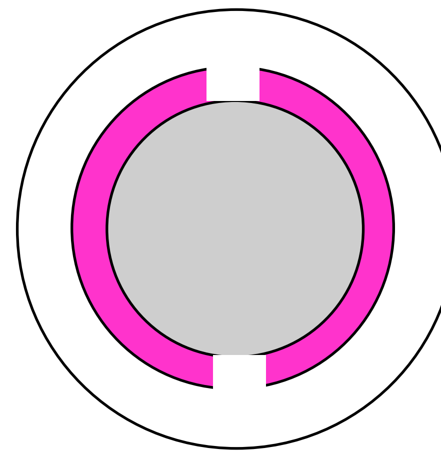
Possible System Configuration for Adv. LIGO





Many Options to fit the charge management system into Adv. LIGO

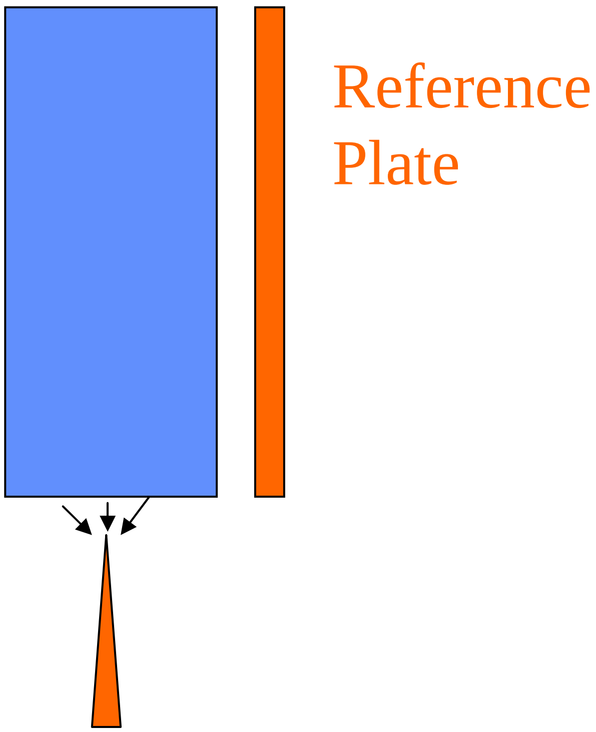
"Charge Management Ring" fits into the suspension assembly?



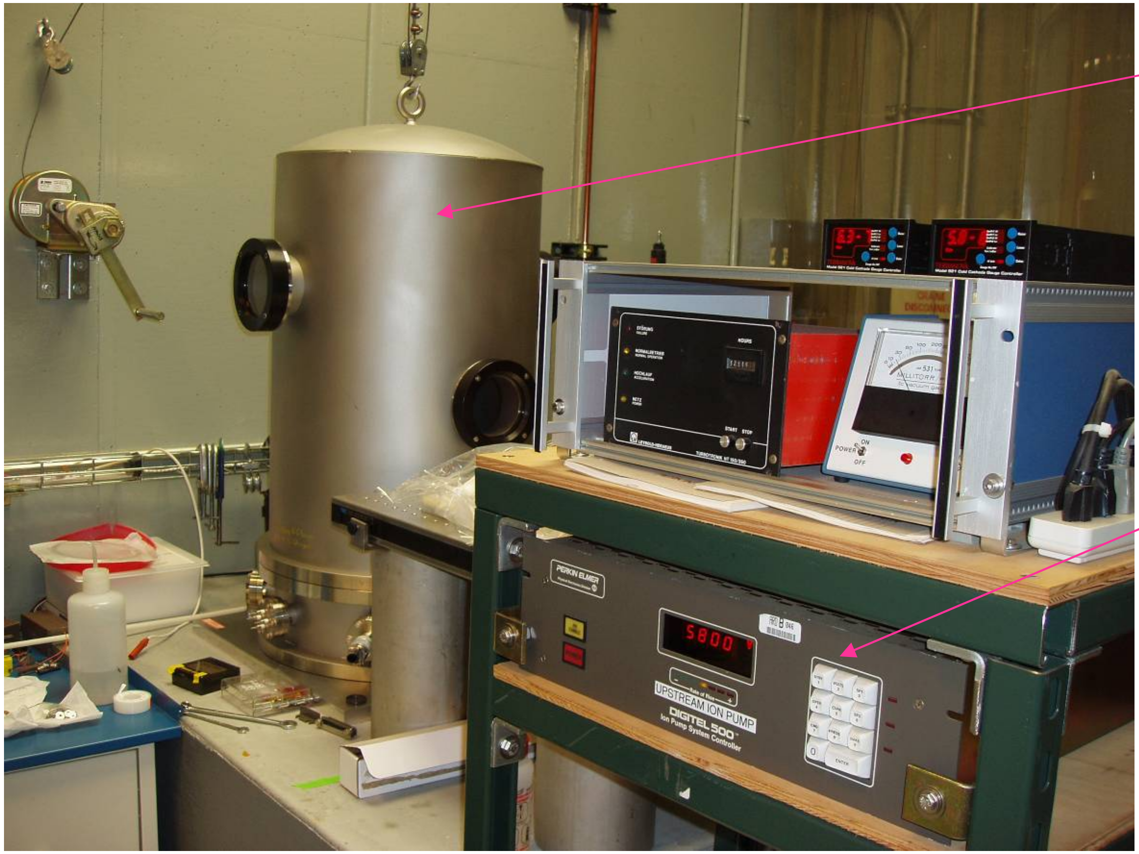
Will work with Rich, Gregg on LASTI related design and deployment

Add-On Schemes: Sharp Pin Discharge

- **Field concentration around a sharp pin**
- **Discharge at the sharp tip**
- **Good for high voltage objects like that in LIGO test mass**
- **Bidirectional charge/discharge possible**



Two Chambers for LIGO Charging Mitigation Work



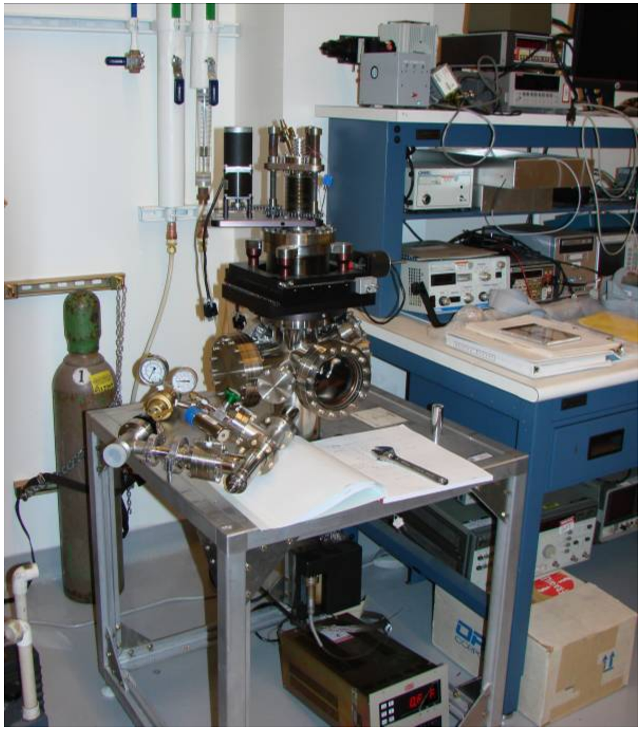
Mid Vac Chamber Probe and Charge Management Experiment

High Vac System UV Irradiation Effect Assessment

Stanford LISA/MGRS Team Moved to New Labs

New Labs, New Capabilities at Stanford

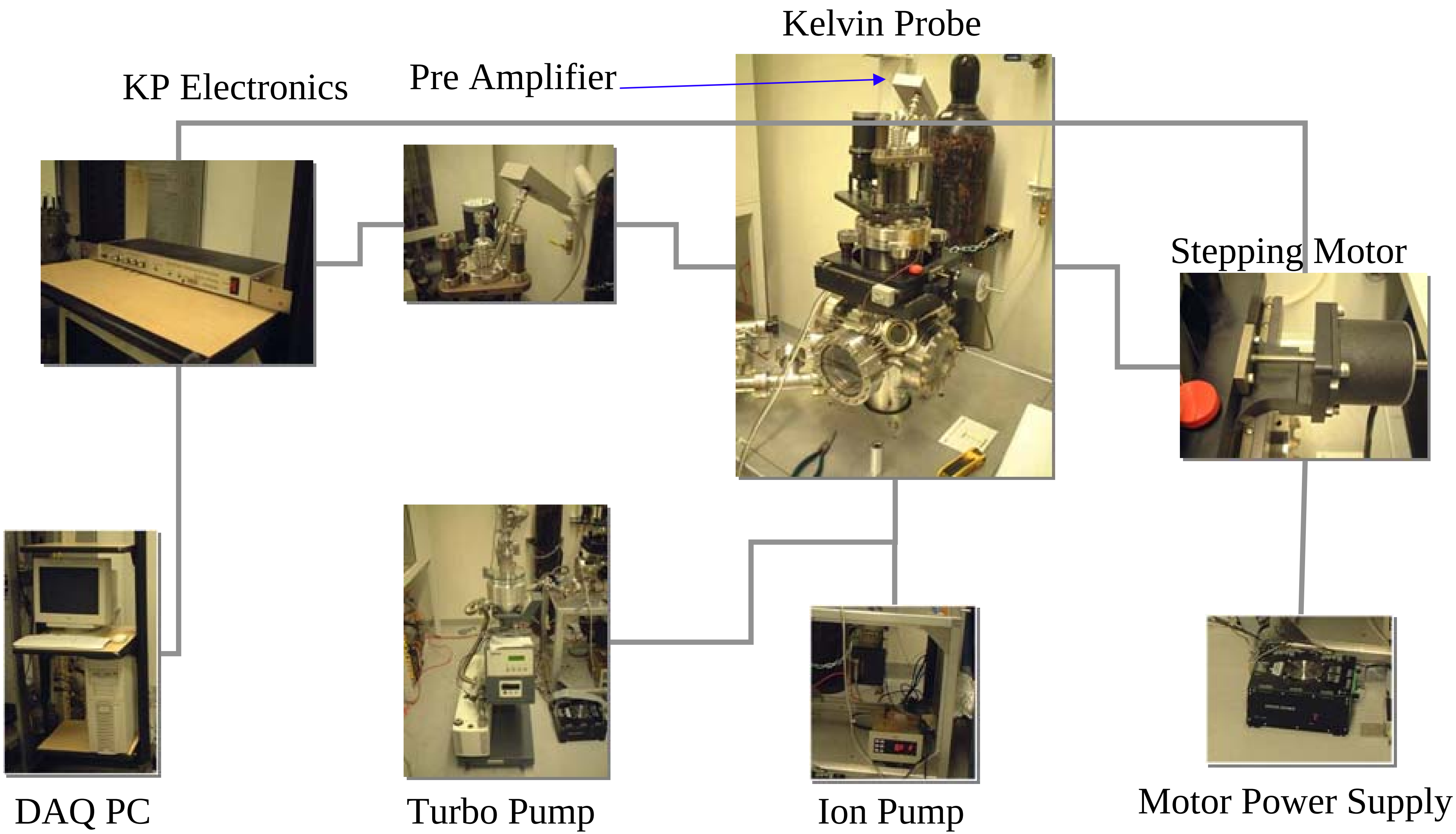
New optics labs, housing total 6 optics tables, enables multiple optics experiments



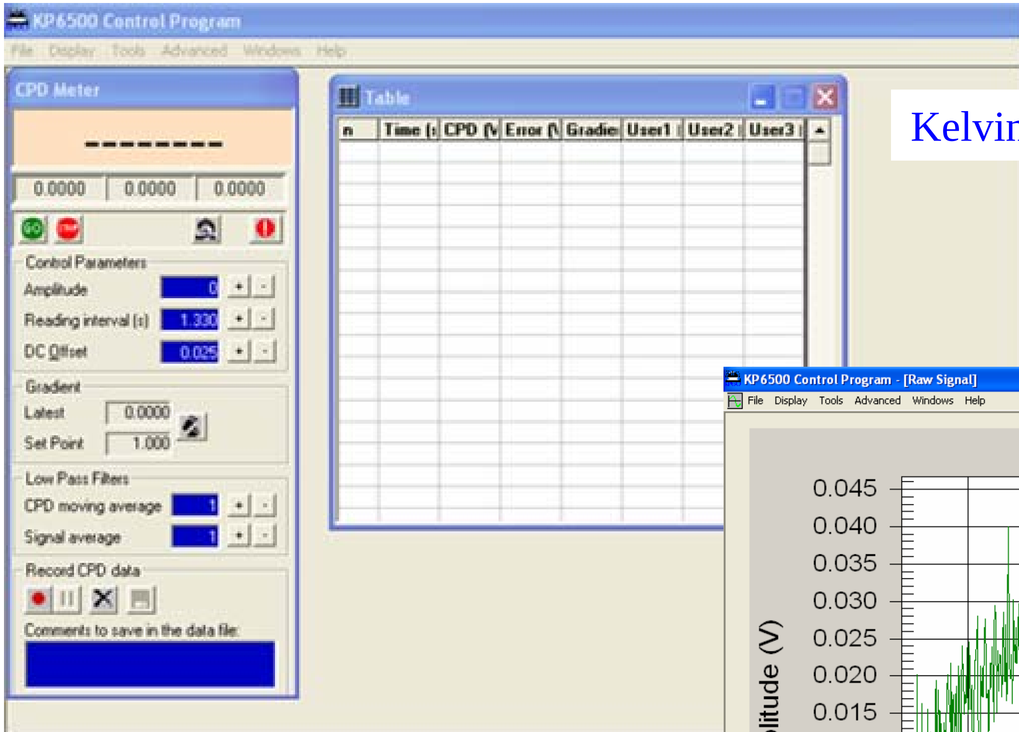
Kelvin probe, on loan from GSFC, for GRS surface effects studies

Stanford applied patent for UV LED based AC charge management technology

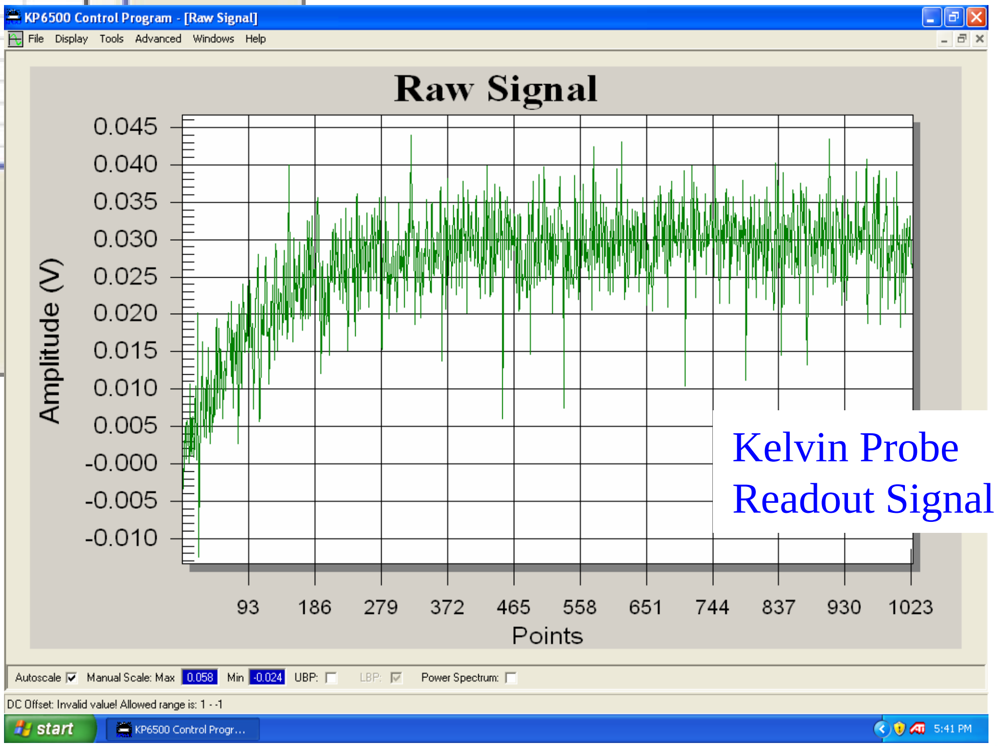
Kelvin Probe Setup @ Stanford Coming Along



Kelvin Probe in Operation Soon



Kelvin Probe Operation Software



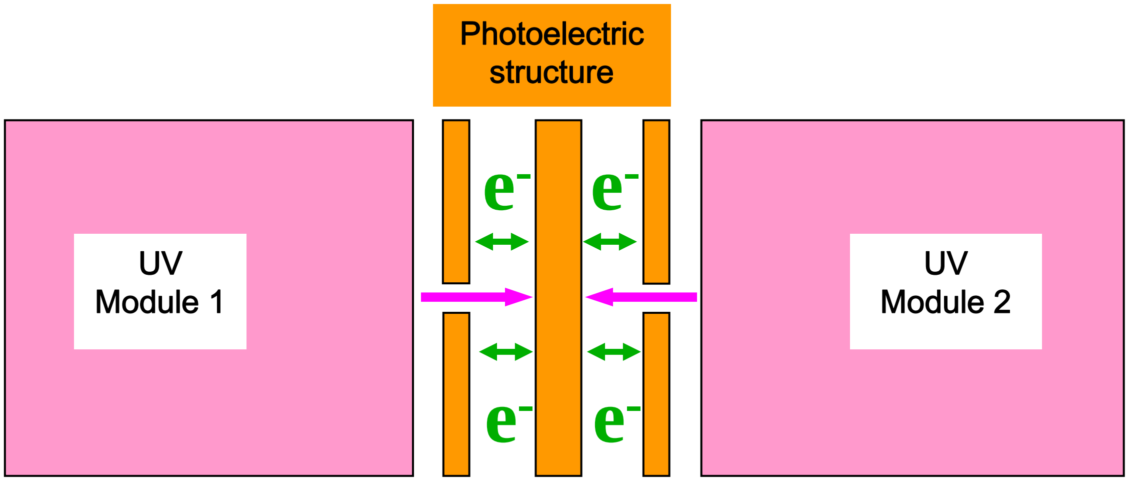
Kelvin Probe Readout Signal

Small Satellites Provide
New Science and Technology Opportunities

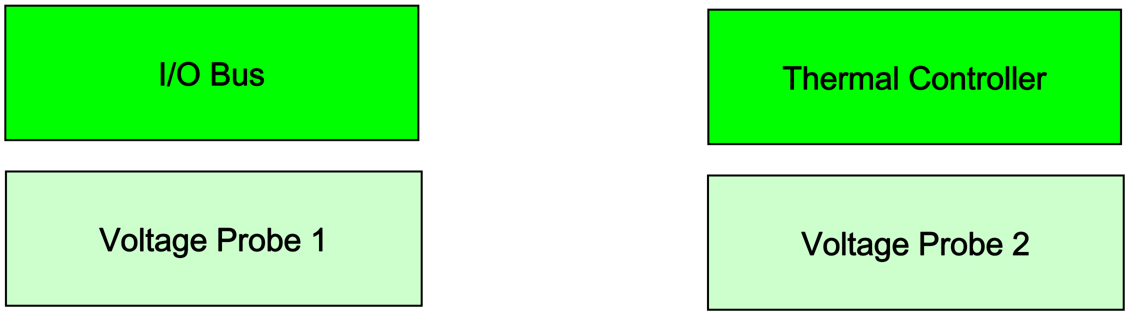
- **Small Satellites**
  - True space flights
  - Economical access
  - Ride along on main flights

- **Payload requirements**
  - Lightweight
  - Low power
  - UV LED Charge management System will fit and operate

UV Satellite Payload Configuration



Upper Deck Top View



Lower Deck Top View

Conclusions

- UV LED AC charge management concept and demonstration
- UV LED charge management system is under active development
- UV LED lifetime exceeds 8,200 hours
- LISA and LIGO specific techniques
- UV irradiations test result for more testing
- LIGO work will be under OWG coordination, participating a range of collaborations