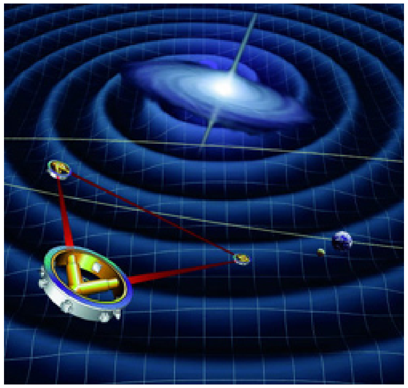
Effects of Ultraviolet Irradiation on LIGO Mirror Coating



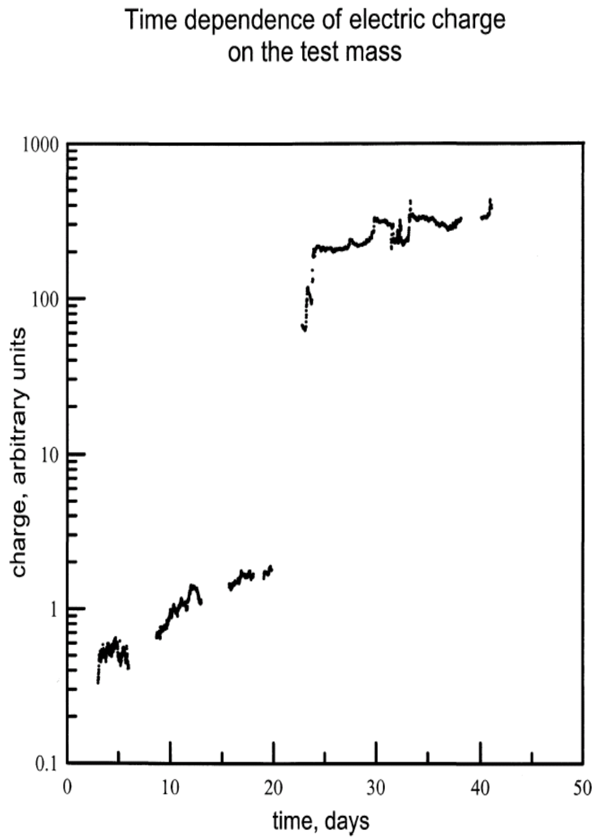
Ke-Xun Sun, Nick Leindecker, Ashot Markosyan,
Sasha Buchman, Roger Route, Marty Fejer, Robert Byer,
Helena Armandula, Dennis Ugolini, Gregg Harry

Workshop on Optical Coatings in Precision Measurements

California Institute of Technology, Pasadena CA

March 20-21, 2008

LISA, LIGO and Adv LIGO Charging Problems



Moscow Data

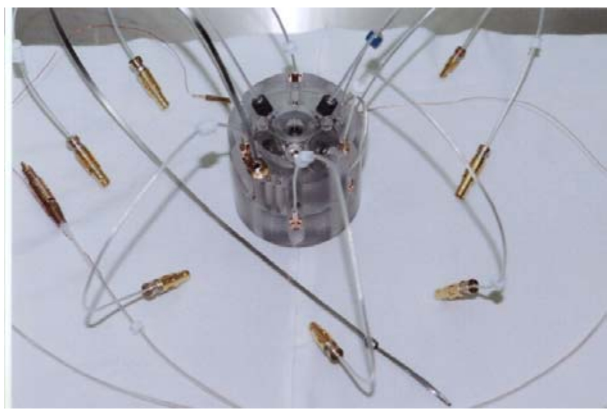
Charging	LISA	LIGO	Adv LIGO
Mechanism	Space Weather Caging Separation	Cosmic Ray Triboelectric	Cosmic Ray Triboelectric
Charging Rate	10^{-11} C/day (max)	10^{-7} C/day	10^{-6} C/day
Test Mass	2 kg	10 kg	40 kg
Displacement Sensitivity	10^{-11} m	10^{-18} m	10^{-20} m
Frequency	0.03 mHz~1 Hz (1 mHz)	10Hz ~ 1kHz (100Hz)	30~2 kHz (30Hz)
Figure of Problem $(C/M\omega^2)/\Delta x$	13	25	6.8×10^4

Advanced LIGO may see more charging problems instead of less

Charge Management In Precision Experiments

GP-B charge management

- Critical to GP-B mission success
  - > Initial gyro lifting-off
  - > Continuous charge management during science measurement



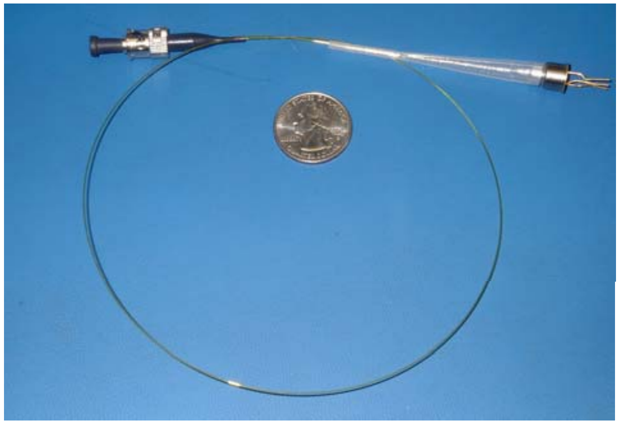
LIGO UV charge management budget

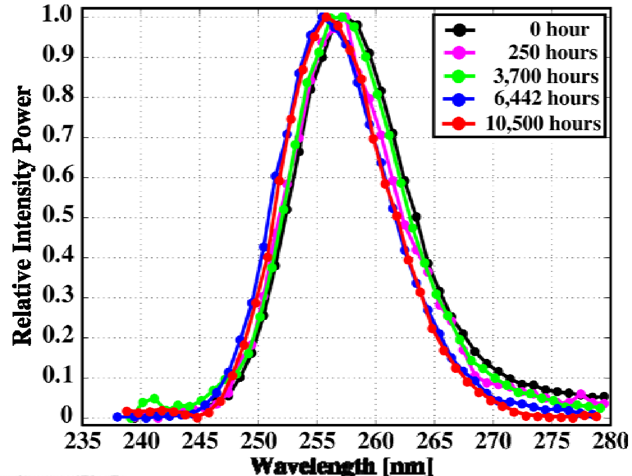
- $Q_c \sim 10^{-7}$ C/m^2 commonly cited
- Charging rate $Q_c \sim 10^{-7}$C/day
- $N_e \sim 10^{12}$ electrons/day
- Photoelectric "Q. E.": $\eta \sim 10^{-6}$
- UV photons required: $N = 10^{17}$
- $P_{UV} = Nhc/\lambda\, T = 8.9\text{x}10^{-6}$ W
- $P_{UV} \sim 10\ \mu$W (average power over a day)
- Dynamic Range ~ 100

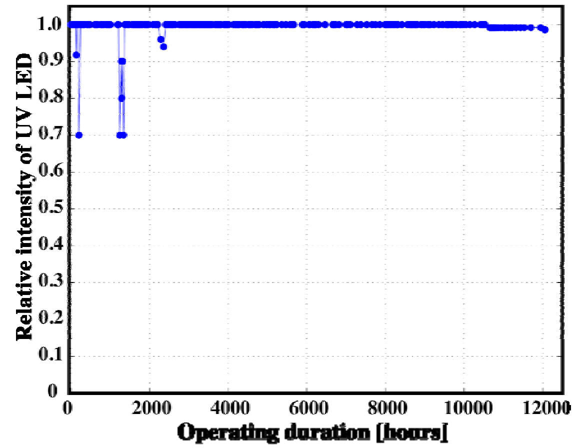
  $P_{UV} \sim 1$ mW (Peak power)

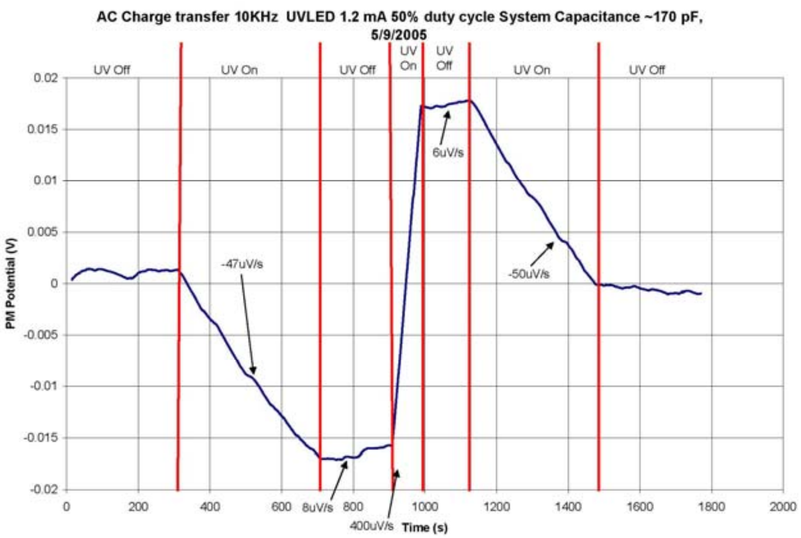
Stanford experiences in charge management: GP-B, ST7, LISA (MGRS)

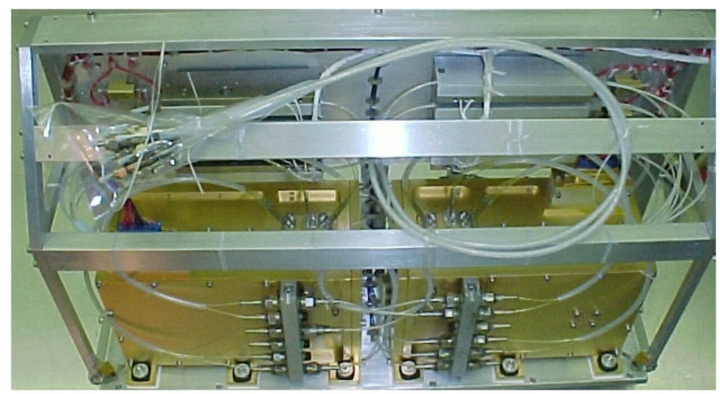
UV Light Source UV LED & Gas Lamps







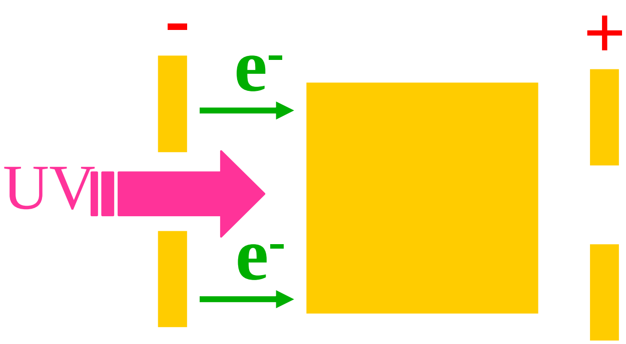


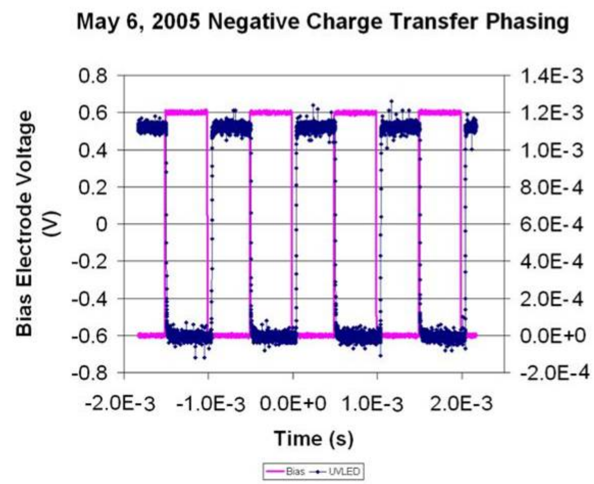


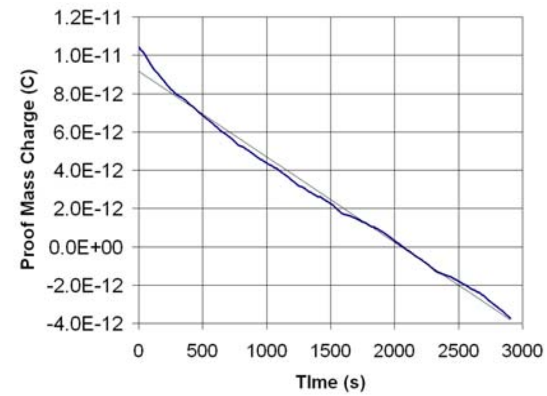
Ke-Xun Sun, Brett Allard, Scott Williams, Sasha Buchman, and Robert. L. Byer, “LED Deep UV Source for Charge Management for Gravitational Reference Sensors,” presented at Amaldi 6 Conferences on Gravitational Waves, June 2005, Okinawa, Japan, Class. Quantum Grav. **23** (2006) S141–S150

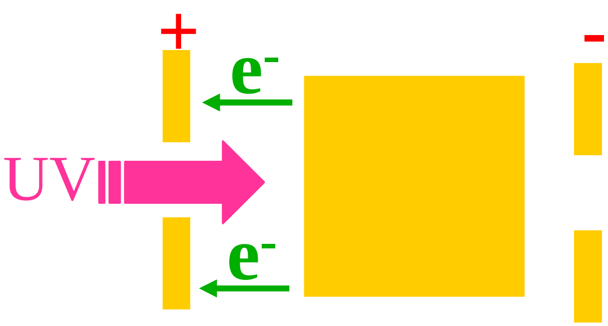
AC Charge Management

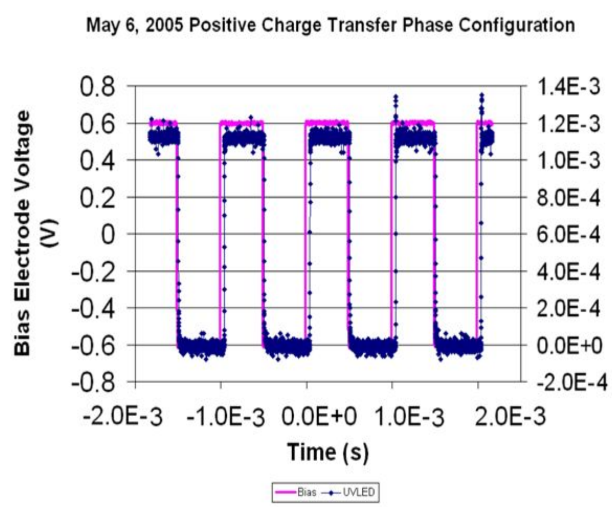
UV LED and bias voltage modulated at 1 kHz

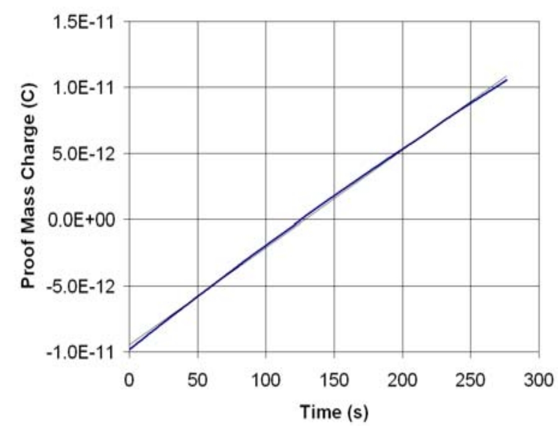






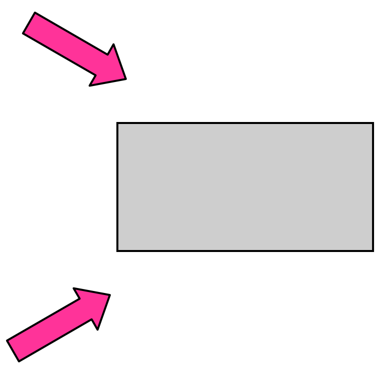






UV Illumination Configurations

- **Direct illumination**
  - UV mercury lamp is routinely used for attachment removal
  - UV LED has sufficient power for cw direct illumination
  - Works for removing charges
    - Metal: GPB, ST7, LISA
    - Dielectric: Glasgow, Trinity, GEO, Moscow
  - UV irradiation may cause problem to coating

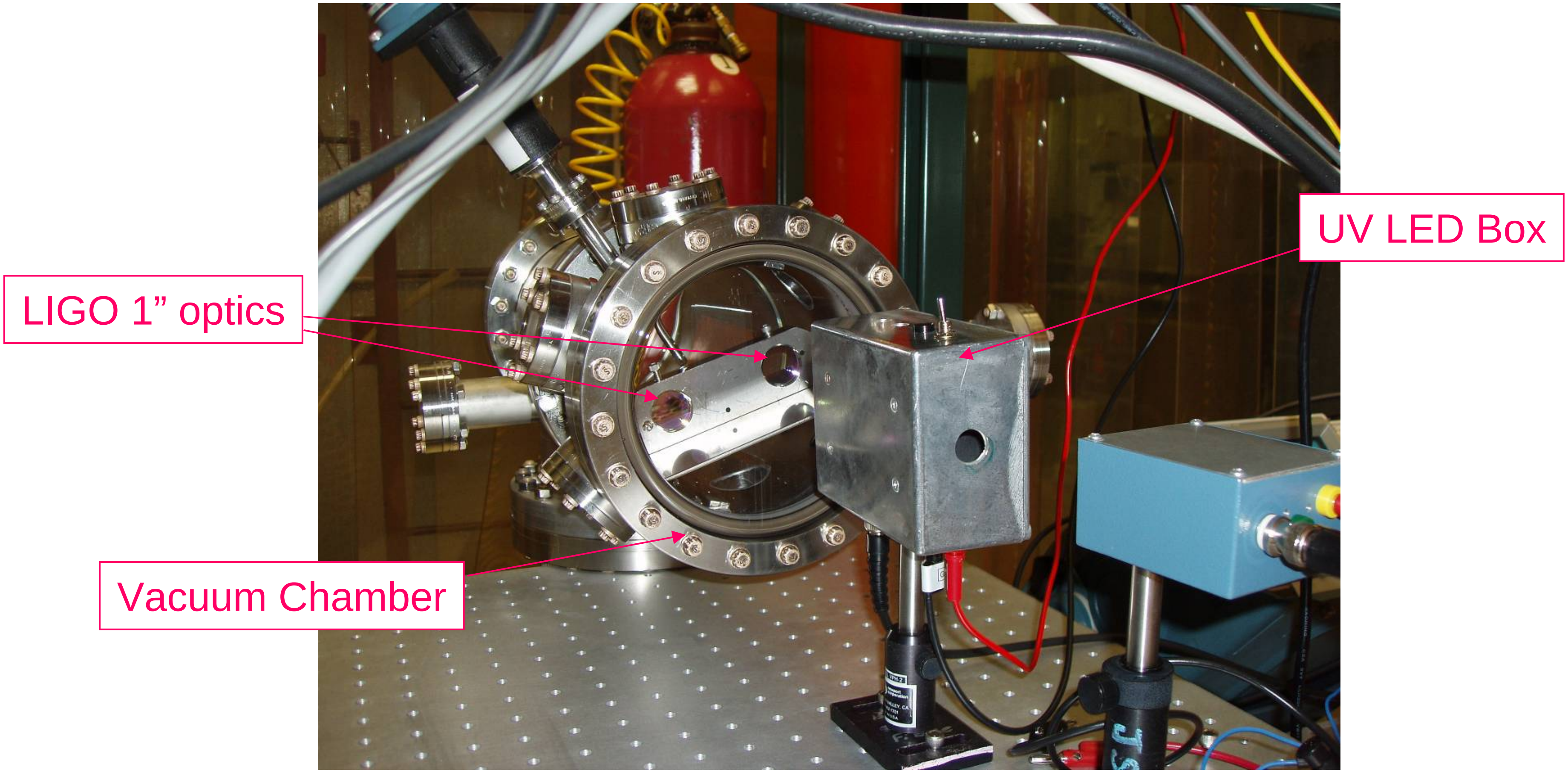


- **Indirect illumination**
  - Au coating on non-critical portions of test mass and suspension structure (P. Willem: 0.1 μm Au coating on barrel, opaque to UV)
  - Photoelectric effect on Au surface has been utilized in GP-B, ST-7, LISA
  - Establish electric field to herd the charges to Au coating
  - UV photoelectric effect continues to remove Charges
  - Higher throughput in charge control
  - No UV illumination on dielectric

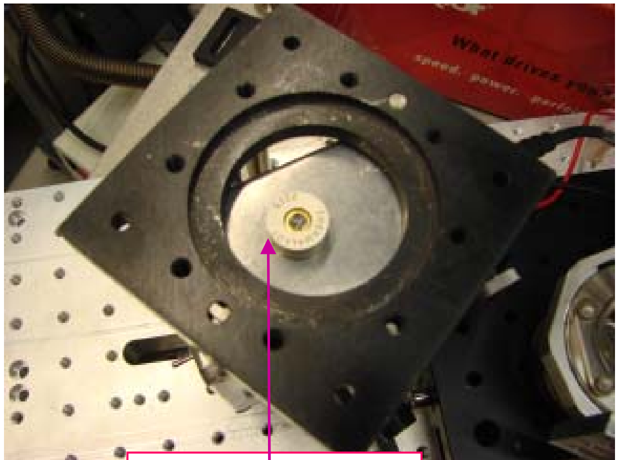
UV Effect Tests

- **Three samples irradiated with UV light**
  - REO #2: Ta_2O_3/SiO2 alternative layers
  - Adv LIGO (LMA: 14 TaO:Ta_2O_3/SiO2)
  - REO #1: Ta2O3/SiO2 alternative layers
    - > UV LED
    - > Xeon Lamp
    - > Heat/Cool cycles
- **Absorption loss measured with PCI**
  - Alternate measurement with UV exposure
  - During measurement the samples are controlled under vacuum

The Initial UV Illumination Geometry

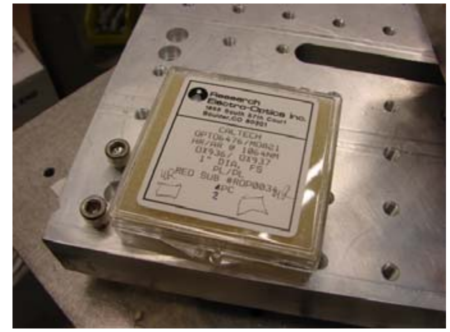


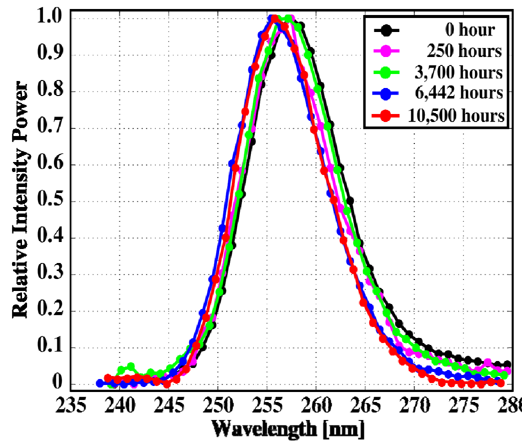
More Localized UV Exposure Geometry

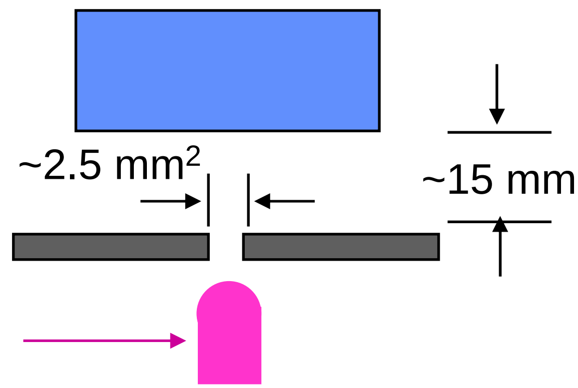


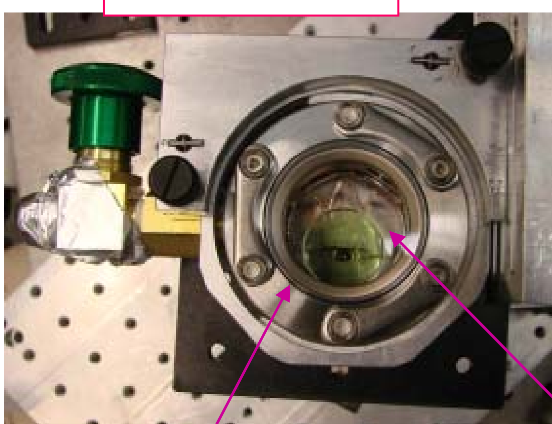
UV LED with a Ball Lens

Initial LIGO recipe coated by REO (2 pcs)
HR/AR OX936/OX937
Ta_2O_5/SiO_2









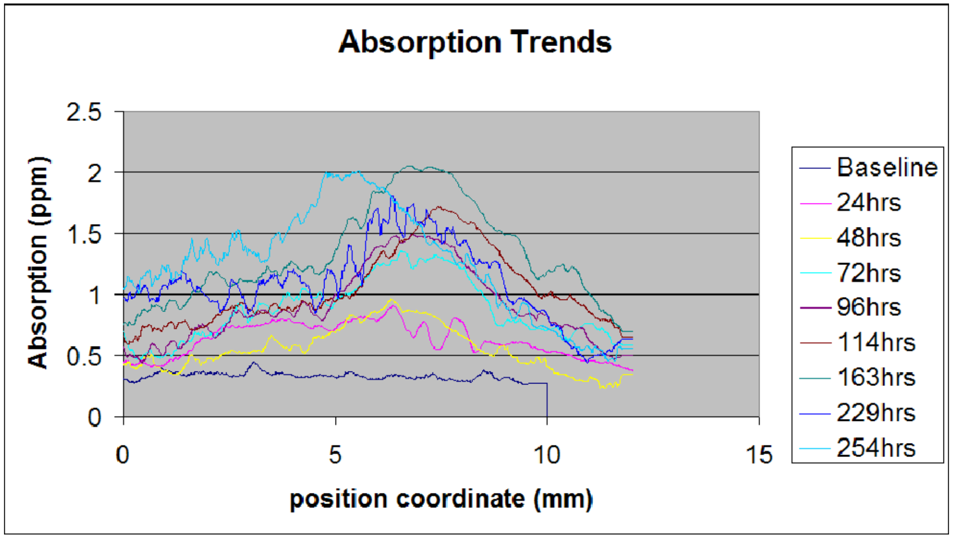
Small aperture localizes irradiation

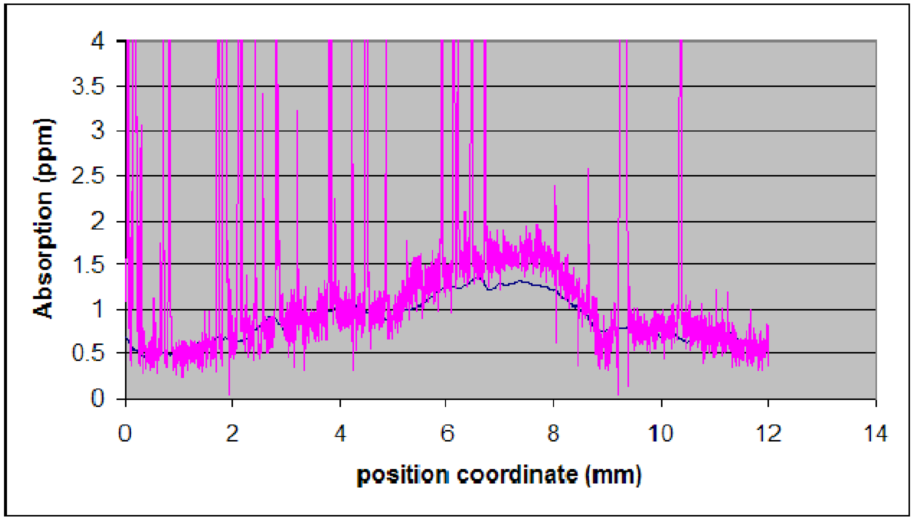
Fused silica window with 93% UV Transmission

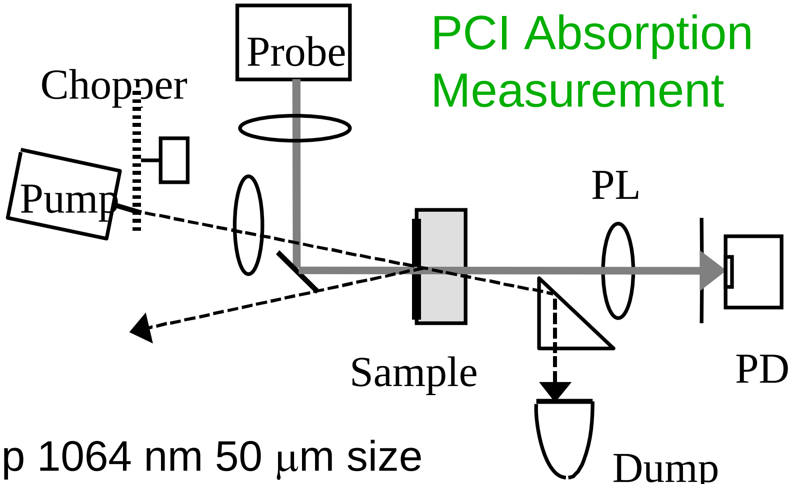
Irradiation by UV LED at 255 nm
Operated with average power 3.3 μW
Irradiation intensity ~15 $\mu W/cm^2$
Irradiation for 254 hours
Total UV energy deposition ~16 J/cm^2
(> $1 J/cm^2$ recommended by Dennis Ugolini)

UV Exposure and Loss Measurement

- Alternate UV exposure and loss measurement
- UV exposure was conducted in vacuum 10^{-7} tor
- UV effect after in air exposure may be more recoverable
- Total UV exposure 16 J/cm^2 (254 hours)
- Equivalent time span for LIGO charge management: 4~40 months



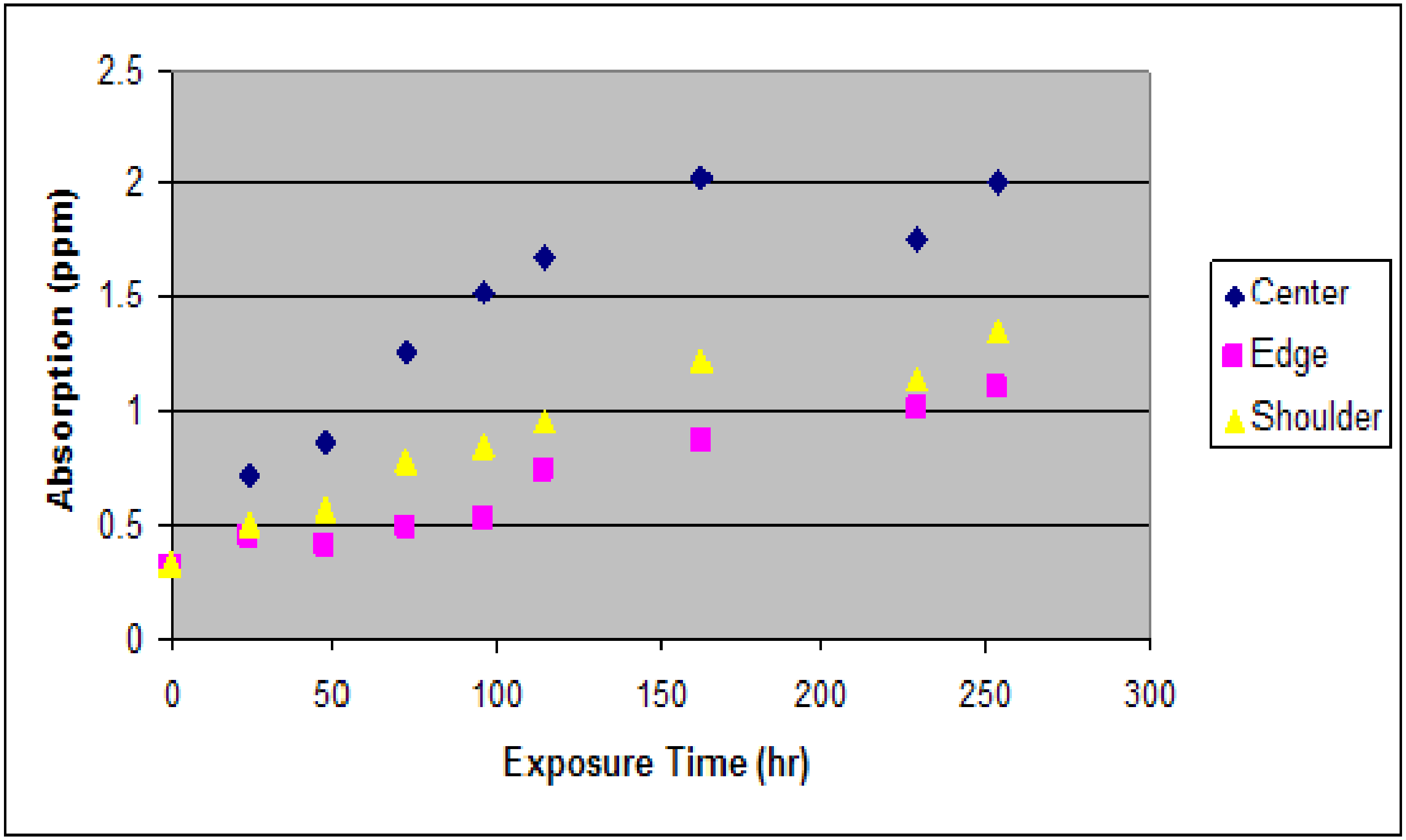




PCI Absorption Measurement

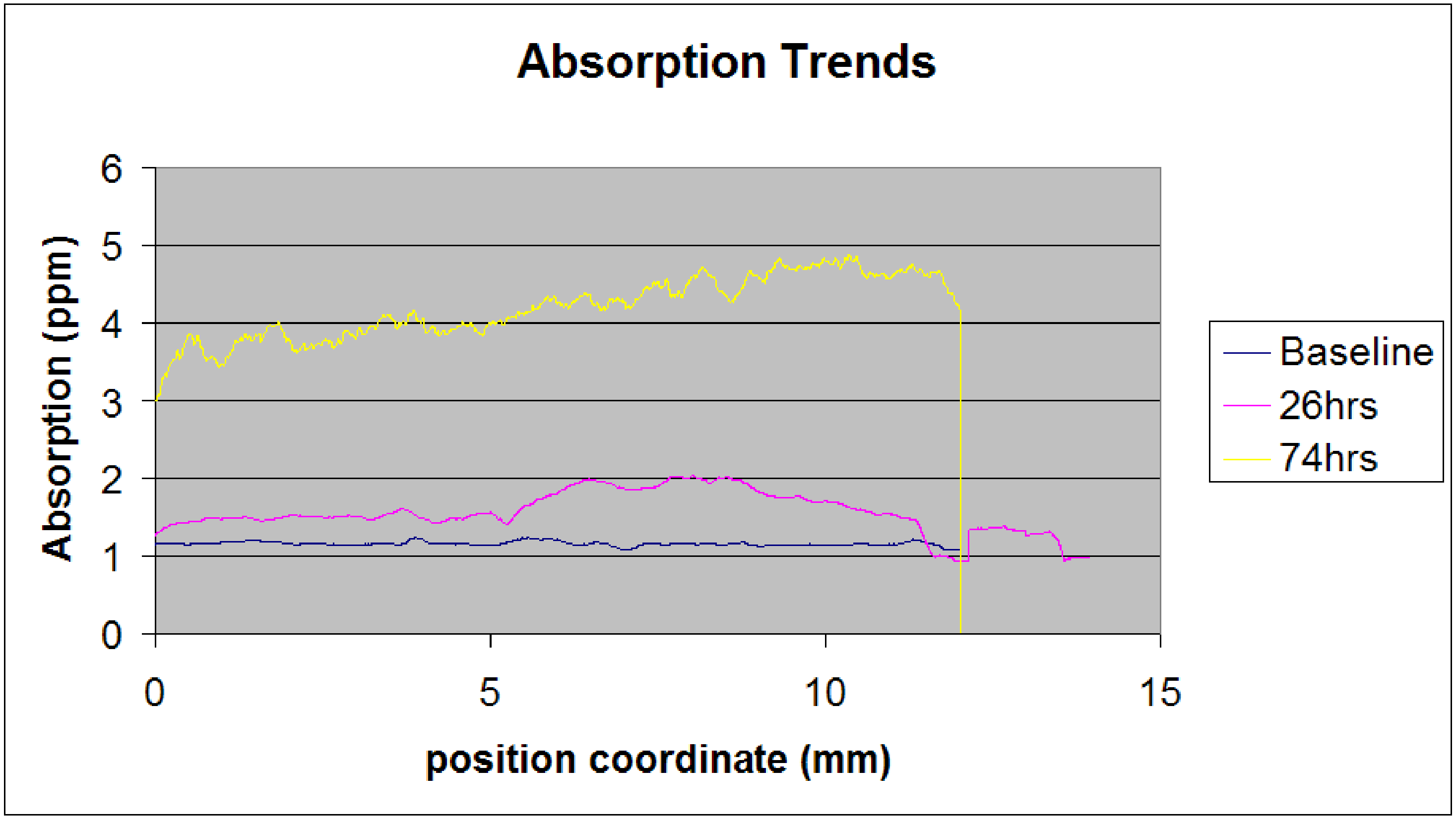
Pump 1064 nm 50 μm size
Power density 460 kW/cm^2

UV Effect on Initial LIGO Sample (REO #2)

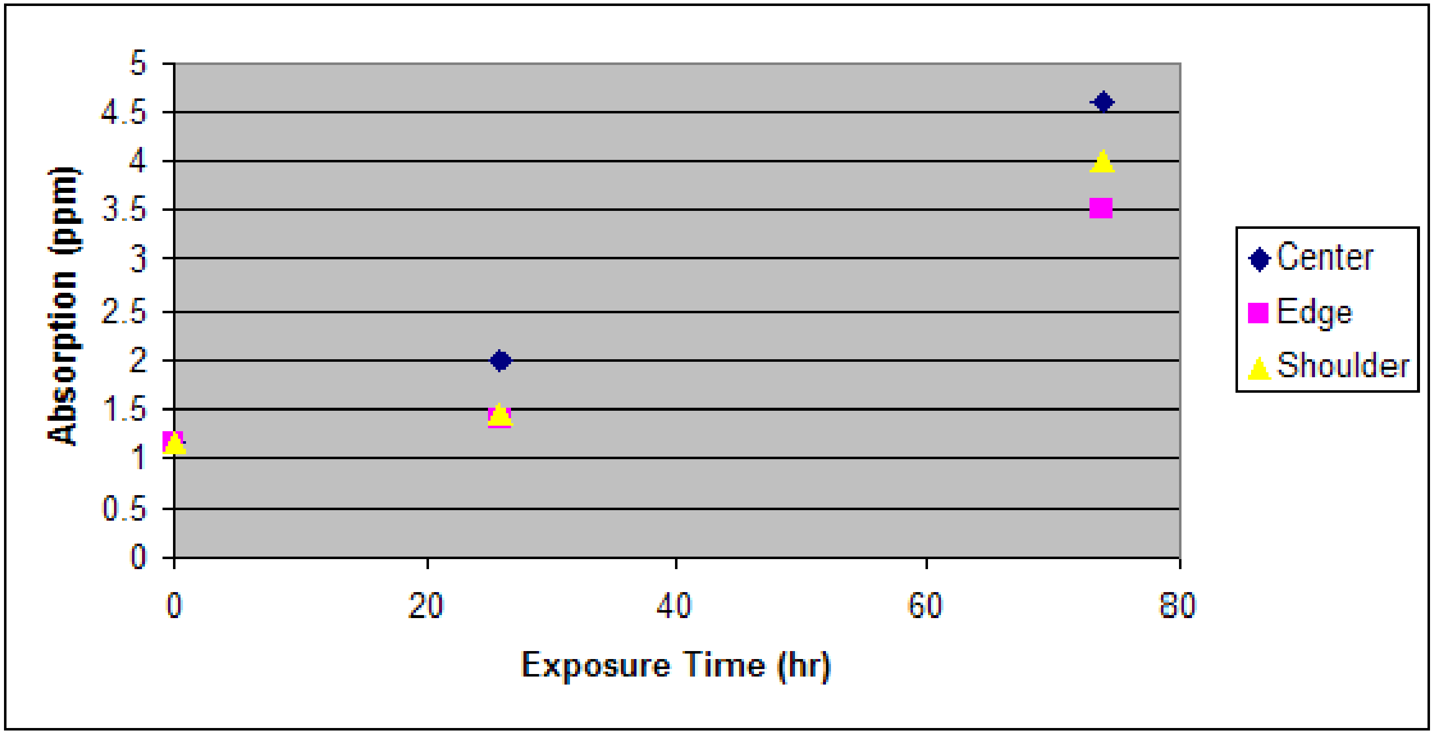


UV Irradiation: Adv LIGO Sample: Spatial Profile

TaO:Ta_2O_3/SiO_2 30 Layers

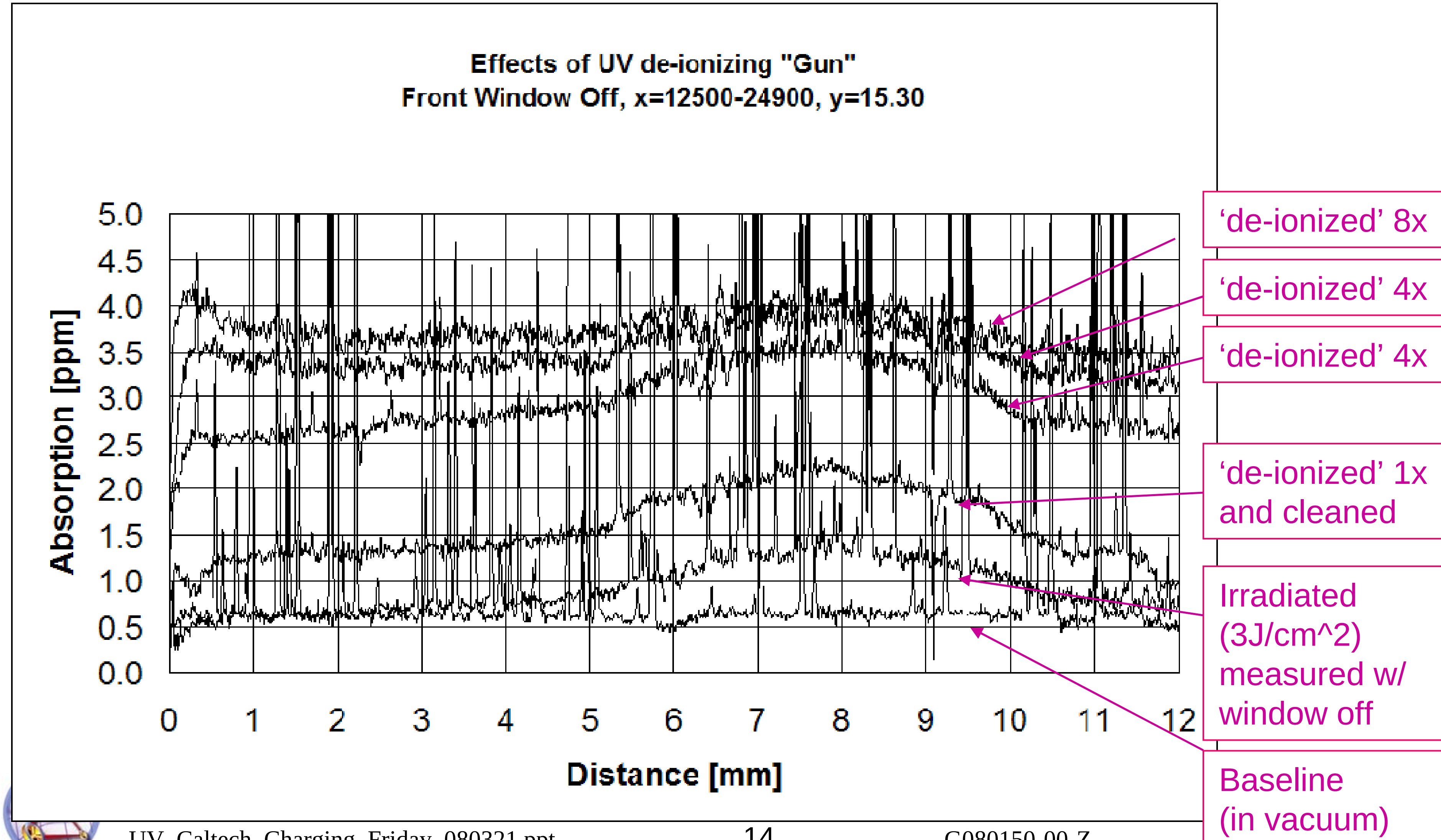


UV Irradiation: Adv LIGO Sample: Temparo Profile

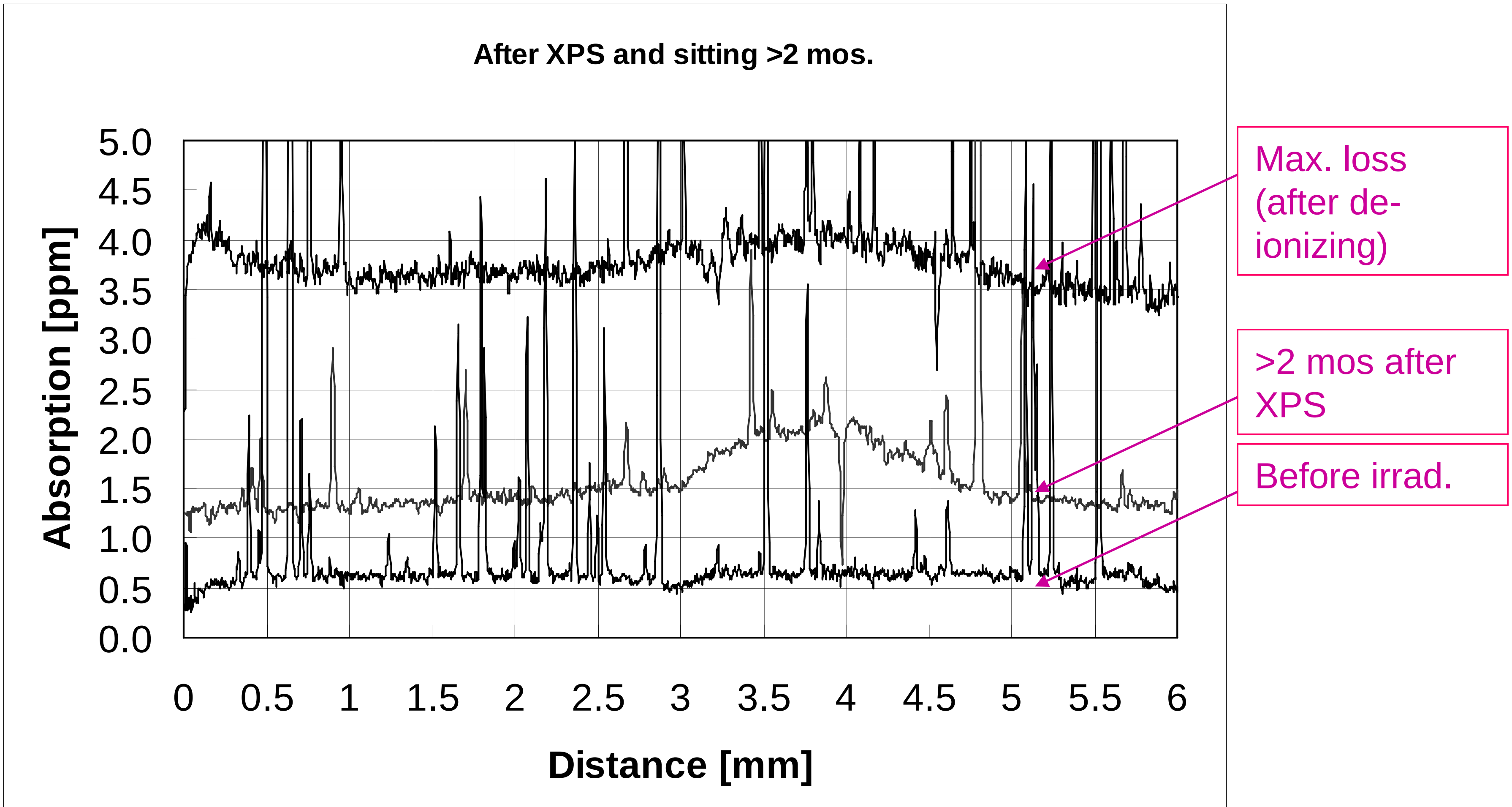


UV 'De-ionizer' as a Cleanser is Problematic

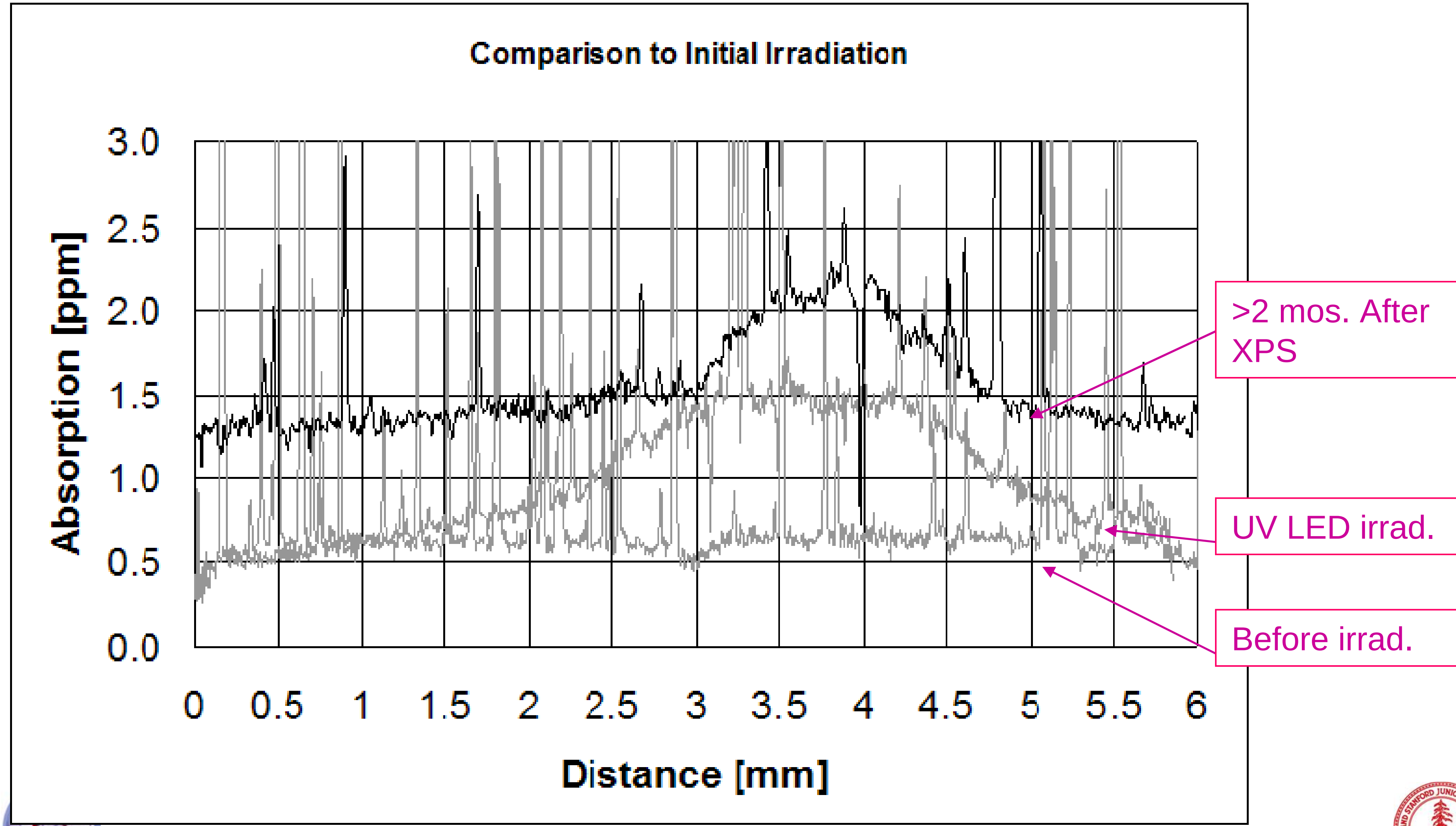
REO Sample #1, Deionizer Exposure in Air with Oxygen



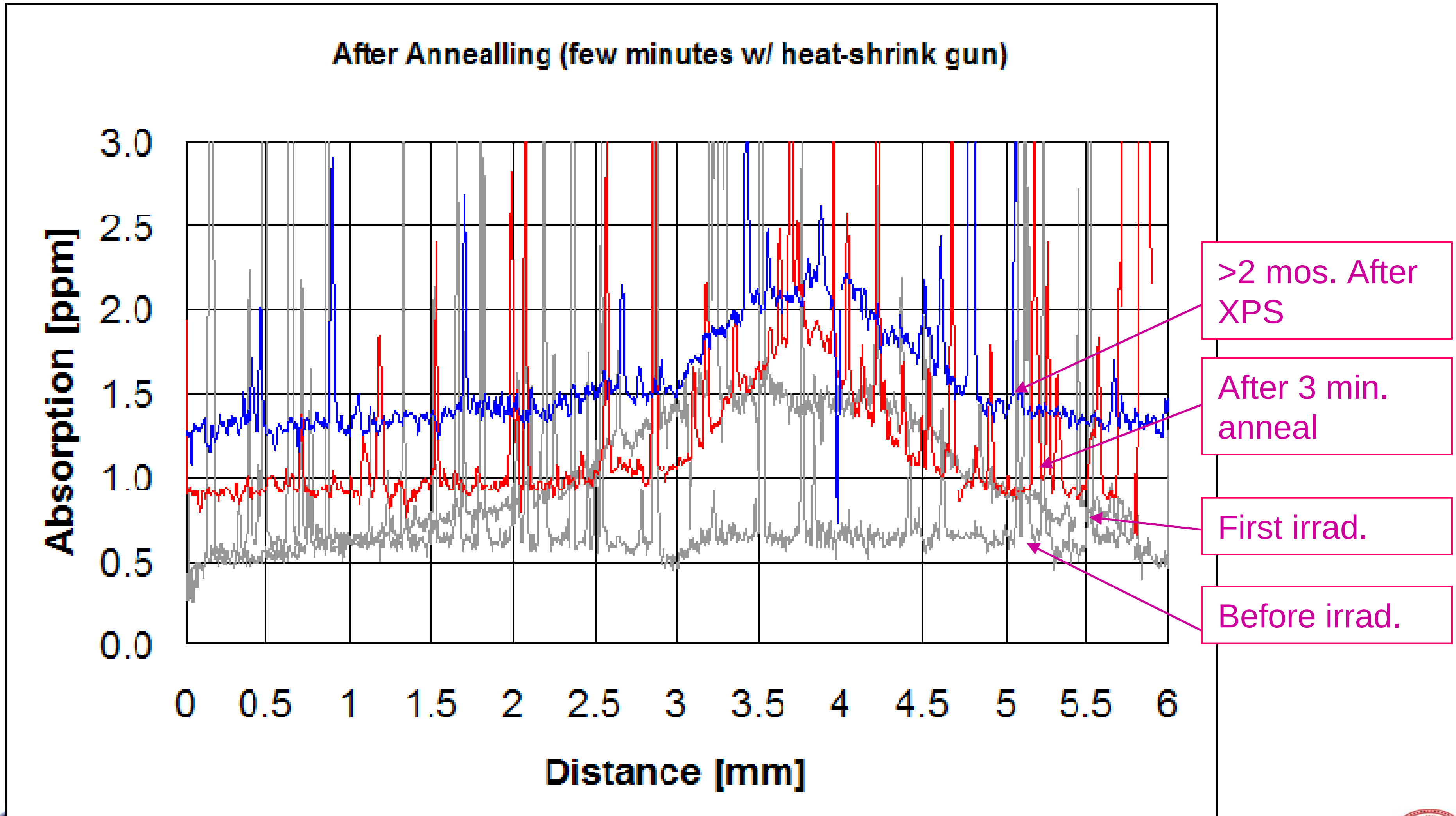
Time Heals the Wound?



Looking back



Effects of Dark Storage and Heat/Cool Cycles



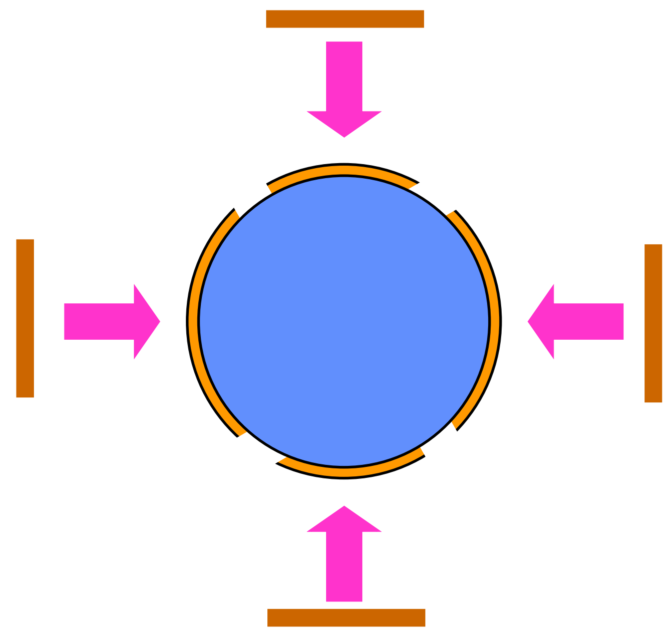
Other Charging Management Techniques

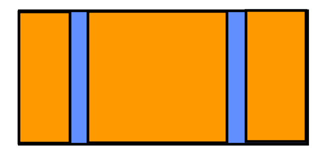
- **LIGO charge management is complicated by the dielectric core**
- **We are still committed to deliver a functional charge management solution to Advanced LIGO**
- **Devise indirect UV schemes for charge management**
  - **UV light does not illuminate the LIGO test mass material**
  - **UV light only produce electrons nearby LIGO test mass**
  - **External voltage (few volts) to steer electrons to equalize the potential**
  - **UV LED passed vacuum operation tests (ongoing for 3 months by far)**
- **Conductive coatings, wires, mass**
  - **Fluoride ($CaF_{2,}$ MgF_2 Often used in UV optics for lithography at 179~193 nm)**
  - **Patterned Au thin film on the barrel**
- **Ion and electron beam**
  - **Alternate ion beam and electron beam**
- **Neutralize the charges on test mass surface**

Au

Indirect Photoelectric Effect for Charge Management

- UV (violet) light not to directly illuminate the test mass
- Illuminate only segmented gold coating on barrel
- Allow electric charge to build up as a potential and field configuration to drive and deplete the charge on the test mass metal coating
- Then remove the charge from the metals





Conductive Coating and Test Mass

CaO:CaF_2

Influence of Oxygen on Electrical Properties of CaF_2 Crystals

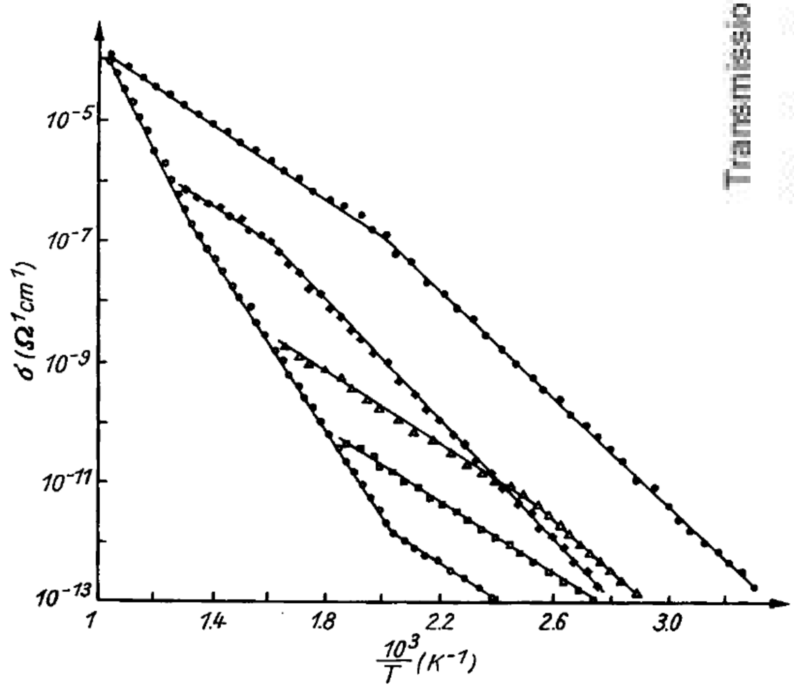
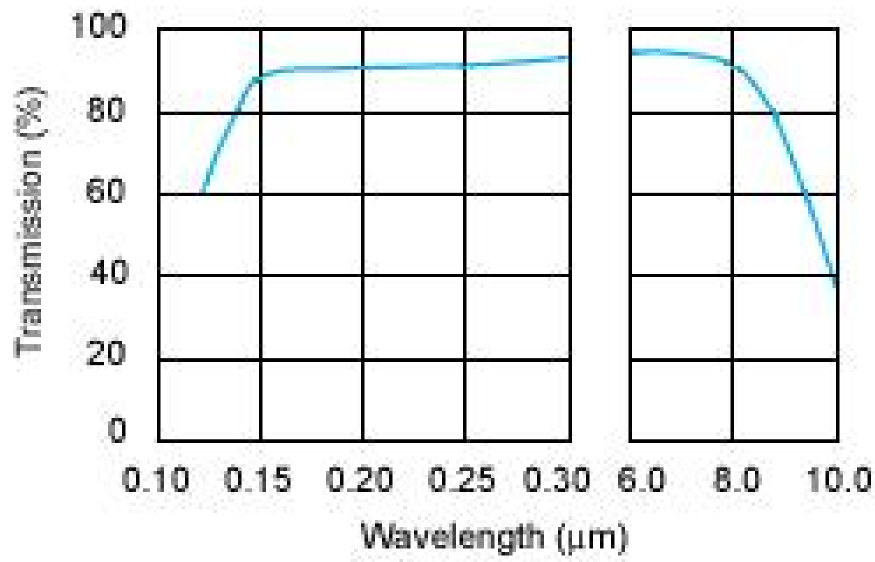
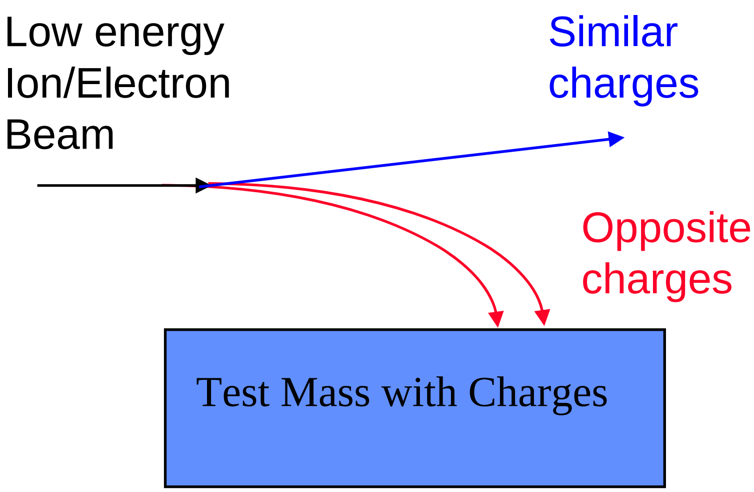


Fig. 1. Electrical conductivity of CaF_2 crystals. Curve 1: ○○○ raw material melted for 2 hours in products of Teflon pyrolysis, and dried previously for 48 hours; Curve 2: □□□ ibid, dried for 24 hours only; Curve 3: △△△ raw material melted for 2 hours in Teflon pyrolysis products; Curve 4: ■■■ CaF_2 crystal prepared at IKAN, Moscow, analyzed 0.01 mole % of oxygen; Curve 5: ●●● CaF_2 crystal with 0.1 mole % CaO

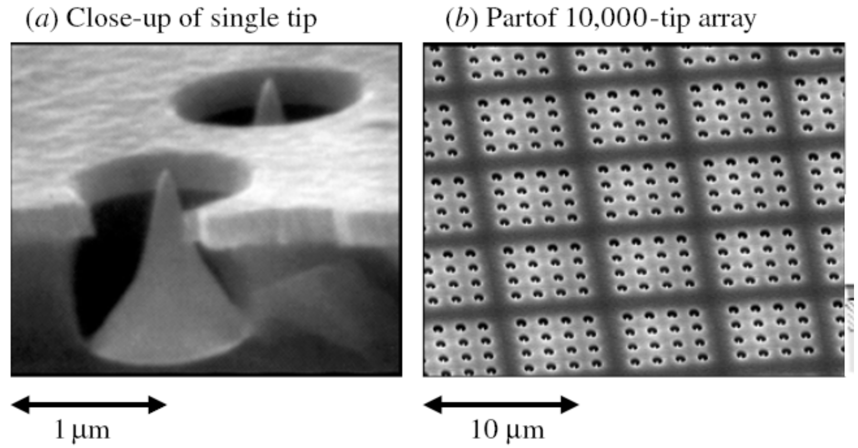


- CaF2
- Transmission 170 nm – 8000 nm
- Ionic conductor
- Electrical conductivity improved by mixing in oxygen CaO

Ion and Electron Beam Charge Management



Spindt (SRI) Cathode Ion Sources



S Buchman1, R L Byer, D Gill1, N A Robertson and K-X Sun, "Charge neutralization in vacuum for non-conducting and isolated objects using directed low-energy electron and ion beams," *Class. Quantum Grav*. **25** (2008) 035004

Ricardo suggested ionized argon gas by flow discharge

Summary

- Charges on LIGO mirror Coating MUST be mitigated, especially for Advanced LIGO
- LIGO charge management present unique challenges beyond that from LISA
- UV light removes charges
- Systematic UV exposure effect measurement on LIGO and Adv LIGO samples
- UV effects on Ta_2O_3 based coating is small but real for bare dielectric coating
- Indirect UV illumination may be more effective and mostly safe for LIGO coatings
- Explore alternative charge management strateges