Charging of the test masses past, present and future

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LIGO Systems Meeting

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Past to present

- Find relation between electrostatic force on test mass and voltage applied to gold traces to be variable and not the expected value.

$$F = -\alpha(V_{\mathrm{bias}} - V_{\mathrm{control}})^2 + \beta(V_{\mathrm{bias}} - V_{\mathrm{control}})$$

- Test for β devised using optical levers to measure pitch and yaw excitation
  - initially noisy and confusing measurements
  - further confusion from mislabeled and bad wiring
  - indications of charge from longitudinal measurements using the full interferometer
  - with care pitch and yaw became reliable
  - now show fluctuating charge density

Past to present 2

- Full interferometer tests
  - initial operation of electrostatic drive exhibited excess displacement noise traced to D/A glitches and noise in driver
  - low pass bias filter reduced noise significantly, low pass control filter reduced noise a little
  - eliminating the electrostatic drive entirely (by using magnets on the penultimate mass) reduced noise a little also but disappointingly little
  - remaining noise in the 40 to 100 Hz band exhibits $1/f^3$ spectrum and varies linearly with bias voltage for bias greater than 200V but remains constant for smaller bias voltages – consistent with fluctuating charge density on the mirror (LIGO T960137) interacting with surroundings
  - ***Need to eliminate charge on the mirror***

Past to present 3

- External injection ionizer applied at LHO ETMY (LIGO-T1100332,LIGO-G1100364,LIGO-T1400535)
  - Reduced charge from 0.4 to 0.01 depending on quadrant. Need to better understand operating conditions –injection times, flow rates and pressures – to optimize performance.
  - Injection used 1 hour, recovery to prior pressure required 12 hours (could be faster)
  - Charge recovered to pre injection values in about 36 hours, 3 hours after ion pump was open to chamber.
  - Ionizer requires more development: improved flow measurement, better equality of + and - ions (described later)

Ionizer at LHO

Chamber pressure N_2 vs time

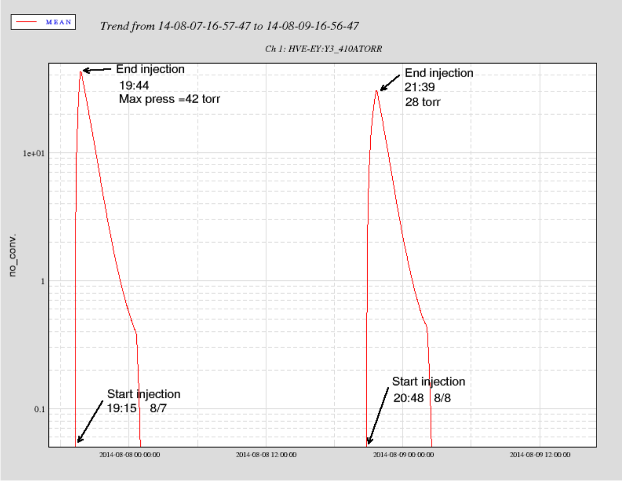


Figure 4 Pirani gauge on the test mass chamber showing pressure profile during the injection and subsequent rough pumping for both test1 and test 2.

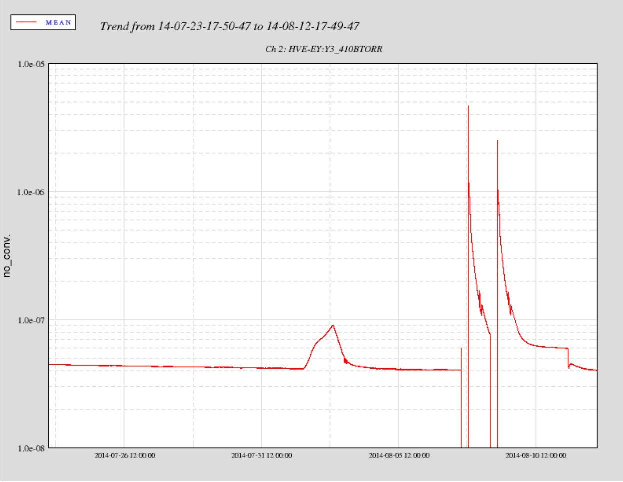
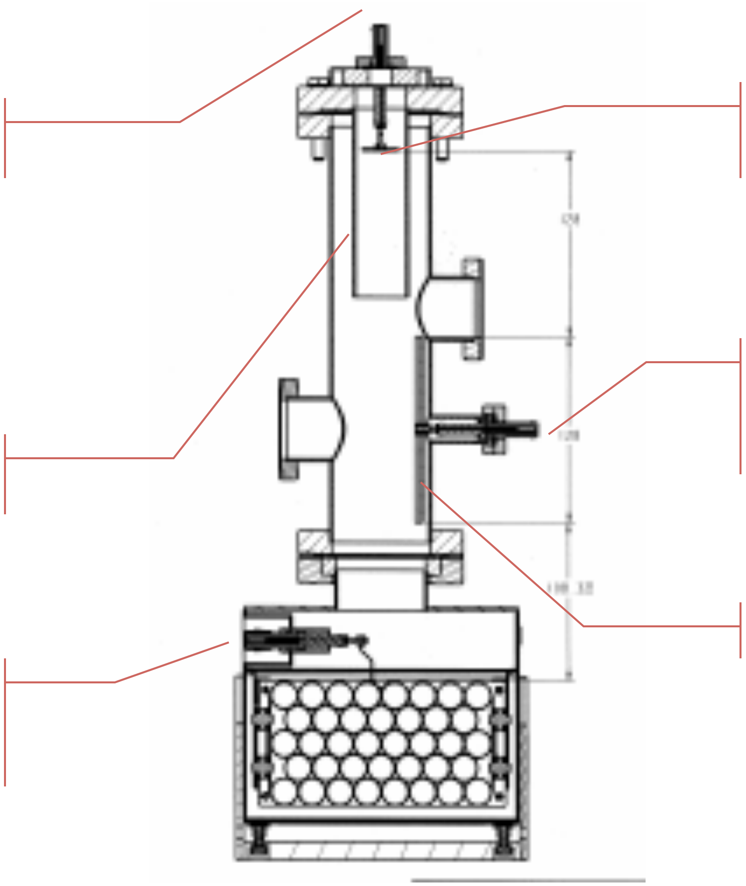


Figure 5 The discharge gauge measured chamber pressure before and after the two injections. In the trace before the first injection the chamber is maintained by its ion pump. The ion pump is closed off from the system before the first injection and turned on again at the downward step after the second injection. The pump out is with a turbo pump.

Past to present 4

- Ionizer test at MIT showed LIGO test mass charge as small (had to induce charging). What is different?
  - No use of First Contact:
    - leaves glass negatively charged
    - neutralization methods were inadequate leaving charge densities 10^{-11} to 10^{-12} coulombs/cm^2 Now improved by ~1/100
  - No green light
    - Possibility of 2 quantum photoemission with SiO_2 work function of 4 volts. Unlikely, though requires only a quantum efficiency of 10^{-13}. Current test not adequate to reject hypothesis.
  - No ion pumps (***the most significant difference***)
    - Experience at MIT, Princeton, JILA, Glasgow in other precision experiments indicates emission of UV and soft X-ray (5eV to 7KeV) photons by ion pumps
    - Optical lever tests on advanced LIGO test masses show correlation of increase and fluctuations in charge with ion pumps on while more constant charge on surfaces with ion pumps off.
    - Charge on test mass mostly positive (direct electron photo emission) and occasionally negative (photo emission by neighboring materials with lower work function and larger quantum efficiency yielding electrons that migrate to test mass)

Gamma Vacuum ion pump test



Collector Feedthrough

Collector Shield

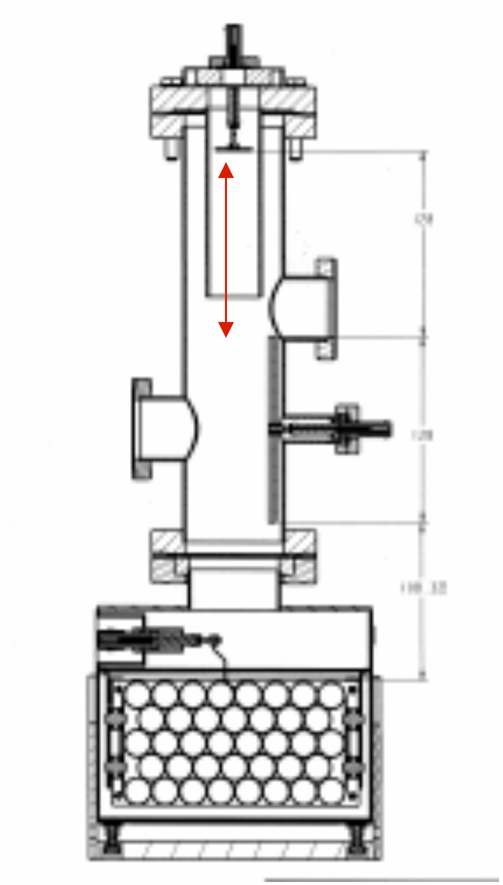
Ion Pump High Voltage Feedthrough

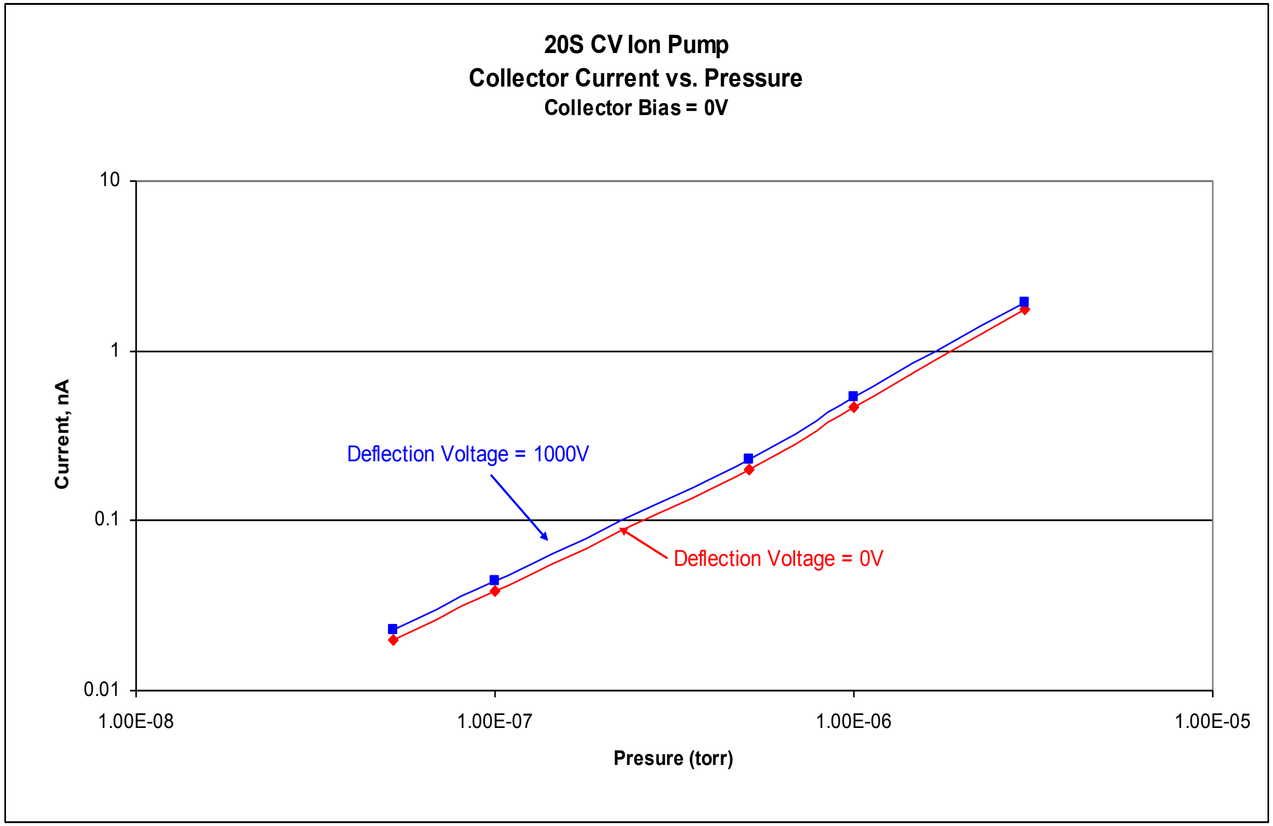
Silver (Ag) Collector

Deflector Voltage Feedthrough

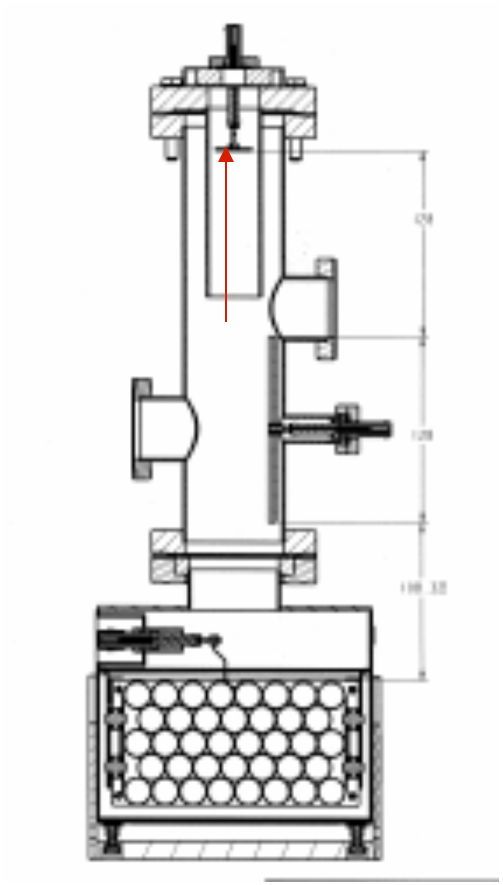
Deflector

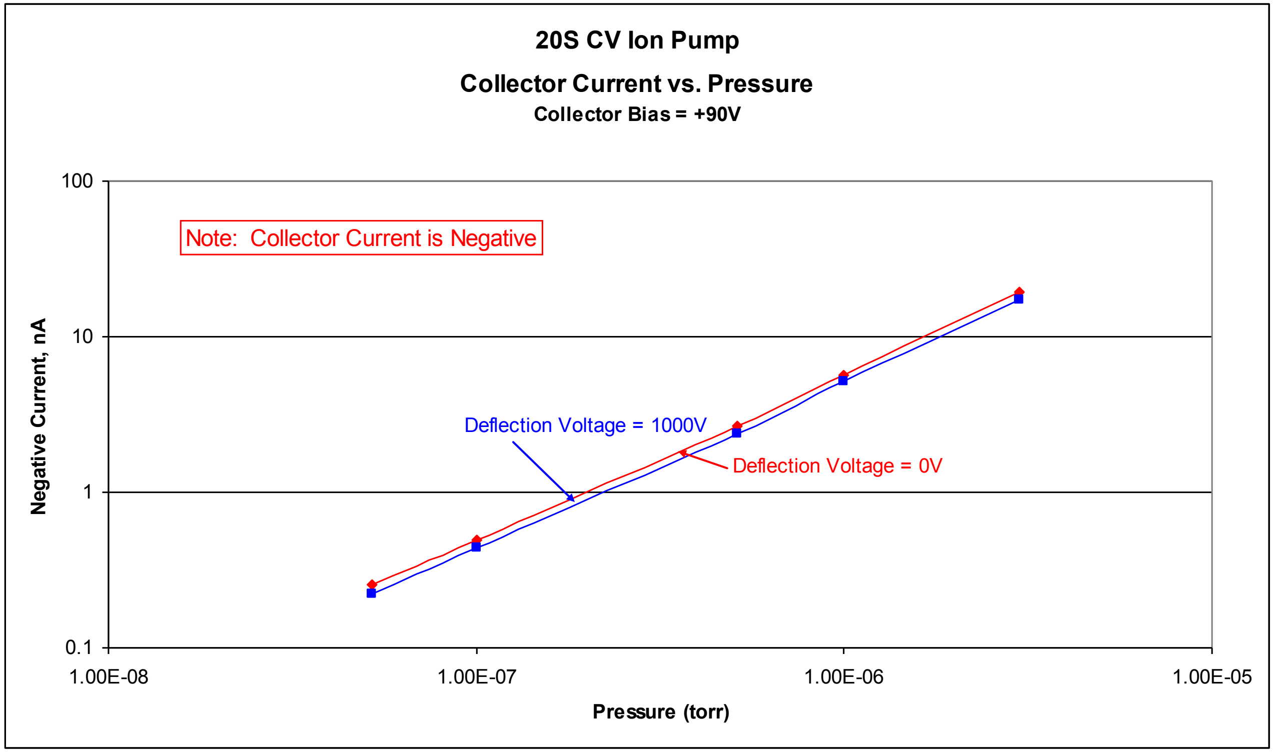
Ground Potential Collector Results



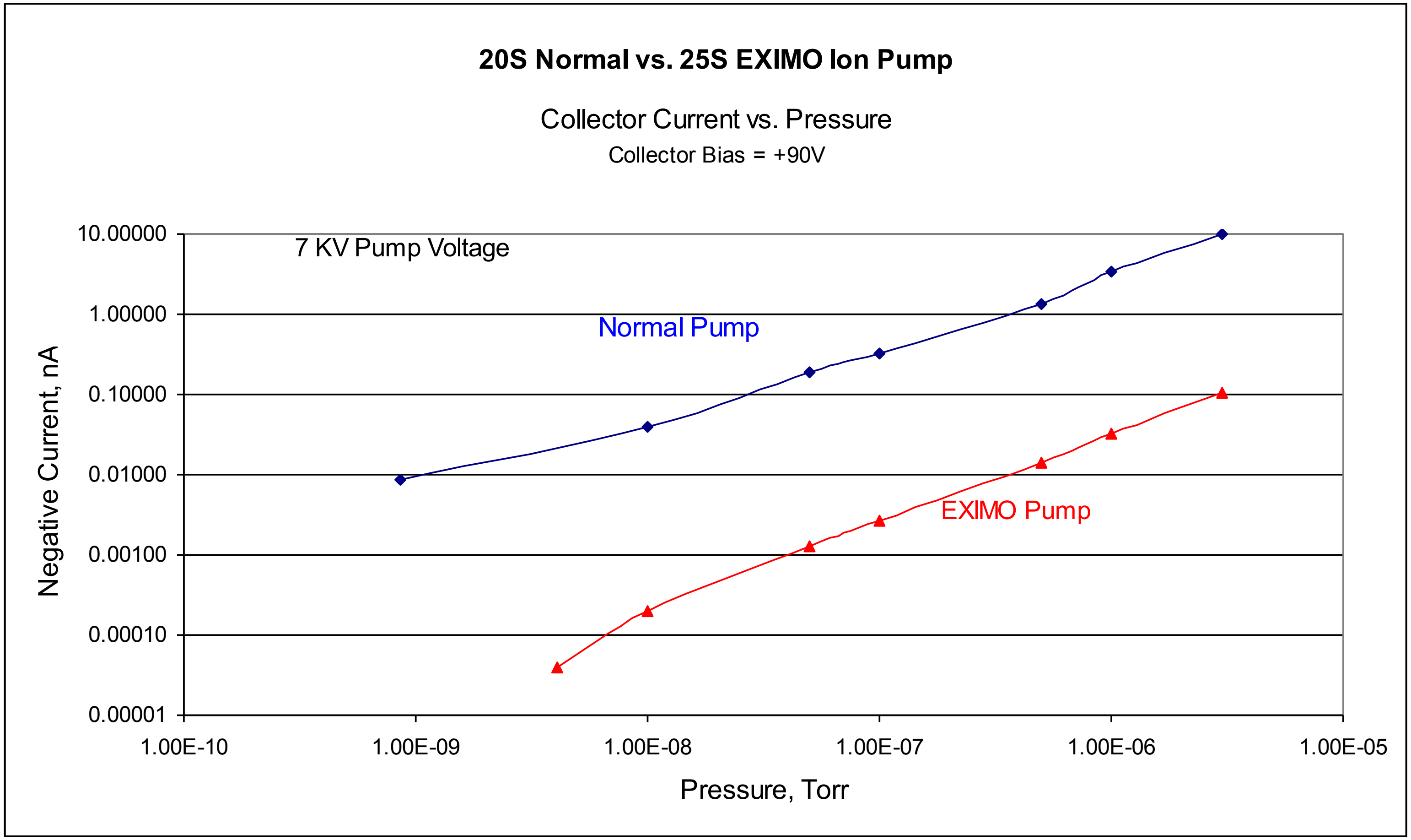


+90V Collector Bias Results

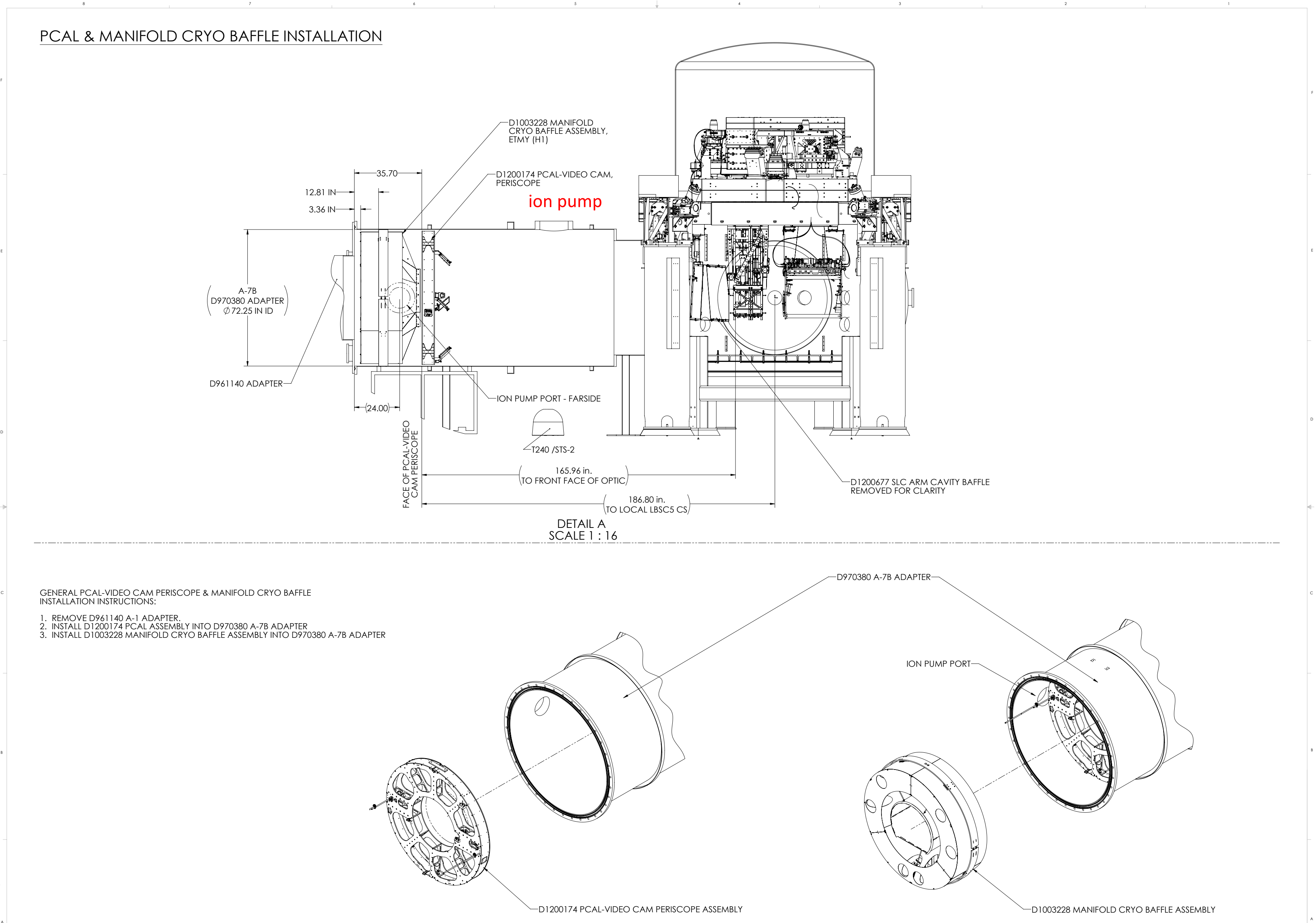




EXIMO Pump Test Results



End station layout



PCAL & MANIFOLD CRYO BAFFLE INSTALLATION

GENERAL PCAL-VIDEO CAM PERISCOPE & MANIFOLD CRYO BAFFLE INSTALLATION INSTRUCTIONS:

1. REMOVE D961140 A-1 ADAPTER.
2. INSTALL D1200174 PCAL ASSEMBLY INTO D970380 A-7B ADAPTER
3. INSTALL D1003228 MANIFOLD CRYO BAFFLE ASSEMBLY INTO D970380 A-7B ADAPTER

Estimate of ion emission at LHO ETMY

ESTIMATE OF UV + SOFT X RAY PHOTONS ON MIRROR

ASSUMPTIONS

NO DIRECT LINE OF SIGHT ION PUMP TO MIRROR (3D PICTURE OF ETM)

PHOTON EMISSION BY ION PUMP REFLECTIVITY ON SS $R \sim 0.2$ 10eV → 30eV

$\sim 10^{-3}$ 200eV → 7KeV

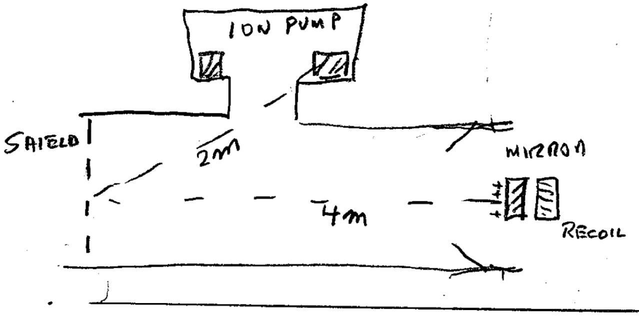
QUANTUM EFFICIENCY ON SS AND S_iO_2 $\eta \sim 10^{-3}$

GAMMA 20 ℓ/s ION PUMP SCALED TO OUR 2500 ℓ/s ION PUMP

PARAMETERS

PHOTON BRIGHTNESS OF GAMMA ION PUMP ($P = 1\times10^{-8}$ TORR) / LITER/SEC $B_\gamma = 2\times10^{11}$ photons/sr

PHOTON BRIGHTNESS OF OUR ION PUMP $B_{\gamma\,\text{OUR}} = 5\times10^{14}$ photons/sr



$$\dot N_{\gamma\,\text{MIRROR}} = \underbrace{\overset{\text{FRACTION OF PUMP AREA VISIBLE AT SHIELD}}{f_r}}_{0.1}\;\underbrace{\Omega_{\text{SHIELD AT PUMP}}}_{0.15}\;\underbrace{\Omega_{\text{MIRROR AT SHIELD}}}_{5\times10^{-3}}\;\underbrace{R}_{0.2}\;B_{\gamma\,\text{OUR}} = 8\times10^{9}\ \gamma/\text{SEC}$$

$$\dot\sigma_\gamma = \frac{\dot N_\gamma}{A_{\text{MIRROR}}} = 8\times10^{6}\ \gamma/\text{cm}^2/\text{s}$$

SURFACE CHARGE DERIVATIVE $\dot\sigma_- = \dot\sigma_\gamma\,\eta = 8\times10^{3}\ e/\text{cm}^2/\text{s}$

TIME TO GET $\sigma_e = 3\times10^{6}\ e/\text{cm}^2$ $t \sim 1$ hour

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ESTIMATE FROM RECHARGING AFTER DEIONIZATION

$t \sim 2$ hours

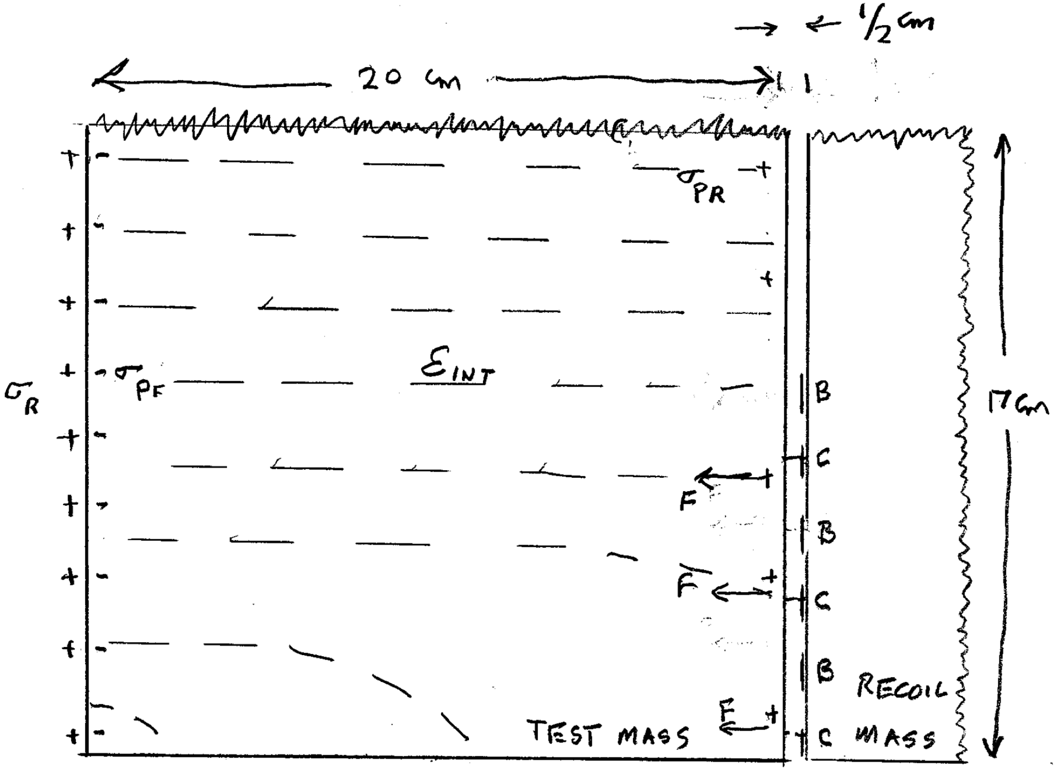
ELECTRIC FIELD AT FRONT SURFACE OF MIRROR

$$\vec{E} = \frac{\sigma_-}{\varepsilon_0} = \frac{4.8\times10^{-9}\ \text{C/m}^2}{8.8\times10^{-12}} \rightarrow 500\ \text{Volts/m}$$

SATURATION ON SURFACE

EXPECT 30–100V TO STOP ELECTRON EMISSION

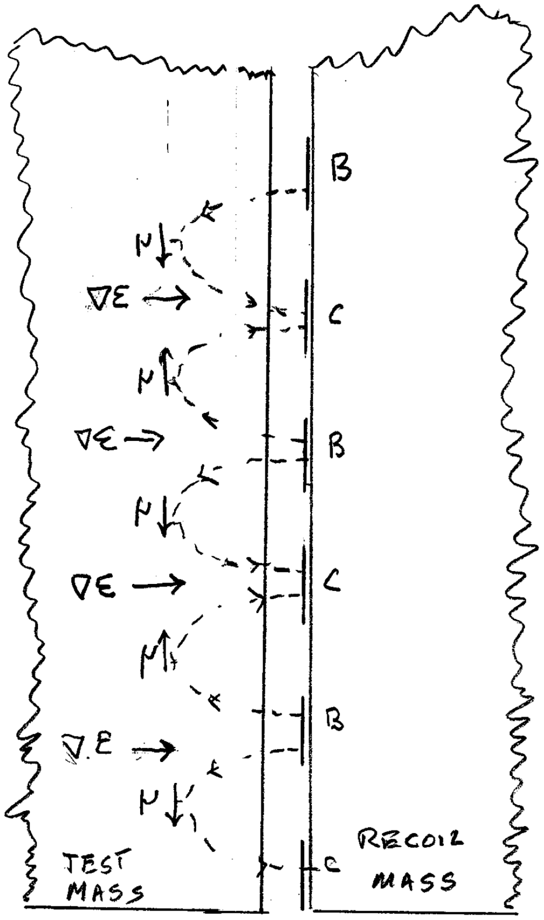
Charging model



CHARGE FORCE

$$F = \sigma_{PR}\, \mathcal{E}\, A_c$$

$$\sim \mathcal{E}$$



DIELECTRIC DIPOLE FORCE

$$F_j = \underbrace{\alpha\, \mathcal{E}_j}_{\mu}\, \nabla \mathcal{E}_k$$

$$\sim \mathcal{E}^2$$

Displacement from the surface charge

FORCE AND TORQUE ON TEST MASS IN OPTICAL LEVER MEASUREMENT

MEASURE

V_D DRIVE VOLTAGE PEAK 91 V AT DRIVE FREQUENCY $f = 4\,Hz$ INERTIAL RESPONSE

V_{OFF} BIAS OFFSET ~ 100V

$\frac{d\theta}{dV}$ OPTICAL LEVER ANGLE SENSITIVITY $= 10^{-13}$ RADIANS/VOLT $\theta(\omega) = 10^{-11}$ RADIANS

SUSPENSION PARAMETERS

TEST MASS $m = 40\,Kg$ DIAMETER $D = 034\,m$ MOMENT OF INERTIA $I = 0.422\,Kg\,m^2$

RECOIL MASS – TEST MASS GAP $d_{TR} = 5 \times 10^{-3}\,m$

CONTROL ELECTRODE AREA $A_c = 6.8 \times 10^{-3}\,m^2$

DIELECTRIC CONSTANT $K = 4$

GEOMETRIC FIELD LOSS FACTOR $f_g \cong 0.05$

FORCE

$$F(\omega) = \frac{V_D(\omega)}{d_{TR}} \sigma_R A_c \left(\frac{K-1}{K+1}\right) f_g$$

TORQUE

$$\tau(\omega) = \sin 45^\circ \frac{D}{2} F(\omega)$$

ANGULAR DISPLACEMENT

$$\theta(\omega) = \frac{\tau(\omega)}{\omega^2 I}$$

SOLVE FOR SURFACE CHARGE ON MIRROR FACE

$$\sigma_R = \frac{\theta(\omega)\,\omega^2 I}{\frac{D}{2\sqrt{2}} \frac{V_D(\omega)}{d_{TR}} A_c \left(\frac{K-1}{K+1}\right) f_g} \rightarrow 6 \times 10^{-9}\,C/m^2 \Rightarrow \boxed{6 \times 10^{-13}\,C/cm^2}$$

Noise from charge fluctuations

DISPLACEMENT NOISE ESTIMATE FROM IMPULSIVE CHARGE DIFFUSION

<u>MEASURED NOISE</u> LLO (29MPC) 40Hz — 100Hz

$x(f) = \dfrac{4.5 \times 10^{-14}}{f^3}$ m/$\sqrt{\text{Hz}}$ USE $x(60) = 2 \times 10^{-19}$ m/$\sqrt{\text{Hz}}$ $F(60) = 1.2 \times 10^{-12}$ N/$\sqrt{\text{Hz}}$

<u>THEORY</u> LIGO T960137

FLUCTUATING FORCE $F(f) = \dfrac{1}{\sqrt{2}\,\pi^{3/2}} \dfrac{\sigma_R^2 A}{f \tilde{\tau}_0^{1/2} \varepsilon_0} \left(\dfrac{K-1}{K+1}\right)^2$

MIRROR AREA $A = 9.1 \times 10^{-2}\ m^2$

DIELECTRIC TIME CONSTANT $\tilde{\tau}_0 = \dfrac{\varepsilon_0 K}{\sigma_{COND}}$

$\tilde{\tau}_0 = 1.4 \times 10^6$ sec UGOLINI

$\rho_{RES} = \dfrac{1}{\sigma_{COND}} \simeq 5 \times 10^{14}$ m ohm

SOLVE FOR SURFACE CHARGE

$$\sigma_R = \left(\frac{F(f)\, f\, \varepsilon_0}{A}\right)^{1/2} \frac{(2\tilde{\tau}_0)^{1/4}\, \pi^{3/4}}{\left(\frac{K-1}{K+1}\right)} \rightarrow 1.4 \times 10^{-8}\ c/m^2 \Rightarrow \boxed{1.4 \times 10^{-12}\ c/cm^2}$$

HOW MUCH SURFACE CHARGE IS ALLOWED

BOUNDARY: $h(f)_{CHARGE} = h(f)_{ALIGO\ ESTIMATE}$ $10 < f < 100$ Hz

$$\sigma_R = 4 \times 10^{-10}\ c/m^2 \Rightarrow \boxed{4 \times 10^{-14}\ c/cm^2}$$

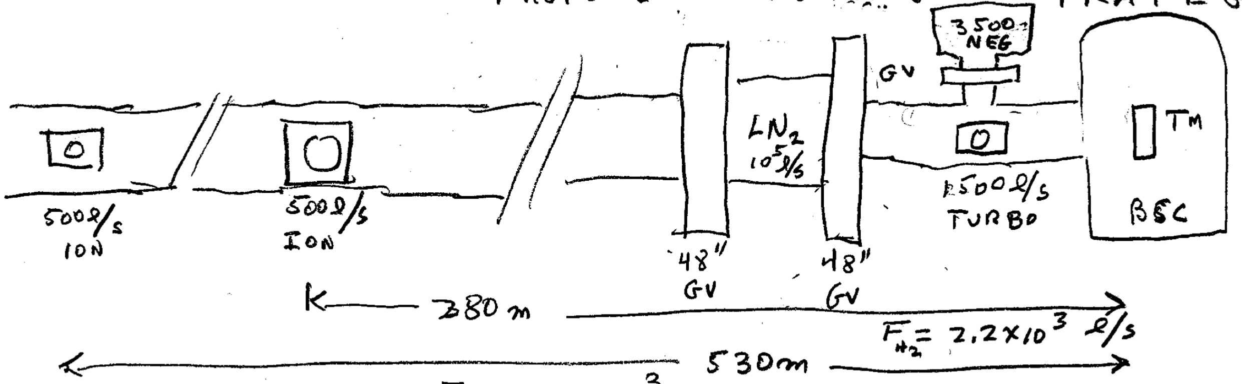
$$h(f)_{CHARGE} = \frac{1.9 \times 10^{-19}}{f^3}$$

Steps to reduce the charging

- Gamma vacuum to see it they can make 1/1000 reduction shield for ion pumps. If so would replace them at all pumps in LIGO near the ITM and ETM
- Replace ion pump on manifold with NEG pump and place more ion pumps on beam tube.
- Improve and multiply the number of ionizers

Proposed pumping strategy

PROPOSED PUMPING STRATEGY



HYDROGEN

$F_{H_2} = 1.1 \times 10^3$ l/s

$\dot{Q}(H_2, 300K)_{\text{TUBE}} = 4 \times 10^{-6}$ TORR LITERS/SEC $\xrightarrow{}$ 2500 l/s $\Rightarrow P_{H_2} = 1.6 \times 10^{-9}$ TORR

$J = 4 \times 10^{-14}$

$\dot{Q}(H_2, 300K)_{\text{CHAMBER}} = 1 \times 10^{-5}$ TORR LITERS/SEC $\xrightarrow{}$ 2500 l/s $= P_{H_2} = 4.0 \times 10^{-9}$ TORR

$J = 1 \times 10^{-11}$

PUMPING RATES AND TIMES TO OPEN SYSTEM TO LN$_2$ TRAP $P_{H_2O} < 3 \times 10^{-7}$ TORR

WATER

WET SYSTEM ADVANCED LIGO

$$P(t) = \frac{1.4 \times 10^{-5}}{t(\text{days})} \text{ torr}$$

TURBO ON

$T_{\text{OPEN } LN_2} = 46$ DAYS

DRY SYSTEM

$$P(t) = \frac{3.3 \times 10^{-6}\, t(\text{days open})}{t(\text{days pumping})}$$

TURBO ON

$T_{\text{OPEN } LN_2} = 11$ DAYS FOR 1 DAY OPEN

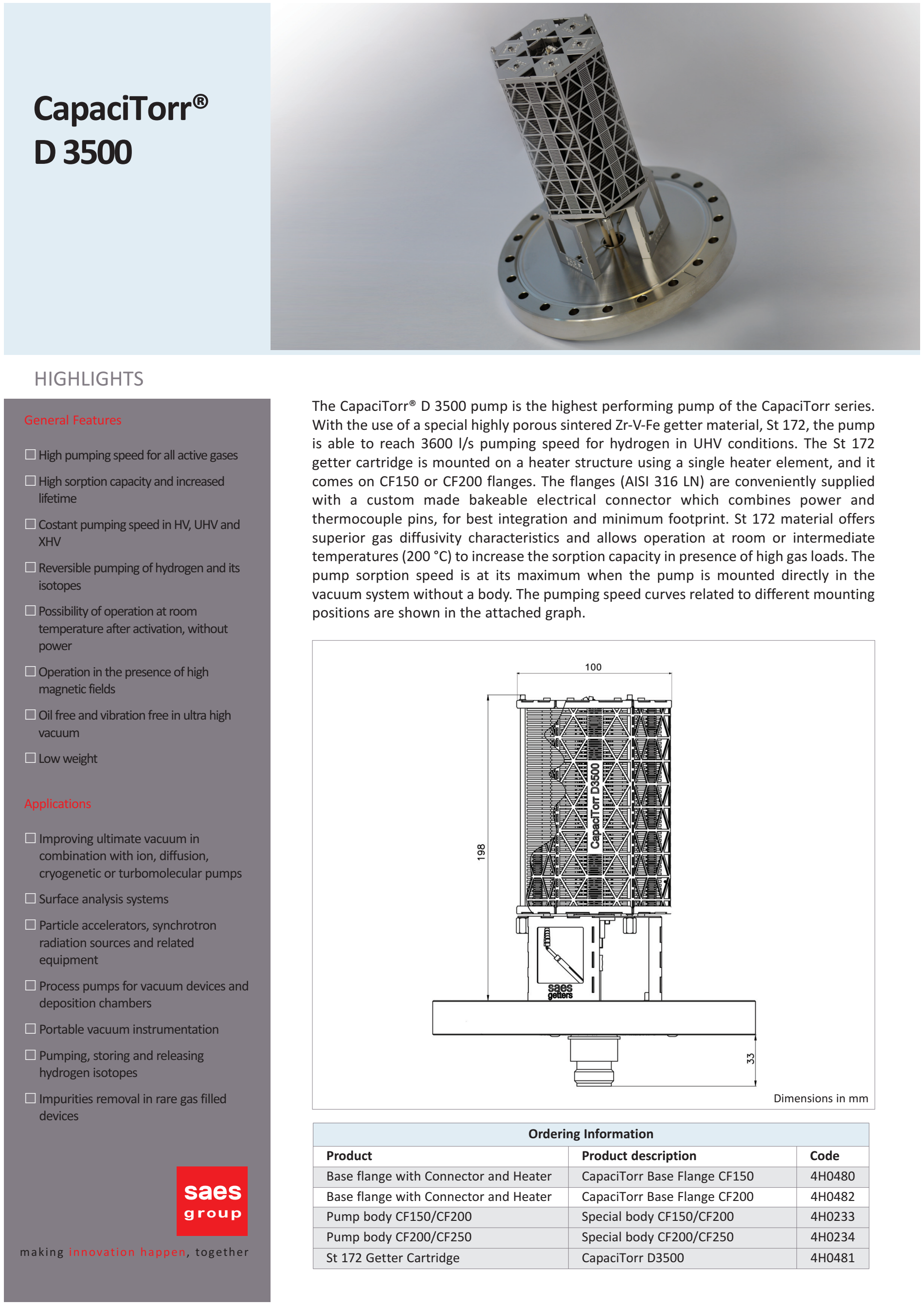
SQUEEZED FILM THERMAL NOISE

$h(f)_{\text{SQUEEZED FILM}} = h(f)_{\text{ALIGO ESTIMATE}}$

$P(H_2) = 4 \times 10^{-9}$ TORR $10 < f < 40$ Hz

$h(f)_{\text{SQUEEZED FILM}} \propto P(H_2)^{1/2}$

Properties of SAES D3500 NEG



CapaciTorr®
D 3500

HIGHLIGHTS

General Features

- ☐ High pumping speed for all active gases
- ☐ High sorption capacity and increased lifetime
- ☐ Costant pumping speed in HV, UHV and XHV
- ☐ Reversible pumping of hydrogen and its isotopes
- ☐ Possibility of operation at room temperature after activation, without power
- ☐ Operation in the presence of high magnetic fields
- ☐ Oil free and vibration free in ultra high vacuum
- ☐ Low weight

Applications

- ☐ Improving ultimate vacuum in combination with ion, diffusion, cryogenetic or turbomolecular pumps
- ☐ Surface analysis systems
- ☐ Particle accelerators, synchrotron radiation sources and related equipment
- ☐ Process pumps for vacuum devices and deposition chambers
- ☐ Portable vacuum instrumentation
- ☐ Pumping, storing and releasing hydrogen isotopes
- ☐ Impurities removal in rare gas filled devices

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making innovation happen, together

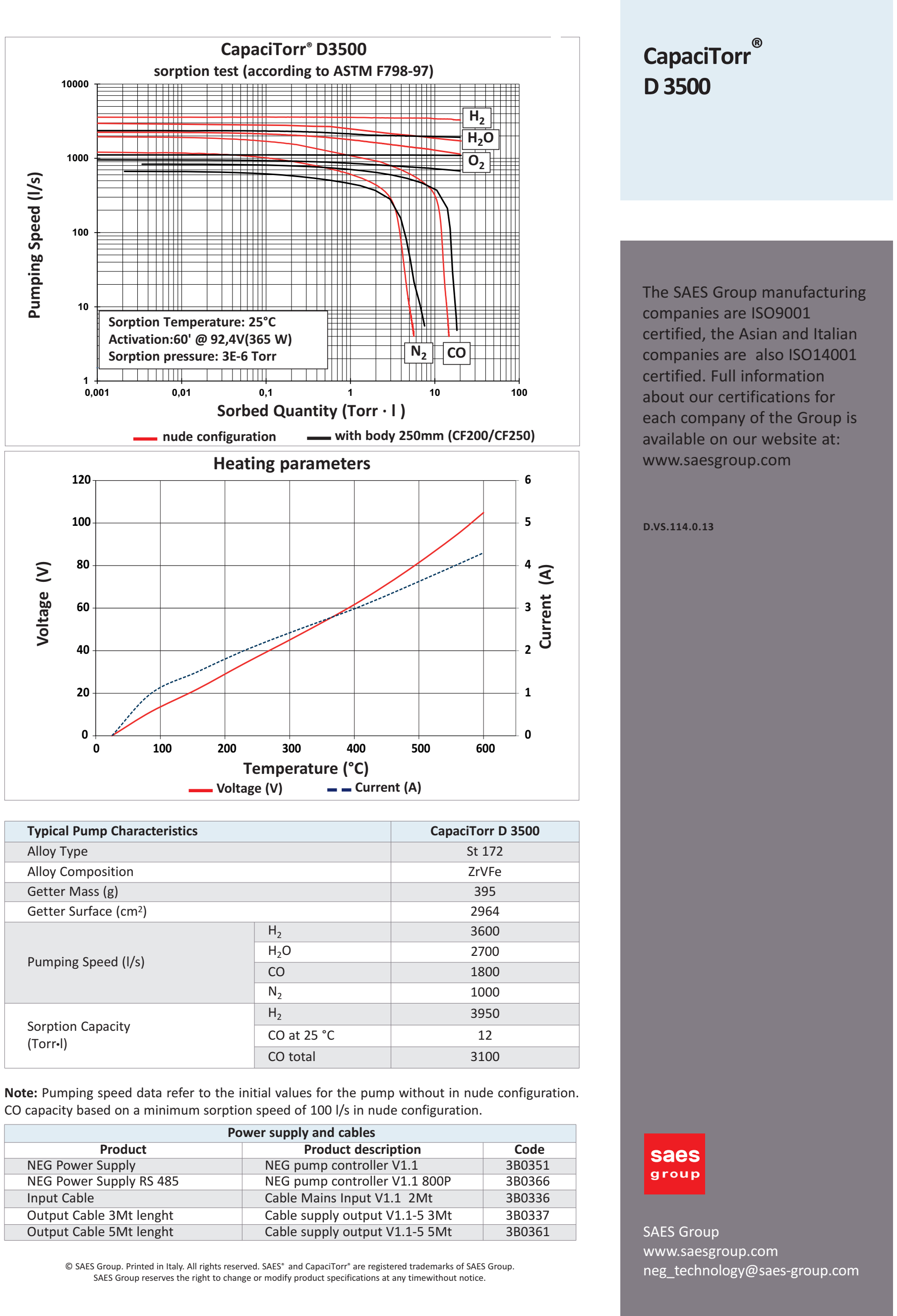
The CapaciTorr® D 3500 pump is the highest performing pump of the CapaciTorr series. With the use of a special highly porous sintered Zr-V-Fe getter material, St 172, the pump is able to reach 3600 l/s pumping speed for hydrogen in UHV conditions. The St 172 getter cartridge is mounted on a heater structure using a single heater element, and it comes on CF150 or CF200 flanges. The flanges (AISI 316 LN) are conveniently supplied with a custom made bakeable electrical connector which combines power and thermocouple pins, for best integration and minimum footprint. St 172 material offers superior gas diffusivity characteristics and allows operation at room or intermediate temperatures (200 °C) to increase the sorption capacity in presence of high gas loads. The pump sorption speed is at its maximum when the pump is mounted directly in the vacuum system without a body. The pumping speed curves related to different mounting positions are shown in the attached graph.

Dimensions in mm

Ordering Information

Product	Product description	Code
Base flange with Connector and Heater	CapaciTorr Base Flange CF150	4H0480
Base flange with Connector and Heater	CapaciTorr Base Flange CF200	4H0482
Pump body CF150/CF200	Special body CF150/CF200	4H0233
Pump body CF200/CF250	Special body CF200/CF250	4H0234
St 172 Getter Cartridge	CapaciTorr D3500	4H0481

Properties of SAES D3500 NEG



CapaciTorr®
D 3500

Typical Pump Characteristics		CapaciTorr D 3500
Alloy Type		St 172
Alloy Composition		ZrVFe
Getter Mass (g)		395
Getter Surface (cm²)		2964
Pumping Speed (l/s)	H_2	3600
	H_2O	2700
	CO	1800
	N_2	1000
Sorption Capacity (Torr•l)	H_2	3950
	CO at 25 °C	12
	CO total	3100

Note: Pumping speed data refer to the initial values for the pump without in nude configuration. CO capacity based on a minimum sorption speed of 100 l/s in nude configuration.

Power supply and cables		
Product	**Product description**	**Code**
NEG Power Supply	NEG pump controller V1.1	3B0351
NEG Power Supply RS 485	NEG pump controller V1.1 800P	3B0366
Input Cable	Cable Mains Input V1.1 2Mt	3B0336
Output Cable 3Mt lenght	Cable supply output V1.1-5 3Mt	3B0337
Output Cable 5Mt lenght	Cable supply output V1.1-5 5Mt	3B0361

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Steps to improve and multiply ionizers

- Reliably generate equal + and – ions
  - different potentials on the needles AC and DC,
  - better instrumentation for flow
  - add oxygen or use argon
  - test in present setup
- Sample industry to determine if they can make 8 ionizer before the New Year
  - Kimball Physics (New Hampshire)
  - Electrostatics Inc (Pennsylvania)
- Possibility to use LIGO engineering to make the 8 ionizers

Steps we need to take

- Establish the charging on the ITM
- Measure the noise with the test masses discharged
  - Probably best to do this at LLO, need to move ionizer to LLO
- Need to put gate valves on all the test mass chambers to receive the ionizer
- Fix the wiring and connectors
- Fix the D/A and reduce noise in ESD amplifiers by making a low voltage version for running

Current state of ESD in vacuum wiring

	LLO ETMX	LLO ETMY	LLO ITMX	LLO ITMY	LHO ETMX	LHO ETMY	LHO ITMX	LHO ITMY
bias	shorted shield	ok	connected not tested	not connected	ok	shorted shield	connected not tested	connected not tested
LL	probably LR	probably LR	connected not tested	not connected	ok	ok	connected not tested	connected not tested
UL	probably UR	probably UR	connected not tested	not connected	ok	ok	connected not tested	connected not tested
LR	probably LL	probably LL	connected not tested	not connected	ok	ok	connected not tested	connected not tested
UR	shorted shield probably UL	probably UL	connected not tested	not connected	ok	ok	connected not tested	connected not tested
2 ¾ " gate valve	yes	no	no	no	yes	yes	yes	yes

To think about for the future

- Stop gambling
  - Develop a conducting coating
    - high resistivity (10s-100sGohms/square)
    - low optical loss at 1 micron
    - Low mechanical loss
    - Most likely ionic coatings
    - Stanford may have tested an applicable electronic coating
  - Develop an annular ring recoil mass
    - Reduces force from charging
    - Reduces squeeze film thermal noise