Laser Interferometer Gravitational – wave Observatory LIGO

some case studies in precision engineering

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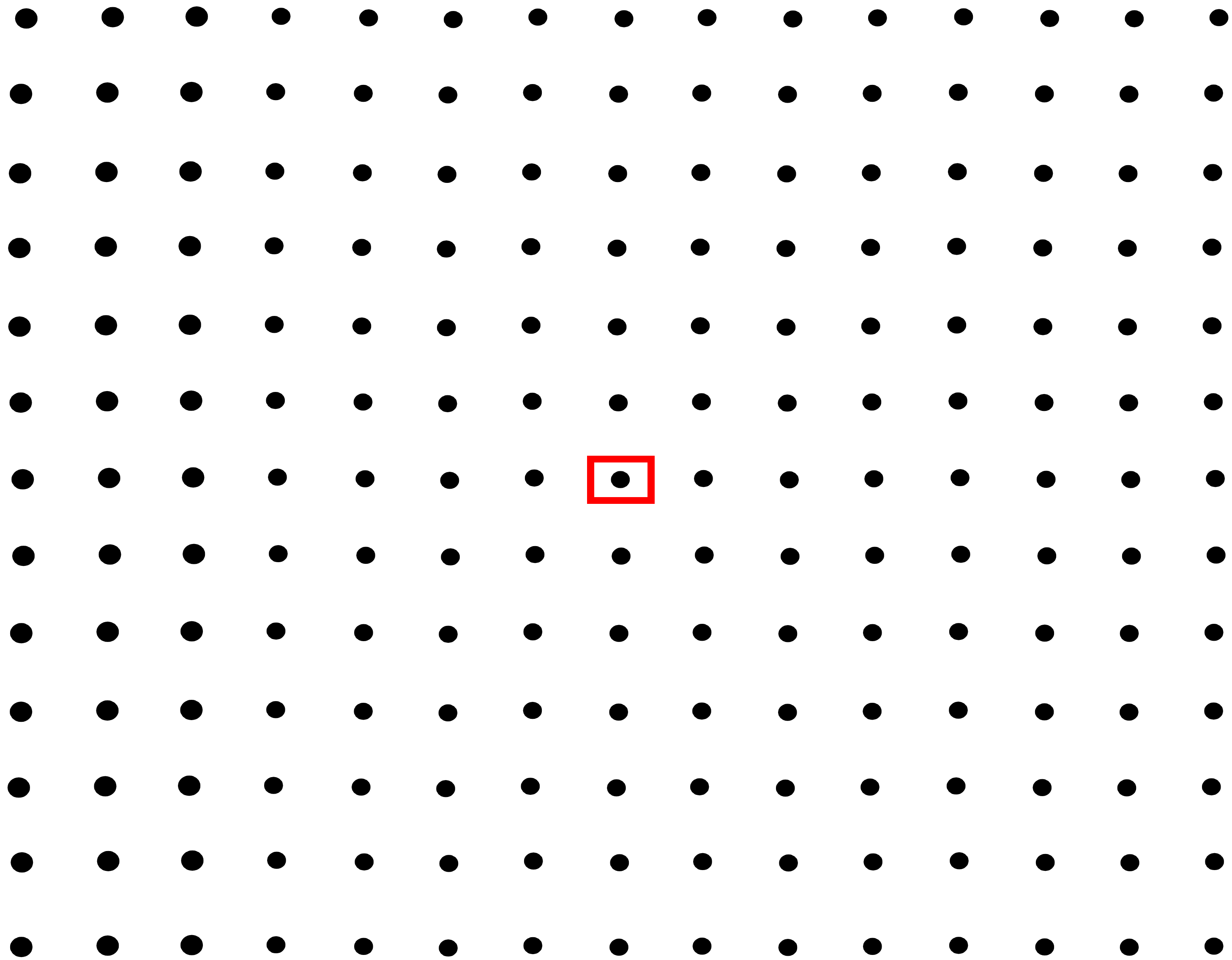
American Society for Precision Engineering

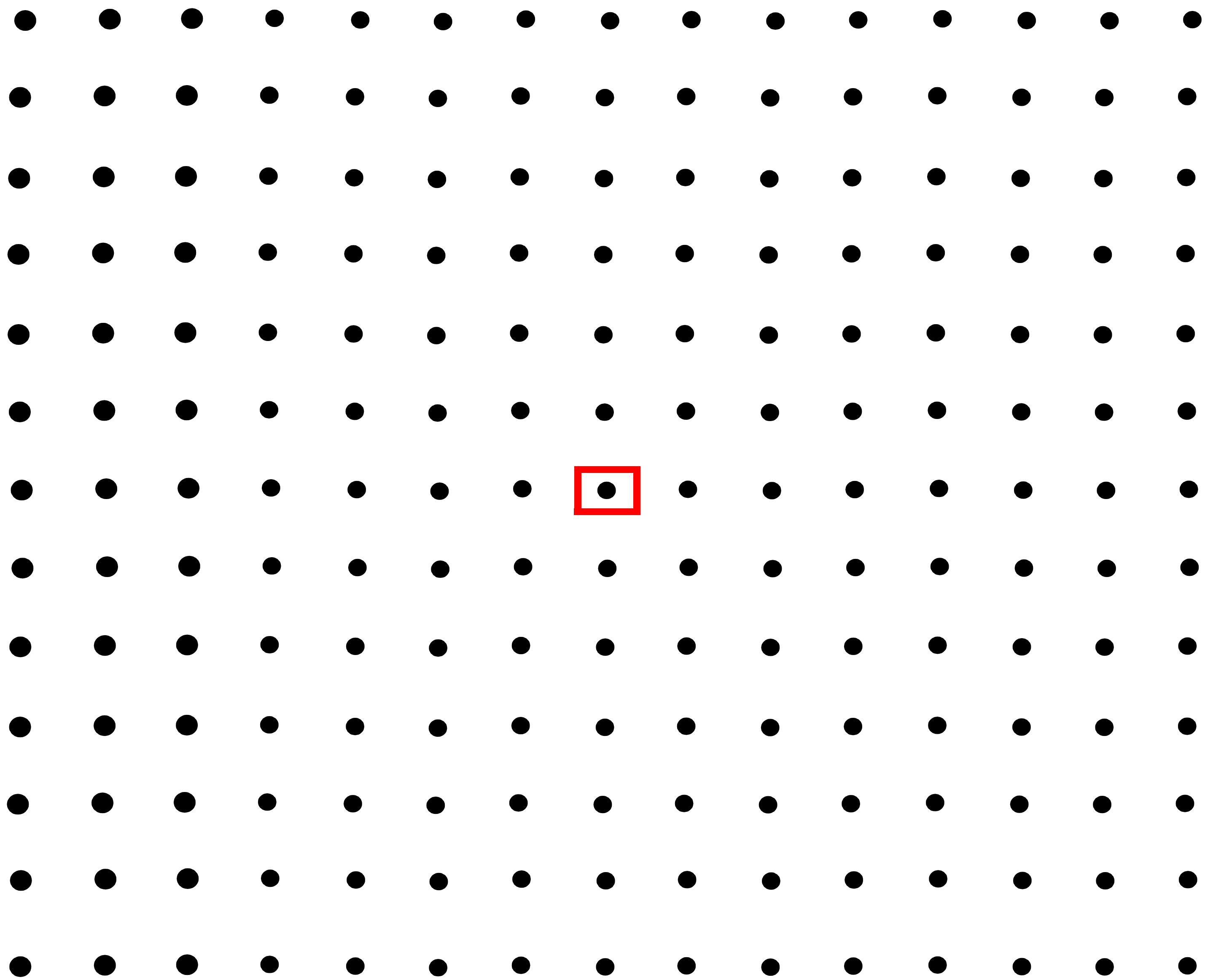
2006 Spring Topical Meeting

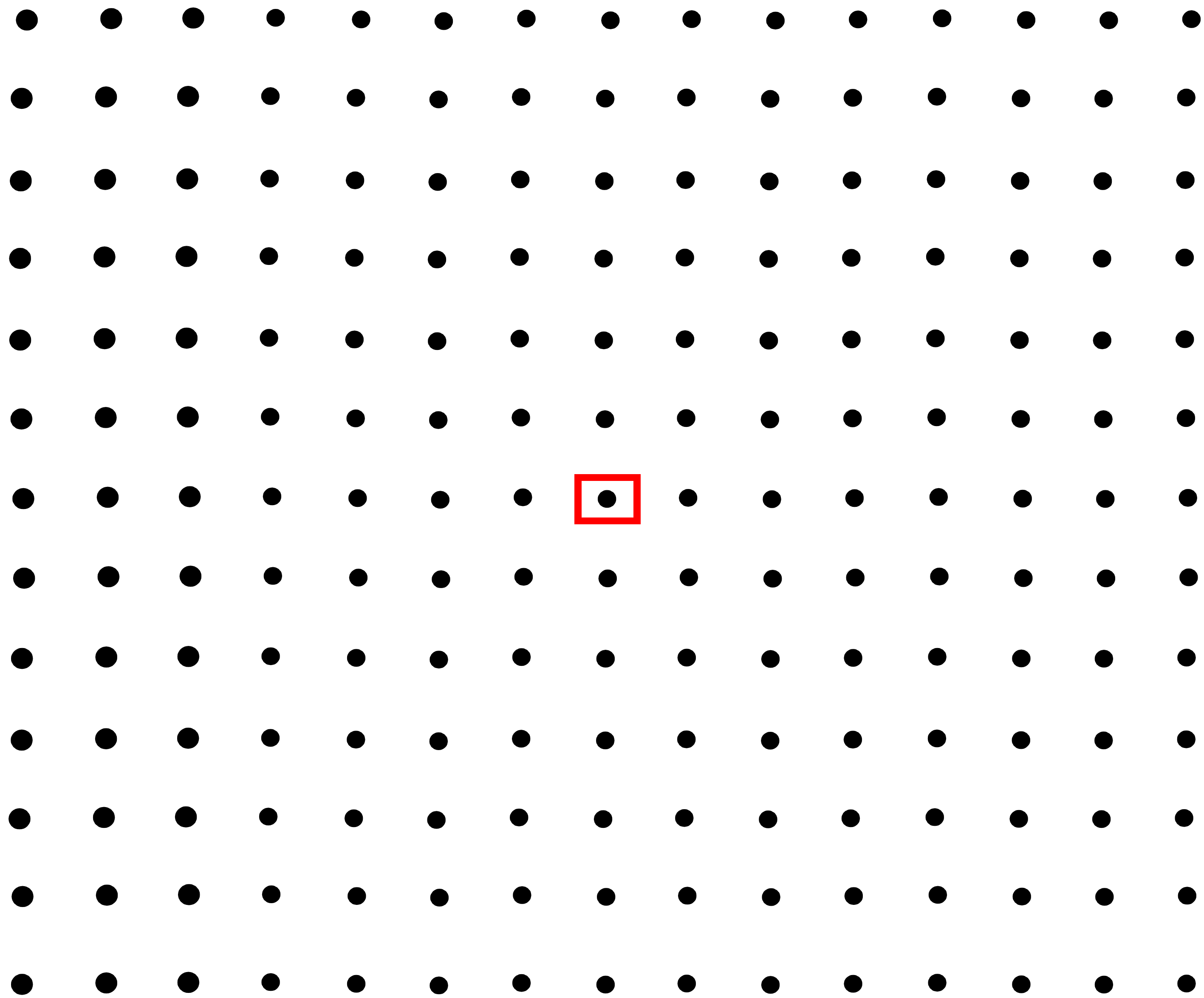
May 2, 2006

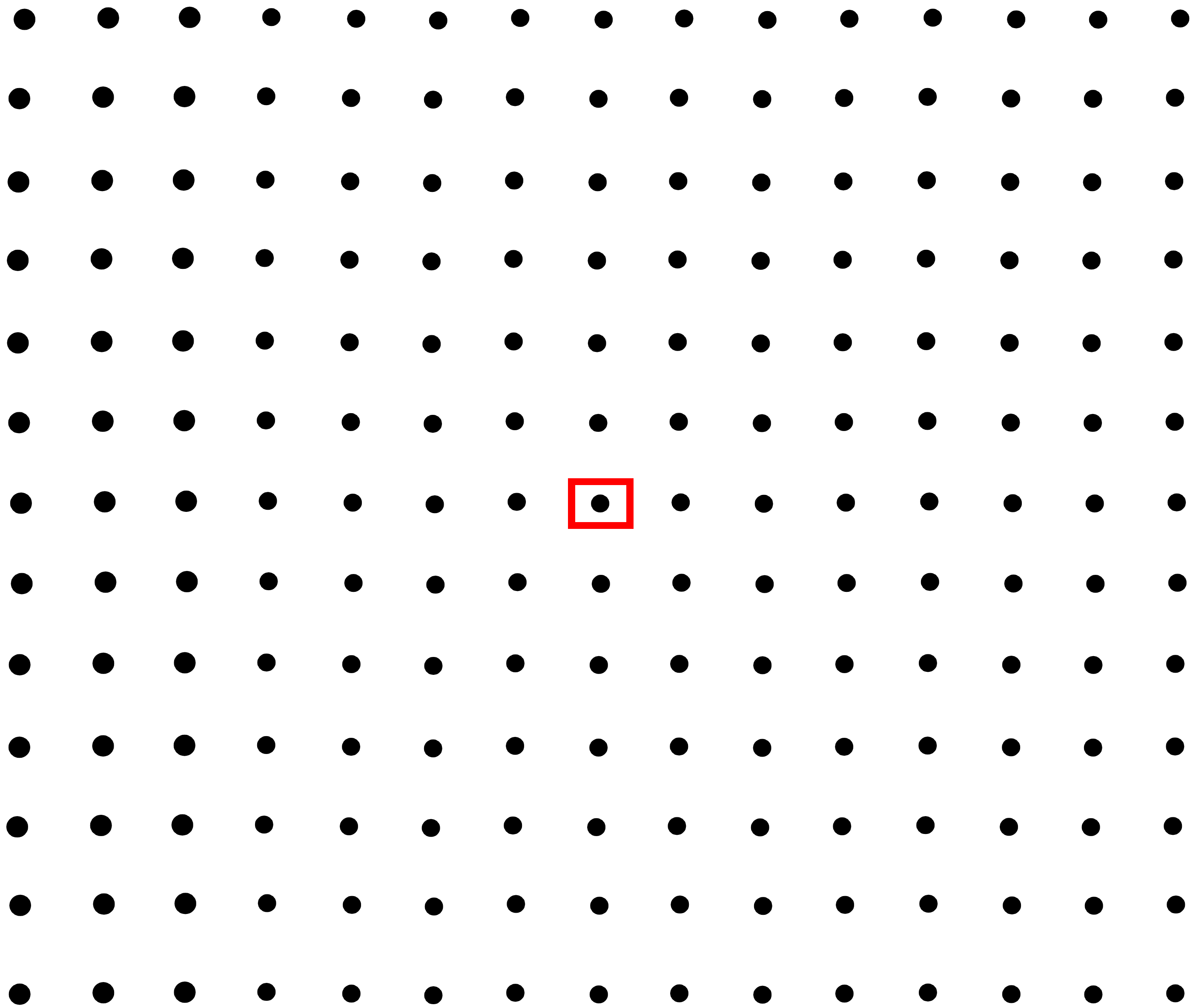
Direct detection of gravitational waves from astrophysical sources

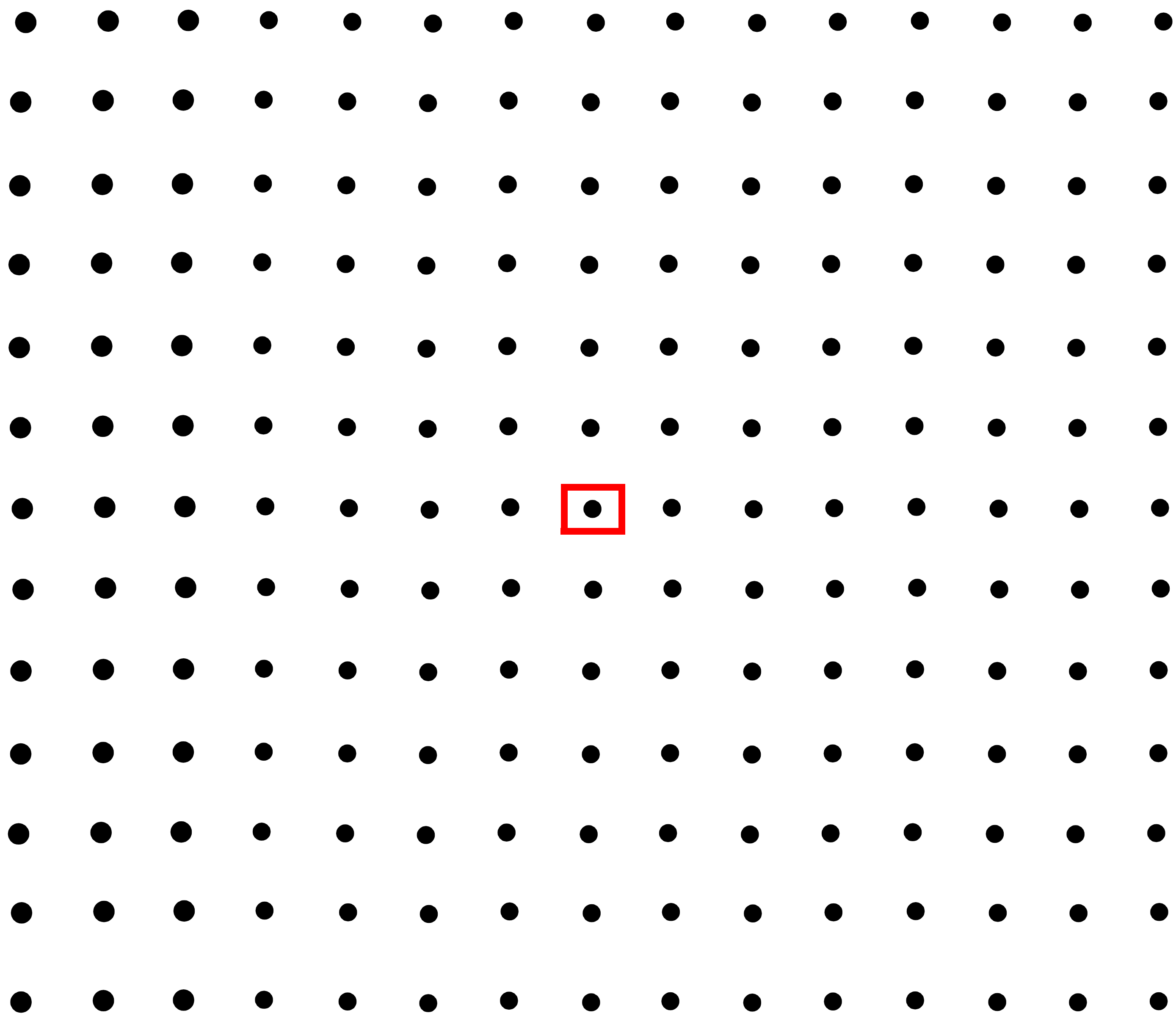
- Physics
  - » Observations of gravitation in the strong field, high velocity limit
  - » Determination of wave kinematics – polarization and propagation
  - » Tests for alternative relativistic gravitational theories
- Astrophysics
  - » Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
  - » Compact binary coalescence – neutron star/neutron star, black hole/black hole
  - » Neutron star equation of state
  - » Primeval cosmic spectrum of gravitational waves
- Gravitational wave survey of the universe

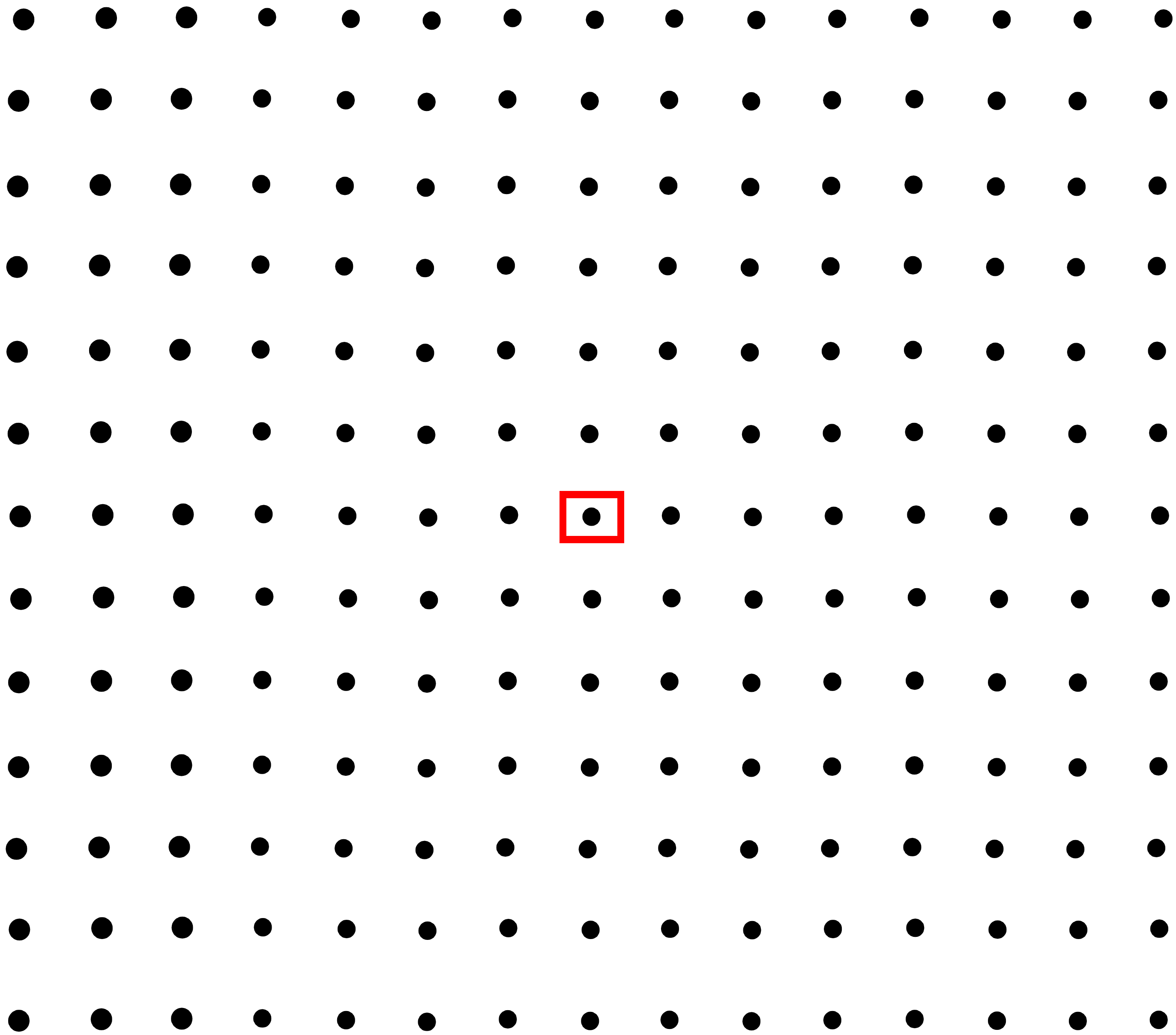


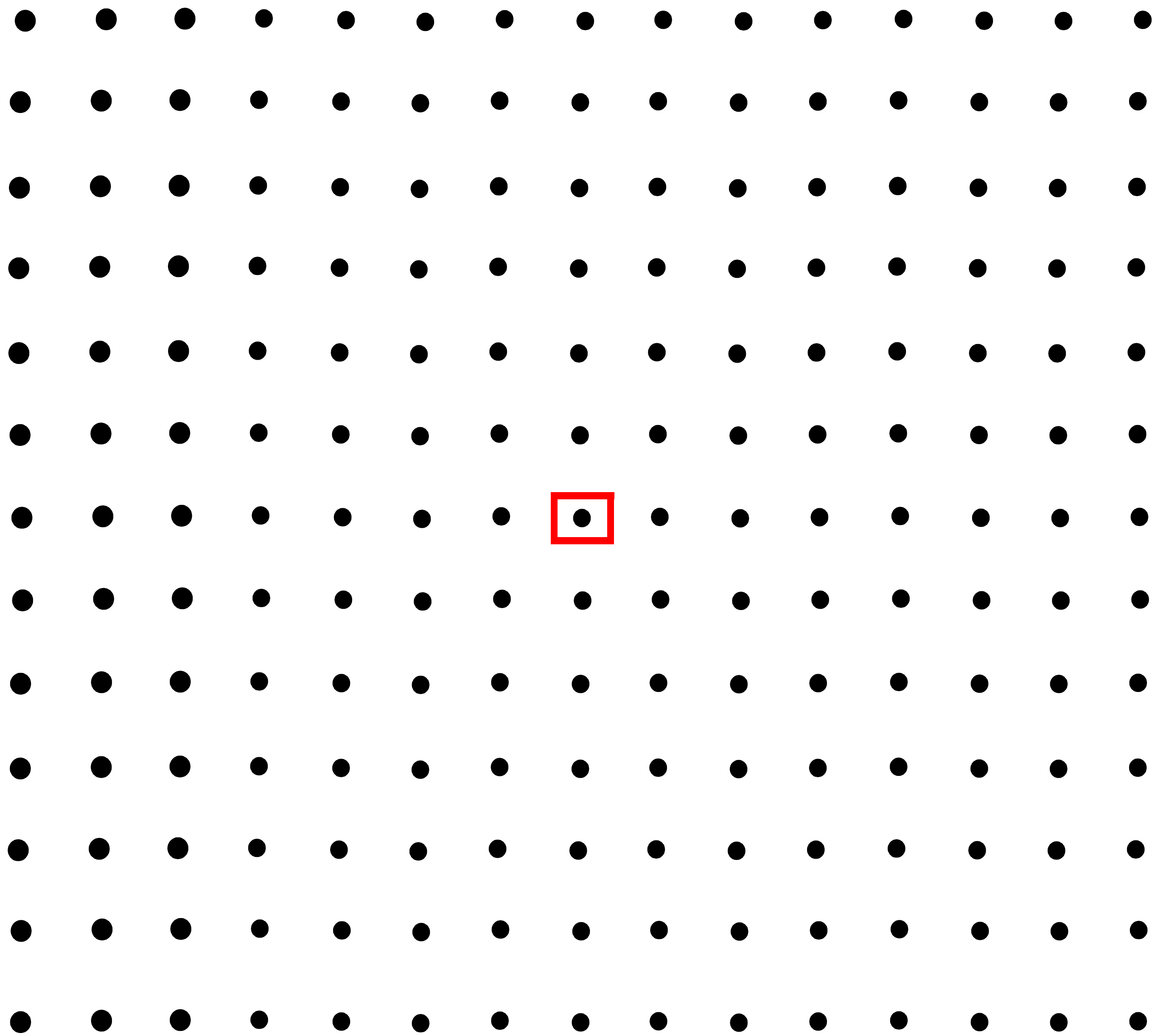


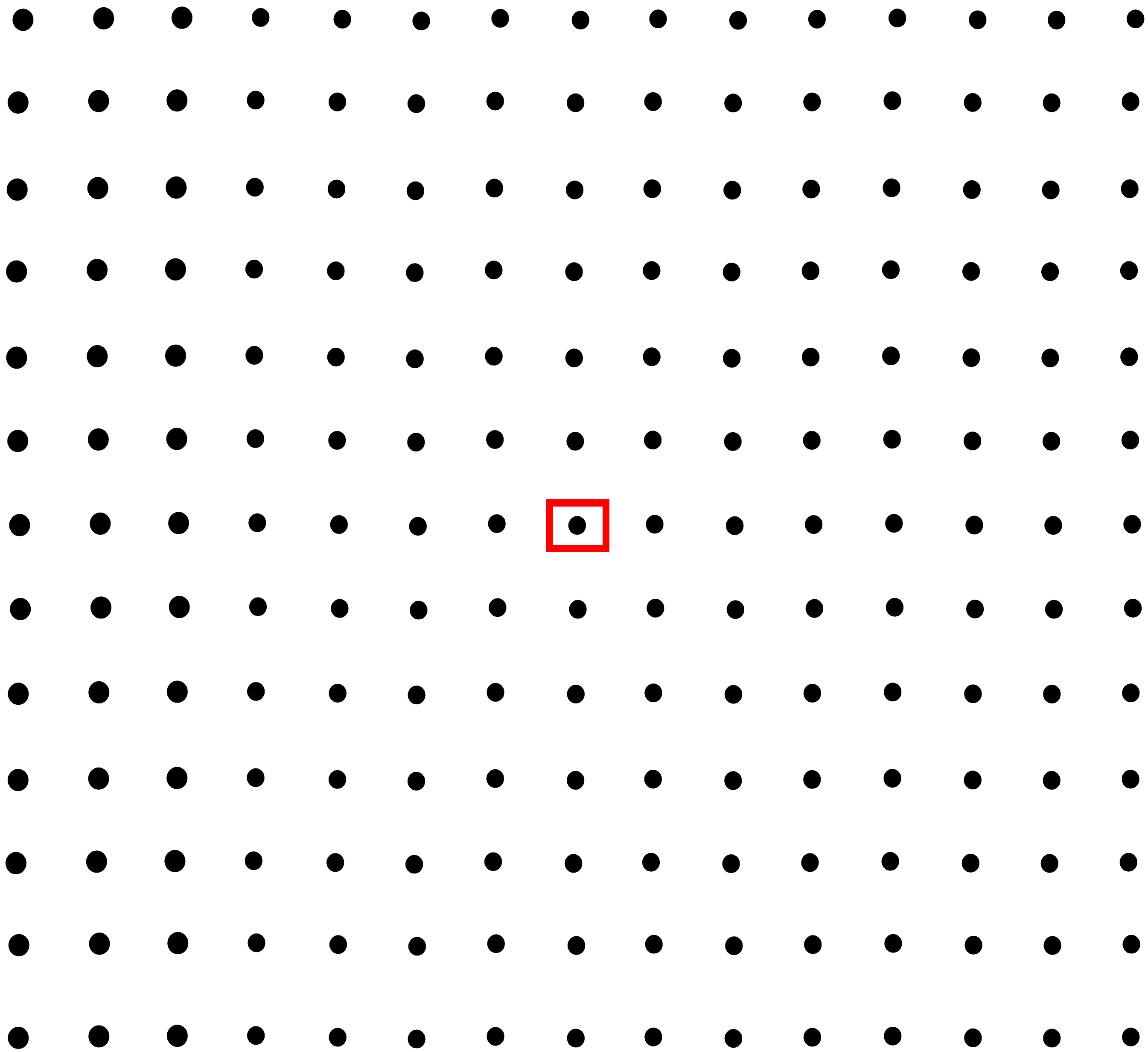


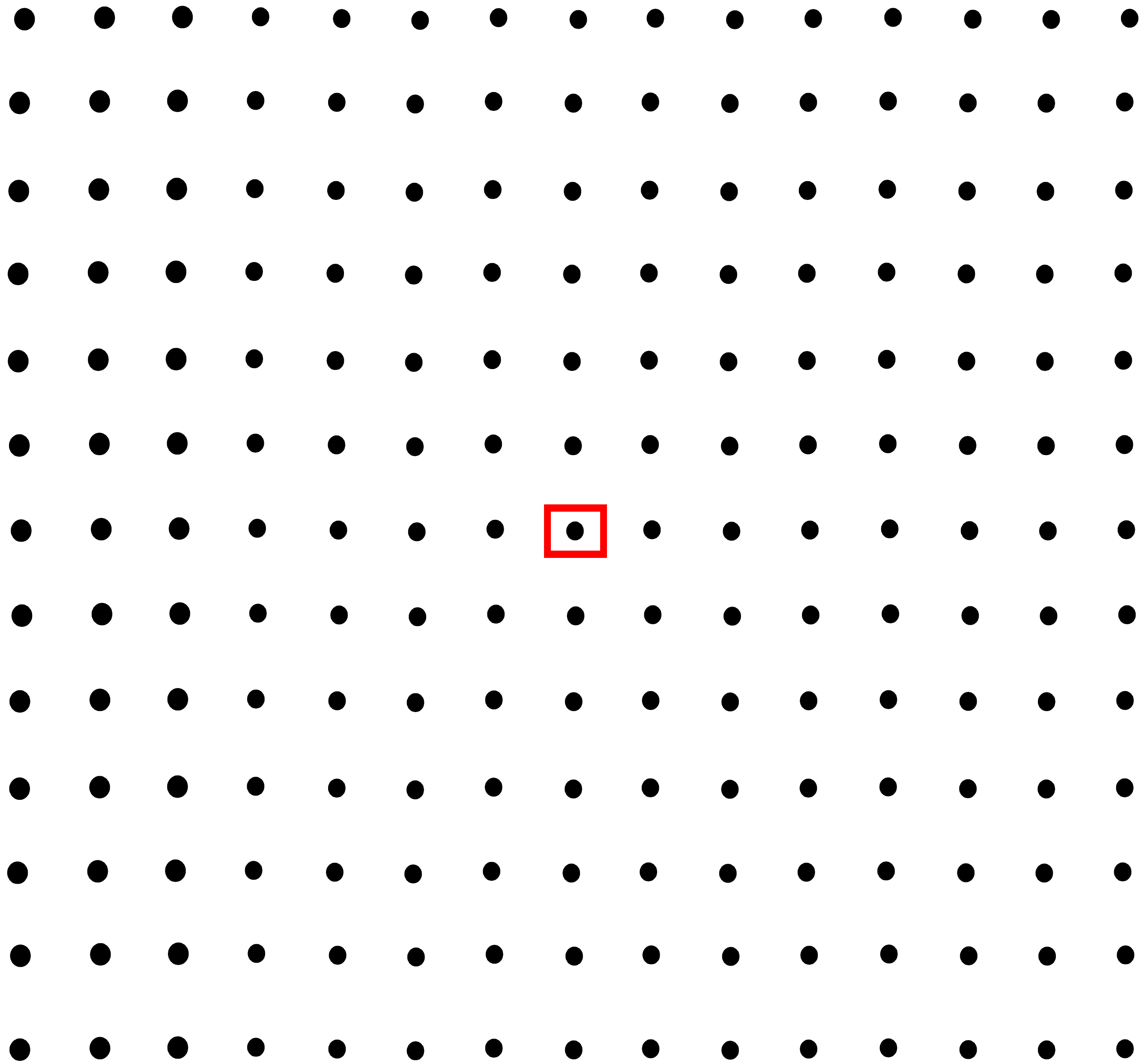


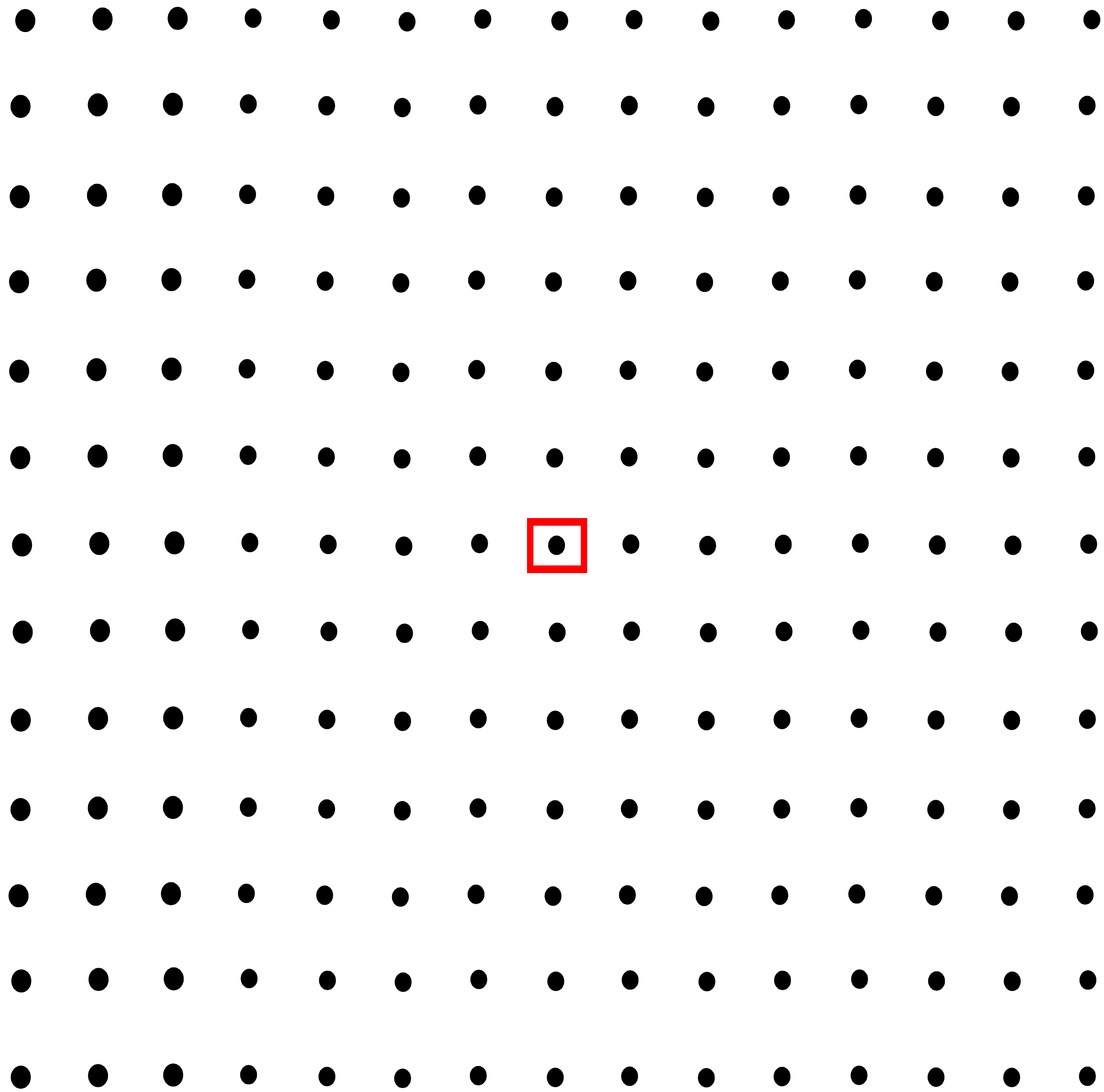


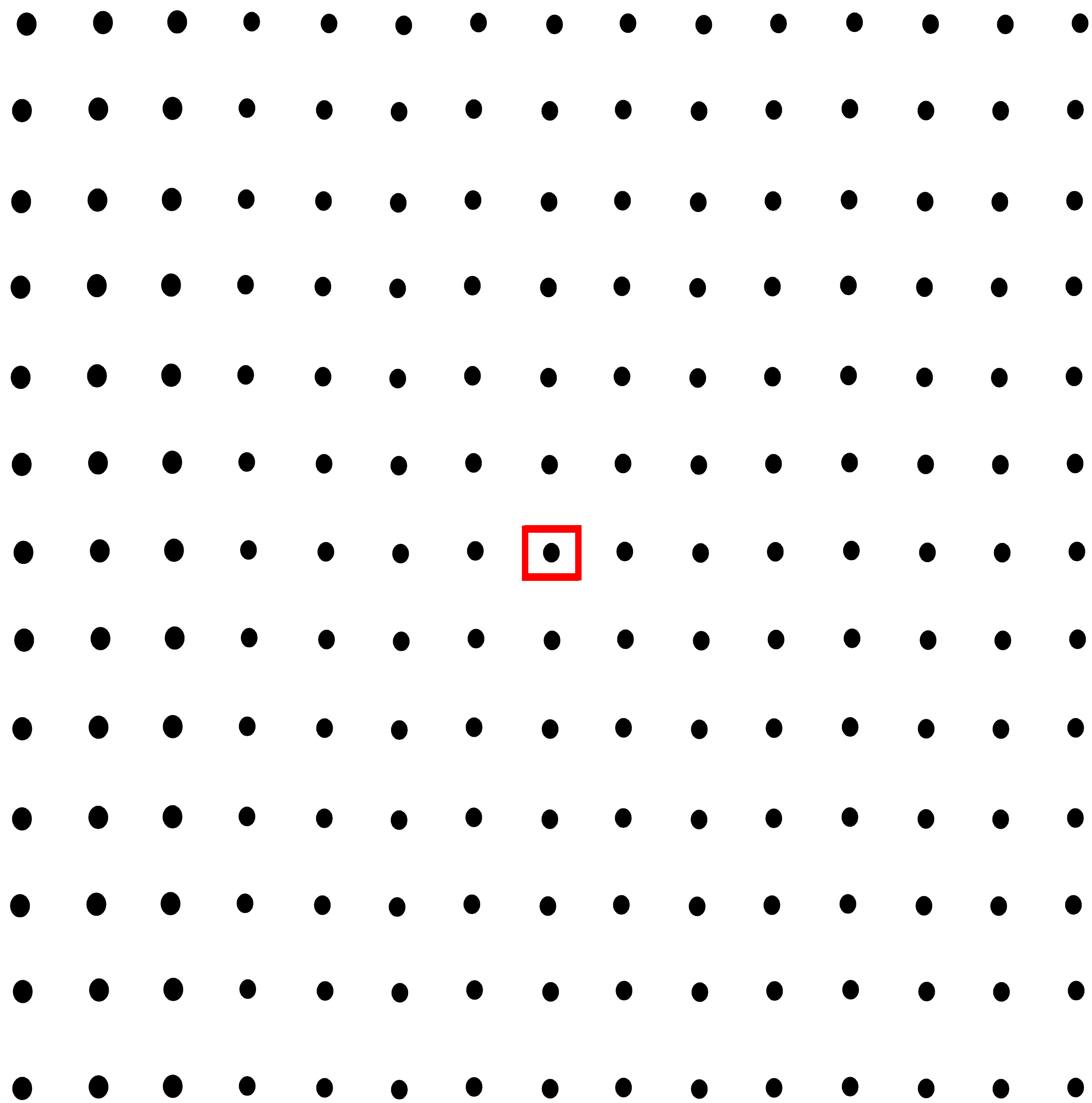


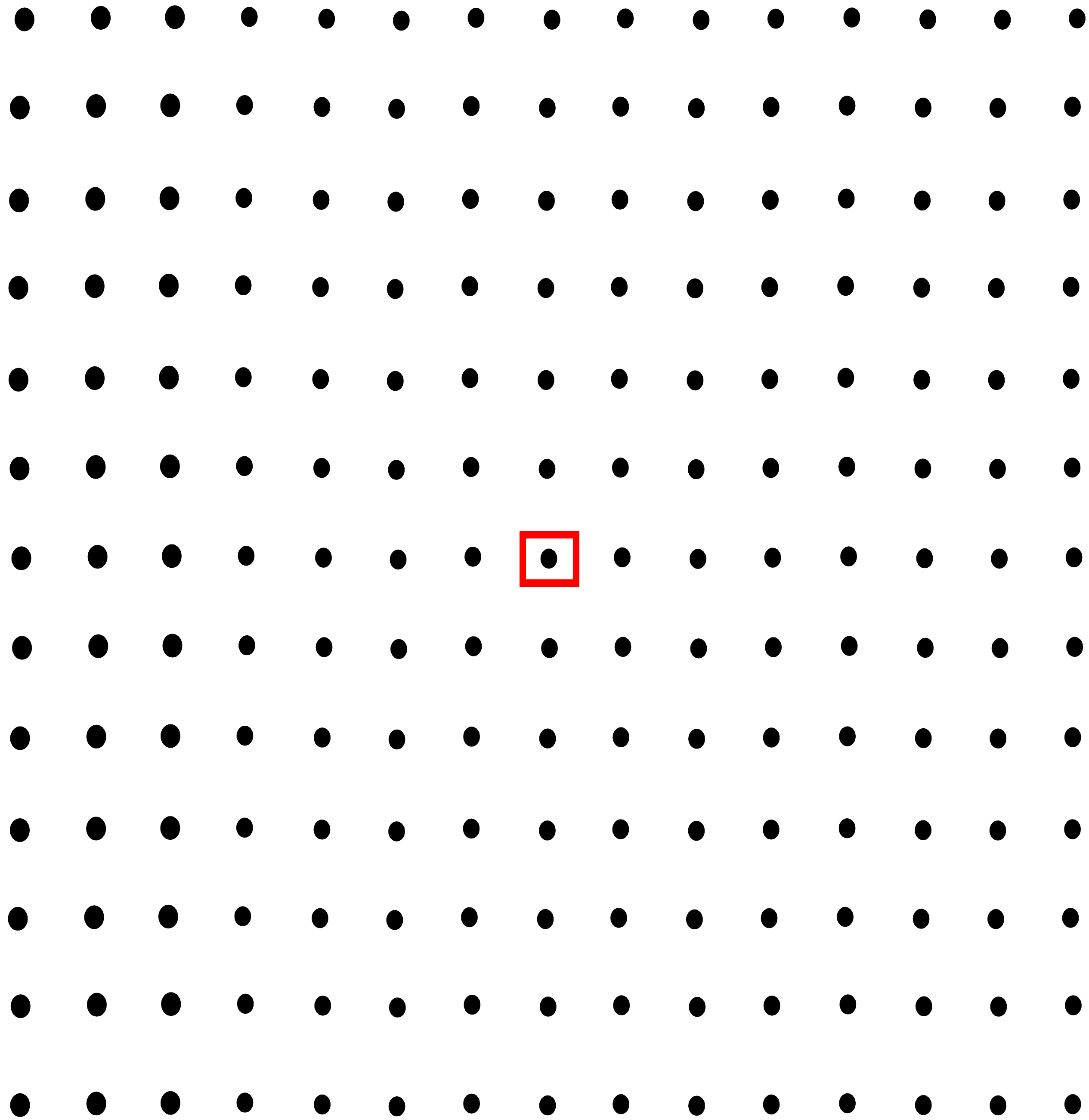


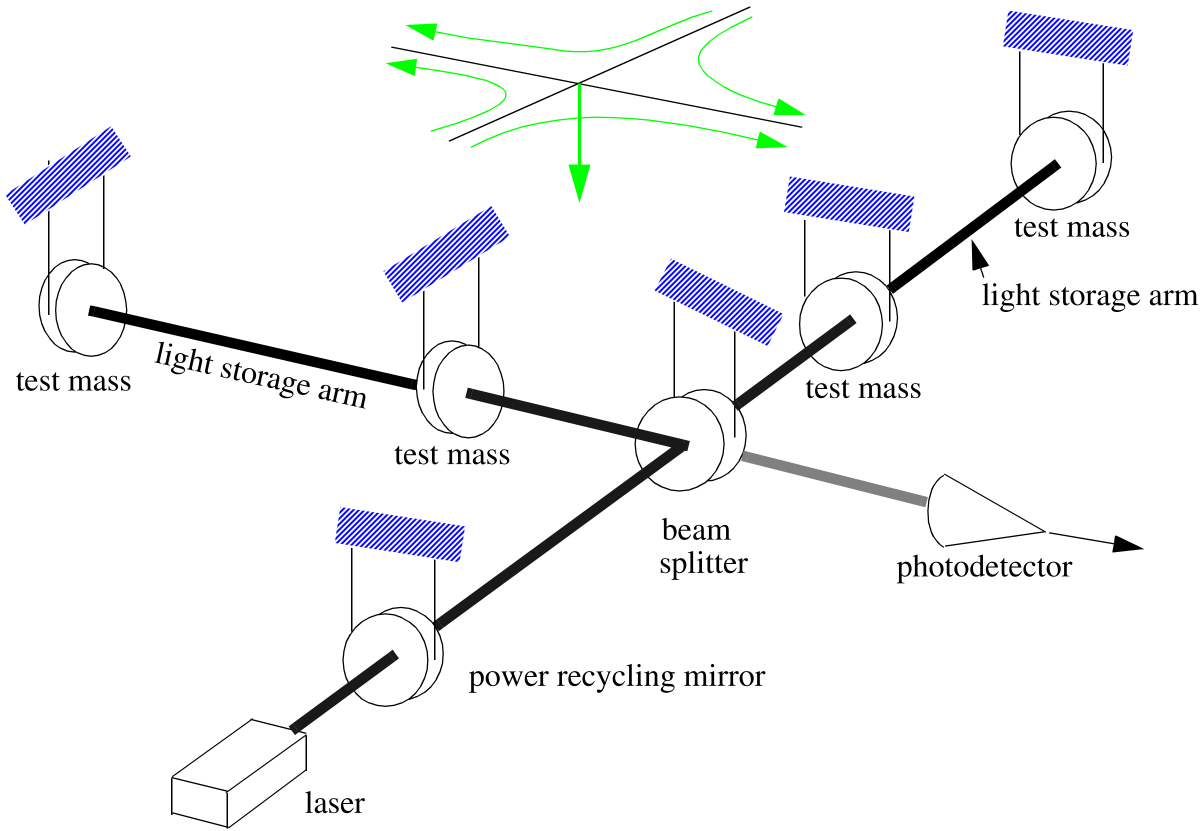











test mass
light storage arm
test mass
test mass
test mass
light storage arm
beam
splitter
photodetector
power recycling mirror
laser

Measurement challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{L b \sqrt{\dot{N} \tau}}$$

arm length = 4000 m

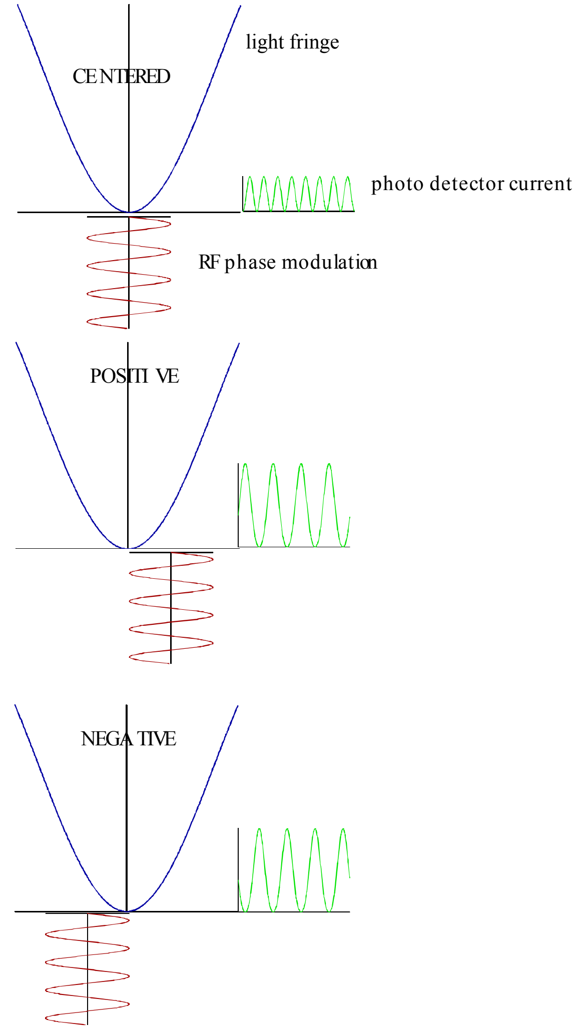
equivalent # of passes = 100

integration time

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



PENDULUM THERMAL NOISE

Pendulum Brownian motion

Dissipation leads to fluctuations

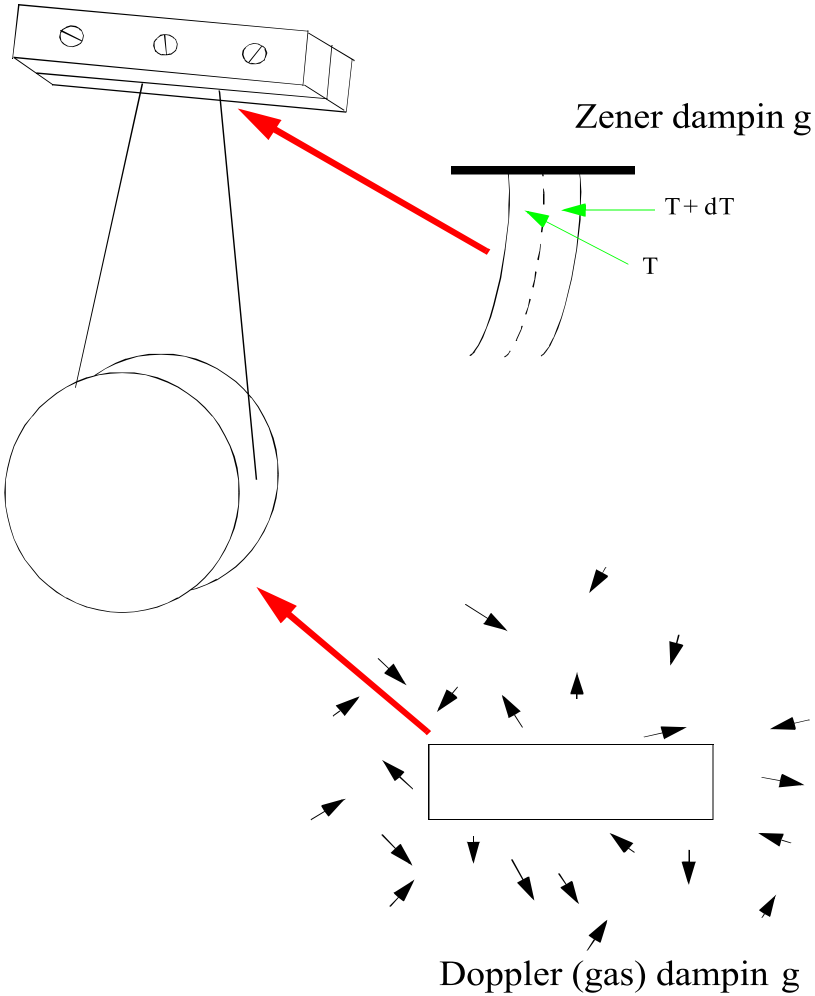
Tc = coherence or damping time

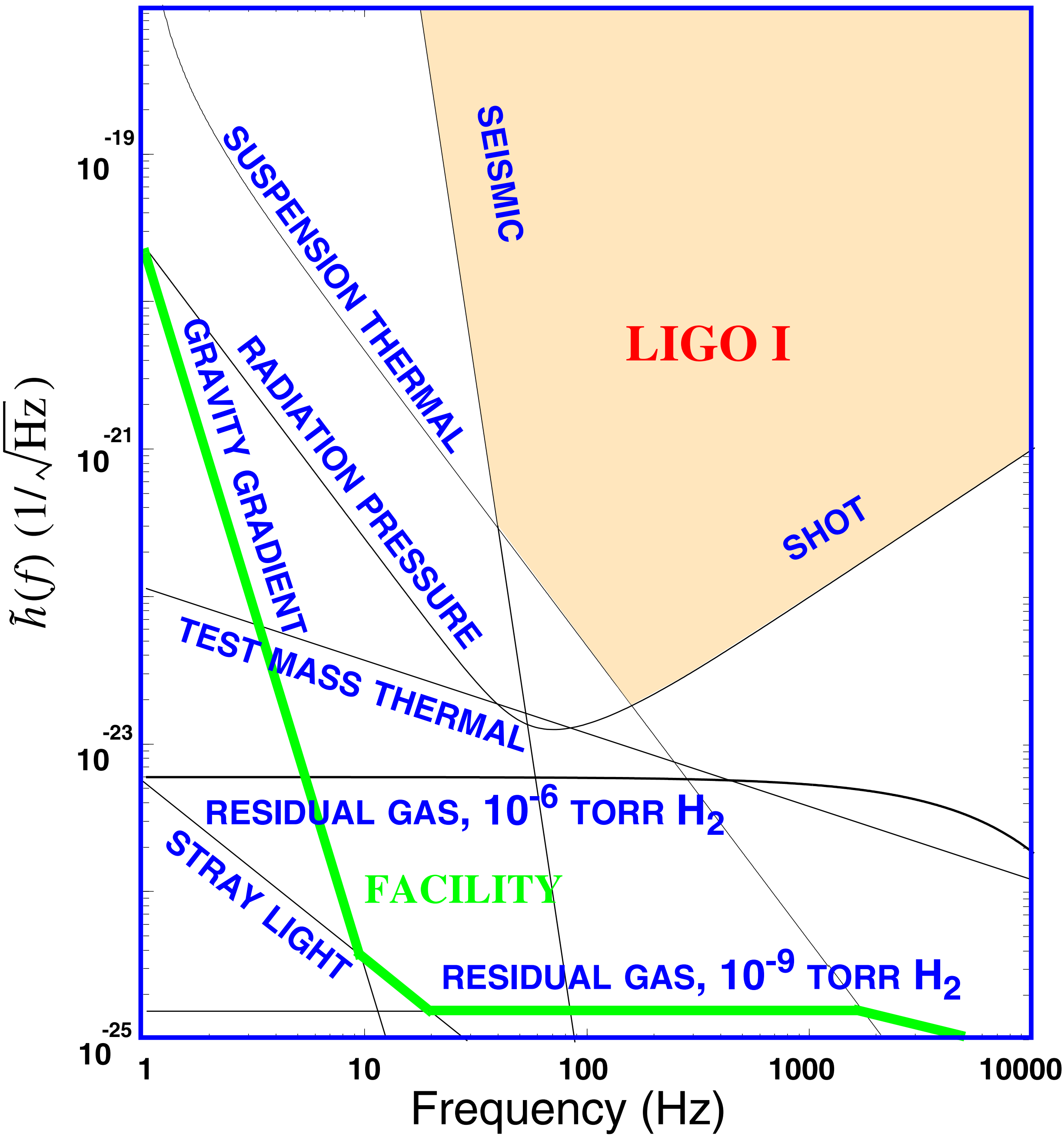
= Q x period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations



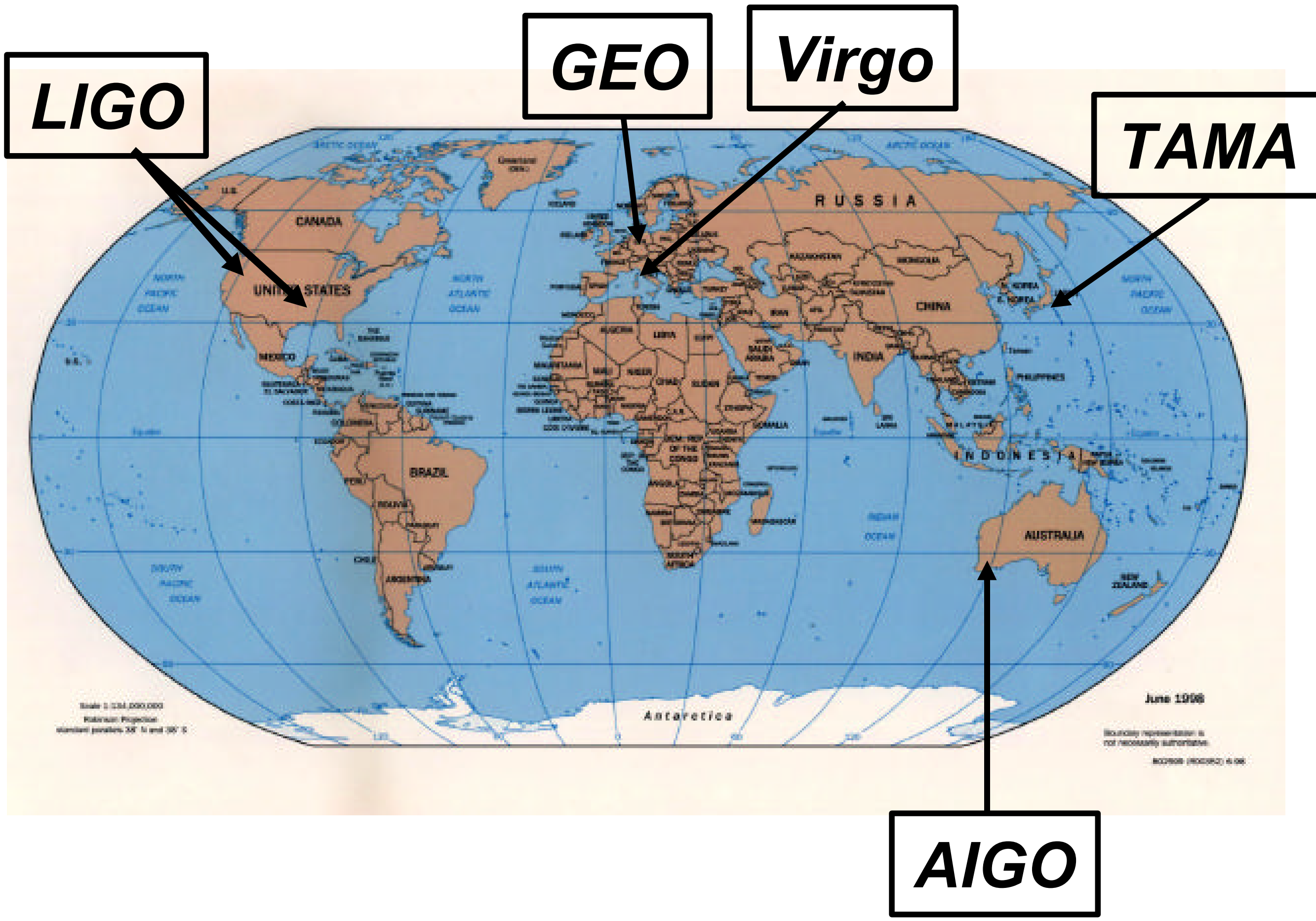


LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)

Interferometers

international network

Simultaneously detect signal (within msec)

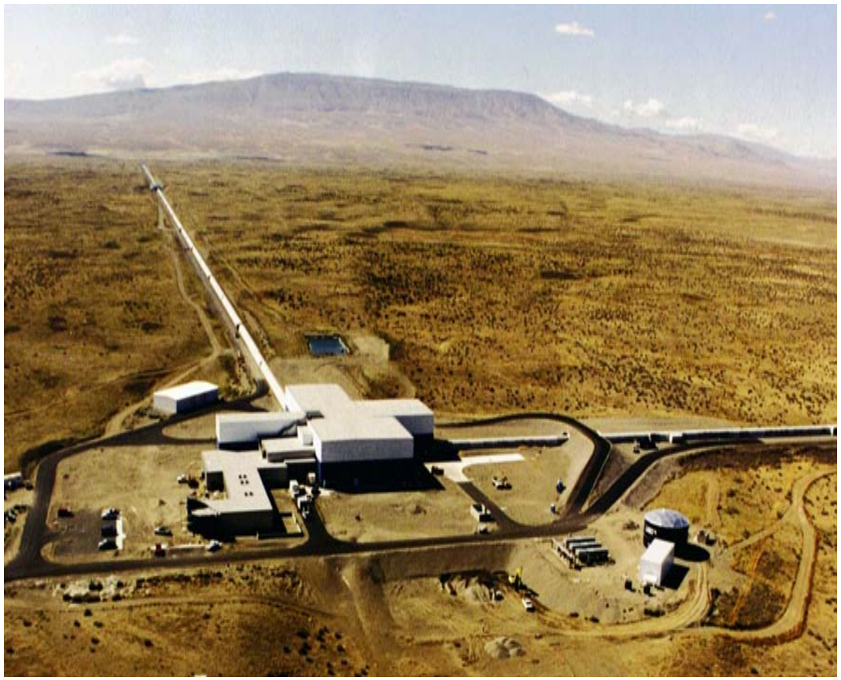


detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

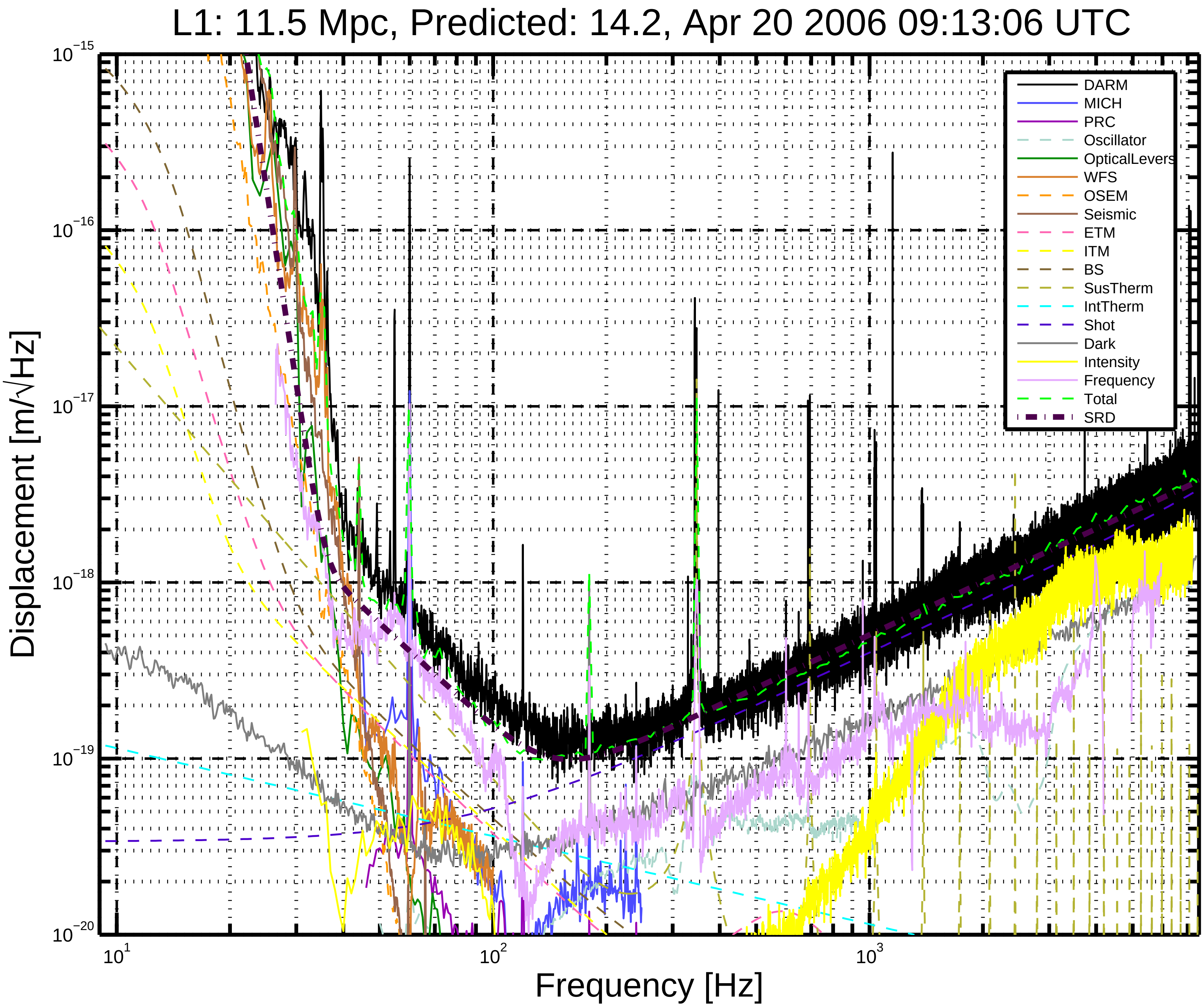
26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer


L1: 11.5 Mpc, Predicted: 14.2, Apr 20 2006 09:13:06 UTC
Displacement [m/√Hz]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

Classes of sources

- Compact binary inspiral: template search
  - BH/BH
  - NS/NS and BH/NS
- Low duty cycle transients: wavelets,T/f clusters
  - Supernova
  - BH normal modes
  - Unknown types of sources
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Foreground sources : gravitational wave radiometry
  - Cosmological isotropic background

Engineering and Technical Challenges

- Large scale economical vacuum system
- Low loss and spatial distortion optics
- Control of optical scattering
- Unprecedented laser frequency and amplitude stabilization
- Control of thermal (Brownian) noise
- High performance vibration isolation
- High speed digital control system

** LIGO research benefited industry*

LIGO

LIGO
beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

LIGO
vacuum equipment

LIGO

LIGO Optic

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Surface uniformity < 1 nm rms

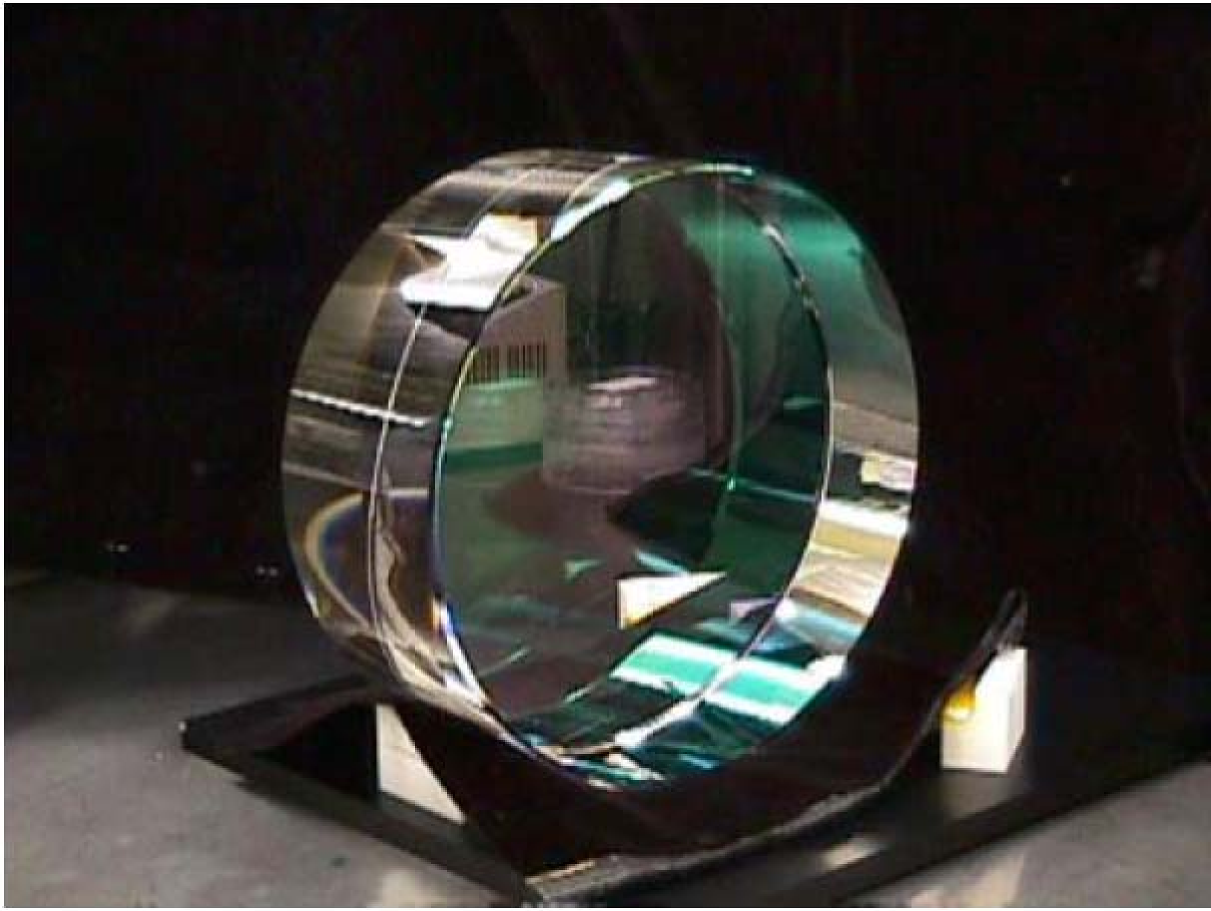
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 2 ppm

Uniformity <10^{-3}



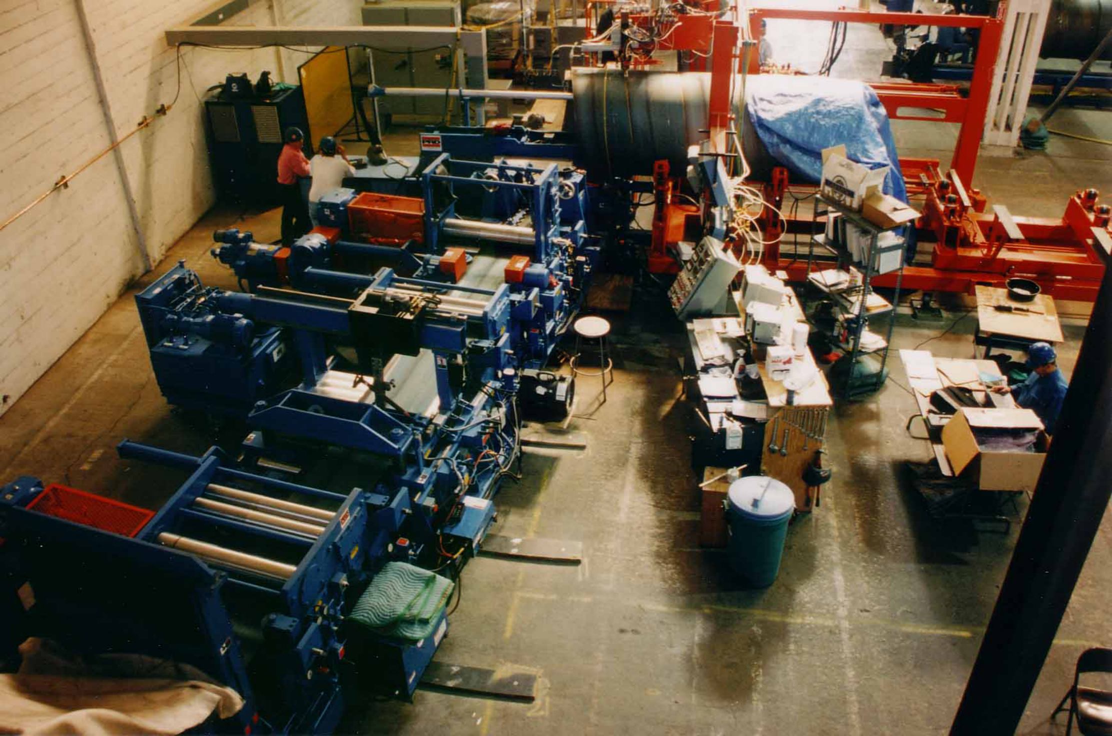
LIGO

Core Optics

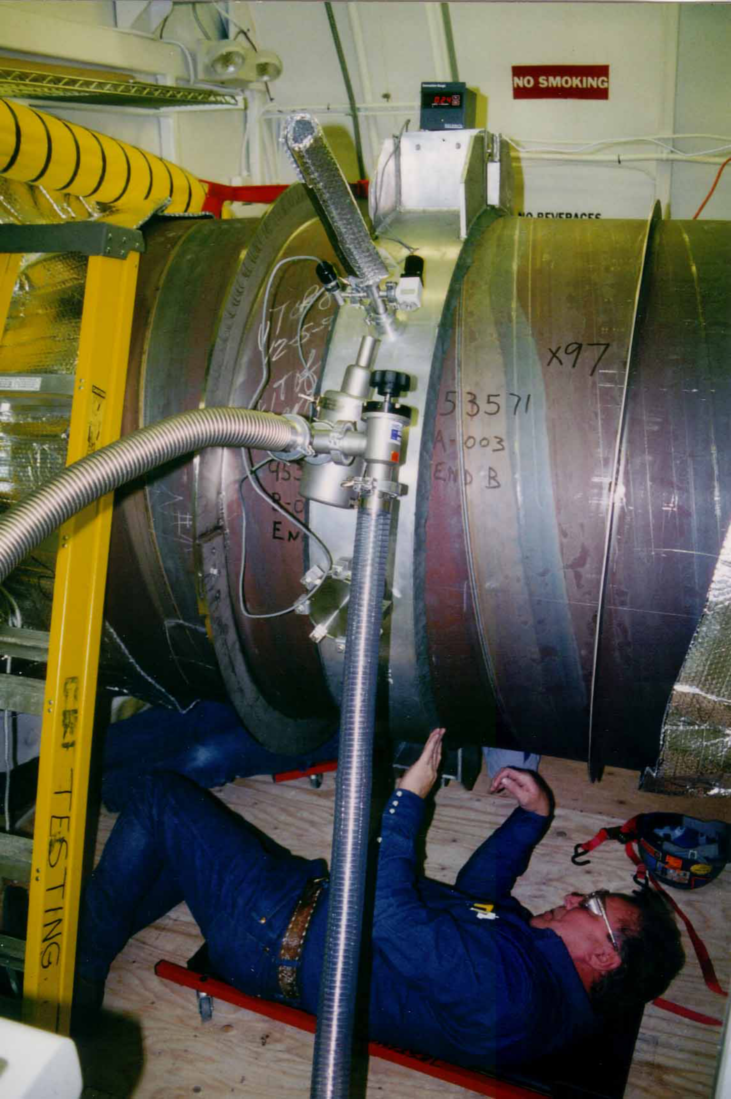
installation and alignment

LIGO Beam Tubes

- Interaction region between gravitational waves and laser interferometers
  - ›› 16 km of vacuum tubing at two sites
  - ›› initial detectors require 10^{-7} torr
  - ›› ultimate detectors require 10^{-10} torr
  - ›› needs to be economical
    - – minimal pumping, exploit passive nature of system
    - – new welding techniques - continuous spiral weld in 304L
    - – low outgassing materials - air bake to reduce hydrogen outgassing, total low 150C bake to reduce water and heavier molecule outgassing
    - – mass production cleaning
    - – global positioning system alignment




VER SIZE LOAD
Lampson
CPT
CPT


NO SMOKING
x97
53571
A-003
END B
TESTING

BEAM TUBE SCIENTIFIC REQUIREMENTS

- VACUUM REQUIREMENTS
  - ›› Residual gas
    - – Leak requirements
  - ›› Contamination
  - ›› Operational requirements
    - – Pump down time
    - – Isolation from chambers
    - – Reliability
- MECHANICAL AND OPTICAL REQUIREMENTS
  - ›› Clear Aperture
  - ›› Forward and Backscatter from walls and baffles
  - ›› Motion of tube walls and baffles

BEAM TUBE REQUIREMENTS

- LEAK LIMITS
  - ››Component Level
    - – 1 x 10^{-10} torr liters/sec
  - ››2 km module with 2500 liter/sec end pumps
    - – 1 x 10^{-9} torr liters/sec
- CONTAMINATION ON OPTICS
  - ›› less than 1 monolayer of hydrocarbon/month

BEAM TUBE REQUIREMENTS

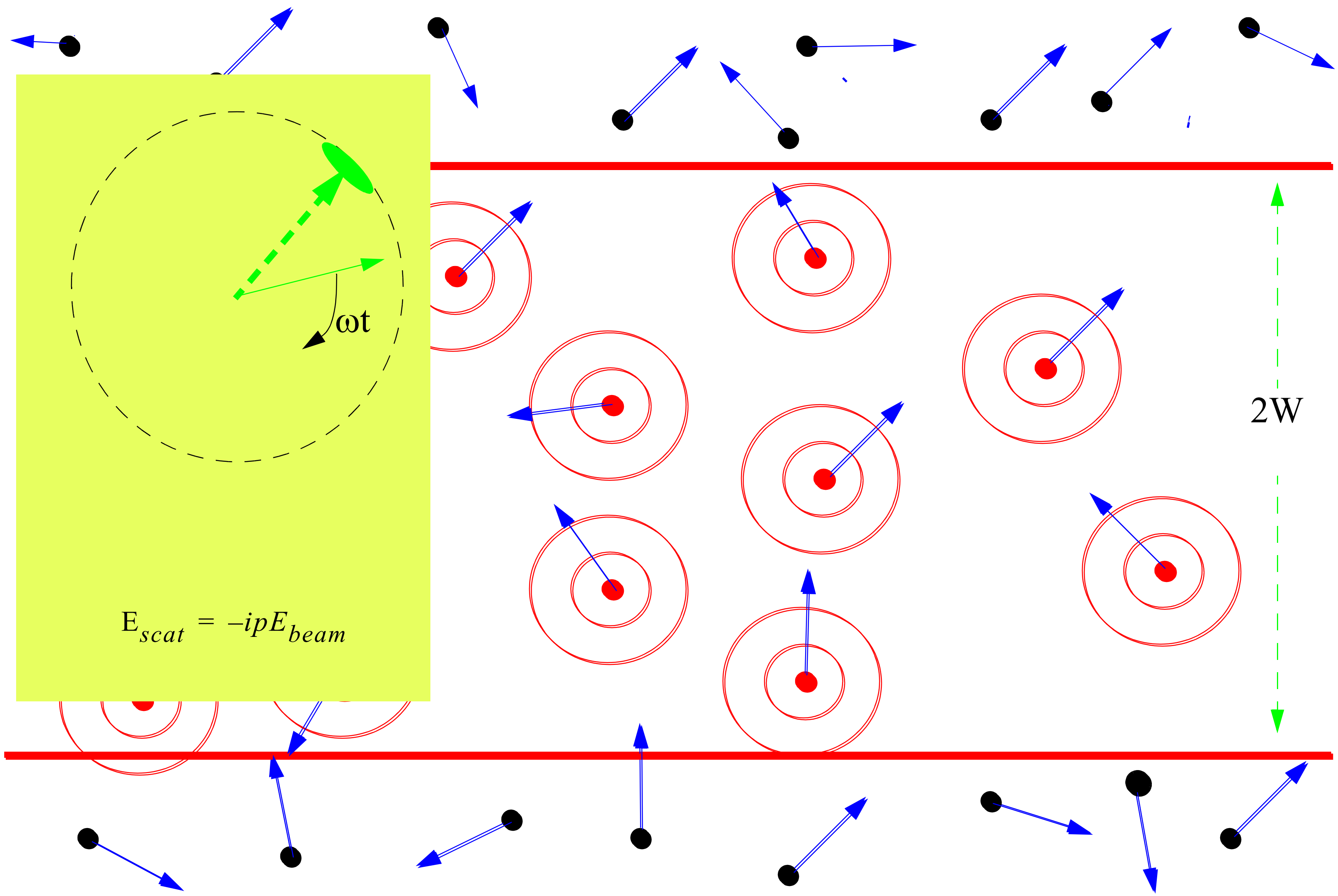
- OPERATIONAL REQUIREMENTS
  - ›› Time to reach required pressure < 2 months
  - ›› Capability to isolate beamtubes from chambers
  - ›› Reliability: leak free state for > 20 years

- MECHANICAL AND OPTICAL REQUIREMENTS
  - ›› Unobstructed aperture 1 meter
  - ›› Backscatter from baffles and tube between 0.5 to 1 micron wavelengths < 2 x 10^{-3} sr^{-1} for angles of incidence greater than 45 degrees
  - ›› Motion of tubes at baffles not to exceed 2 x the ambient seismic noise except in narrow bands

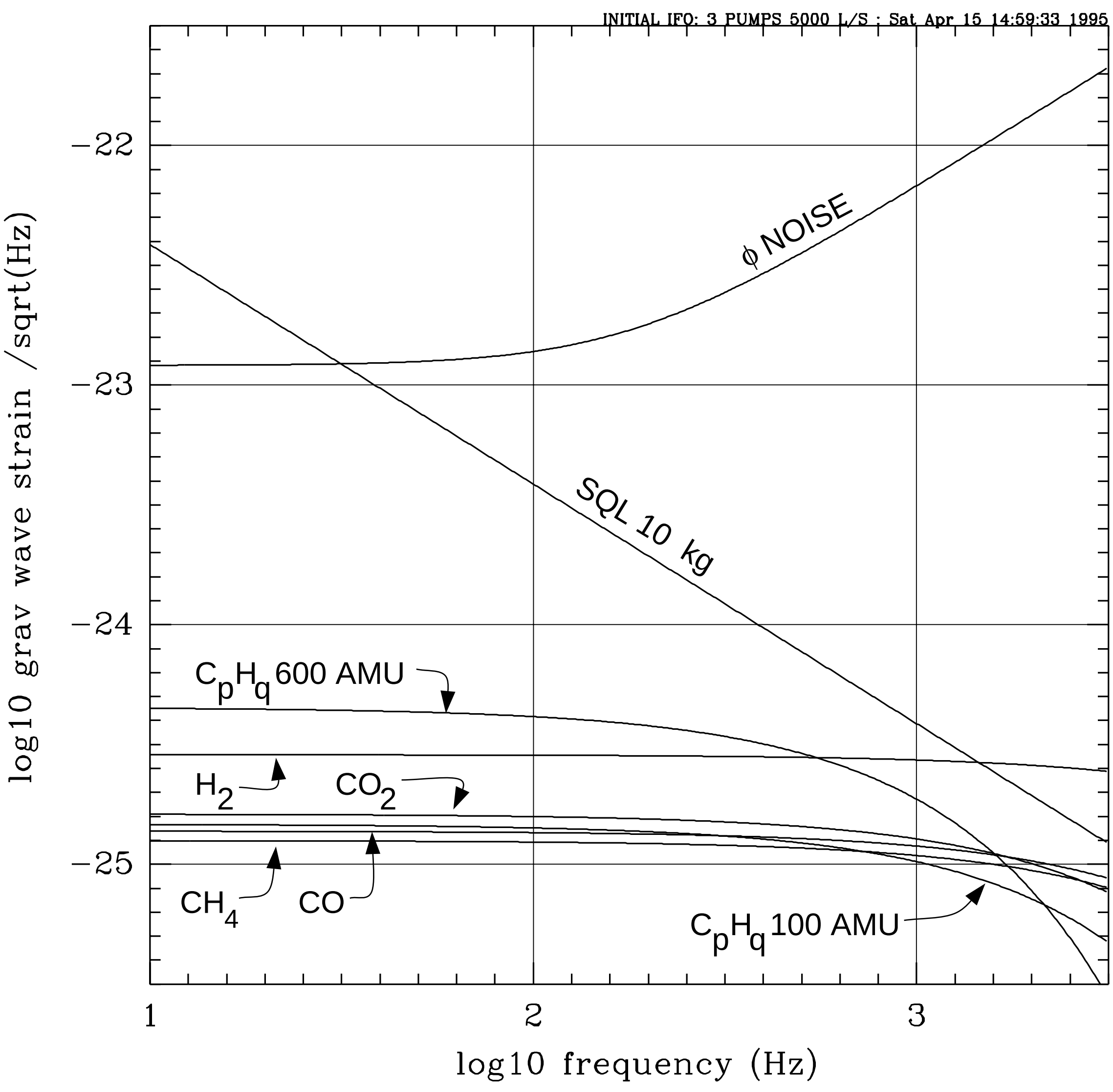
Beam Tube Properties

module length	2 km
25 cm diameter pump ports/module	9
radius of beam tube	62 cm
volume of module	4.831×10^{6} liters
area of module	1.55×10^{8} cm^2
initial pumping speed/surface area	1.94×10^{-5} liters/sec/cm^2
length/short section	1.90×10^{3} cm
wall thickness	3.23×10^{-1} cm
stiffener ring spacing	76 cm
stiffening ring width	4.76×10^{-1} cm
stiffening ring height	4.45 cm
expansion joint wall thickness	2.67×10^{-1} cm
expansion joint convolutions	9
expansion joint longitudinal spring rate	1.5×10^{9} dynes/cm

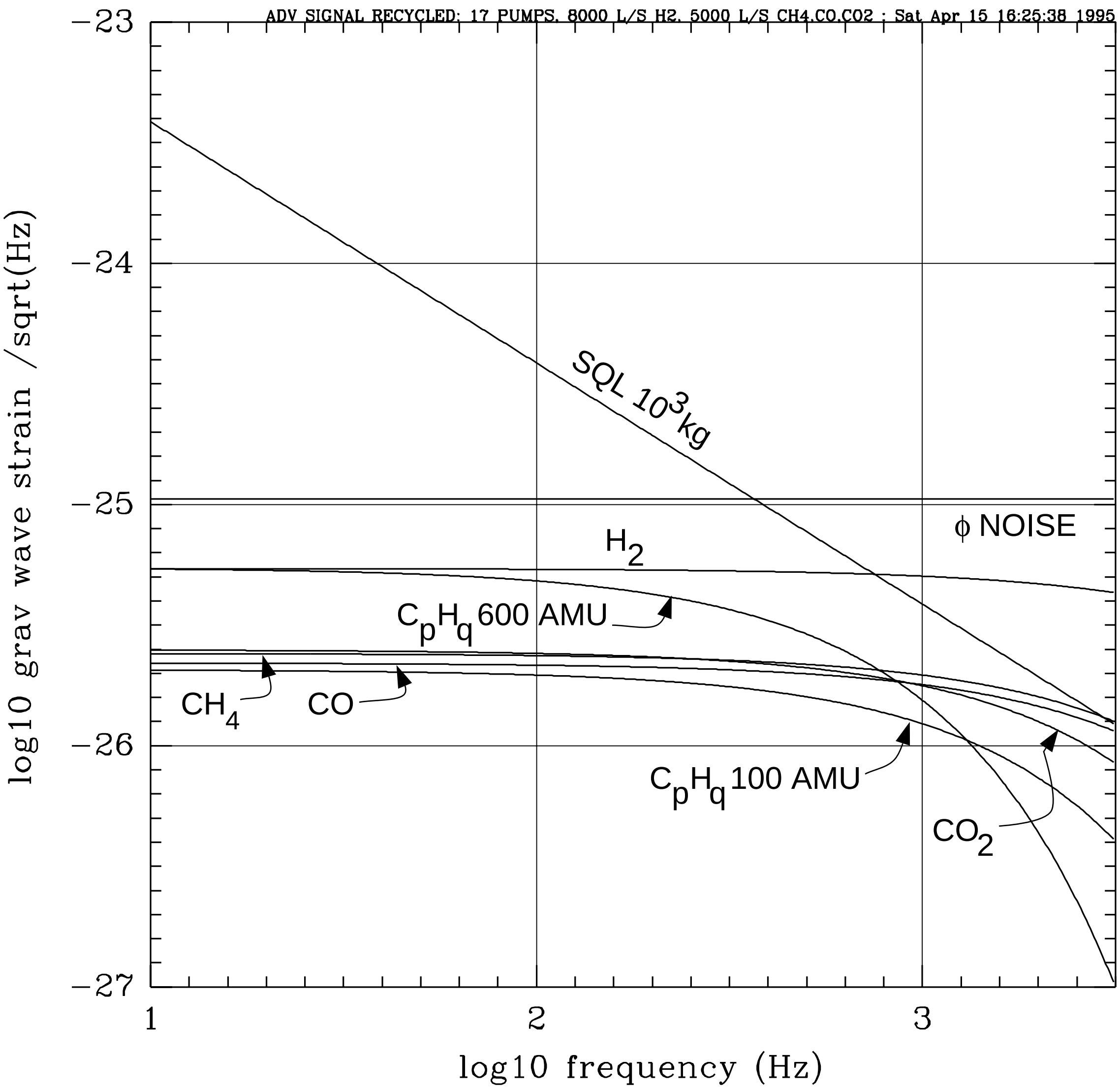
Phase noise from molecular scattering



Initial Interferometer Noise Budget



Advanced Interferometer Noise Budget



Advanced amplitude recycled interferometer parameters:

$A_m = 10^{-5}$

$P_{in} = 100$ W $\qquad P_{circ} \sim 1$ MW

$\varepsilon_{opt} = 0.3$

$\lambda = 1.06\ \mu$

BEAM TUBE BAKEOUT

- Requirements and goals

  ›› Initial interferometer residual gas phase noise (100Hz)

$$h(f) < 5\times10^{-24}$$

  ›› Advanced interferometer residual gas phase noise (100Hz)

$$h(f) < 1.5\times10^{-25}$$

  ›› Relation bewteen pressure and phase noise

$$h(f) = 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

BEAM TUBE BAKEOUT

Table 1: Residual gas phase noise factor and average pressure

Gas Species	$R(x/H_2)$	Requirement (torr)	Goal (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}
AMU 100 hydrocarbon	38.4	7.3×10^{-10}	7×10^{-13}
AMU 200 hydrocarbon	88.8	$1.4x10^{-10}$	$1.4x10^{-13}$
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	$2.5x10^{-11}$	$2.5x10^{-14}$
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	$9.0x10^{-12}$	$9.0x10^{-15}$

BEAM TUBE BAKEOUT

- Average pressure and outgassing rate

$$\langle p \rangle_L = J\left[\frac{2\pi a L}{nF} + \frac{L^2}{4va^2(n-1)^2}\right]$$

- Outgassing rate vs temperature and time

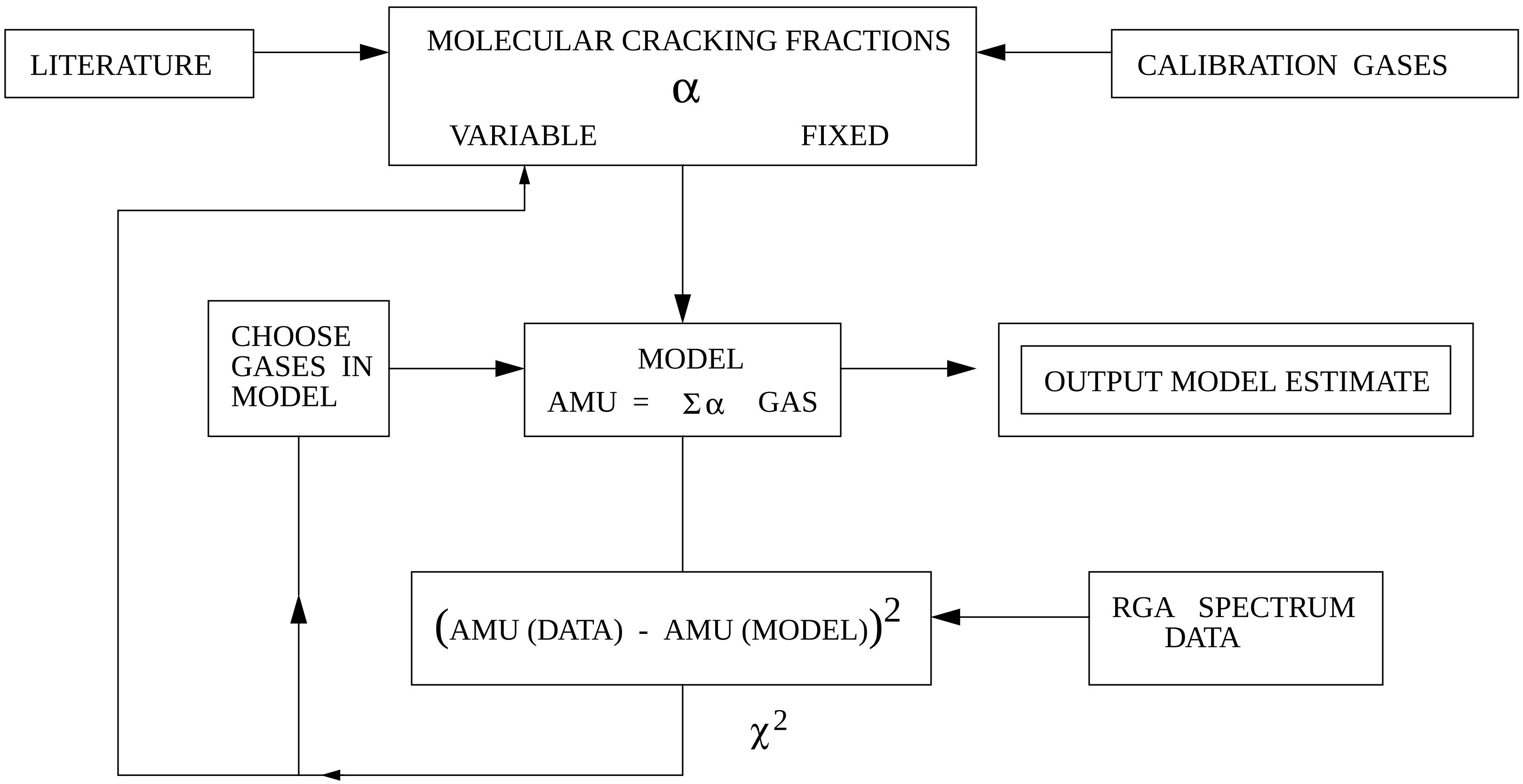
$$J(T) = ae^{-\frac{T_0}{T}}$$

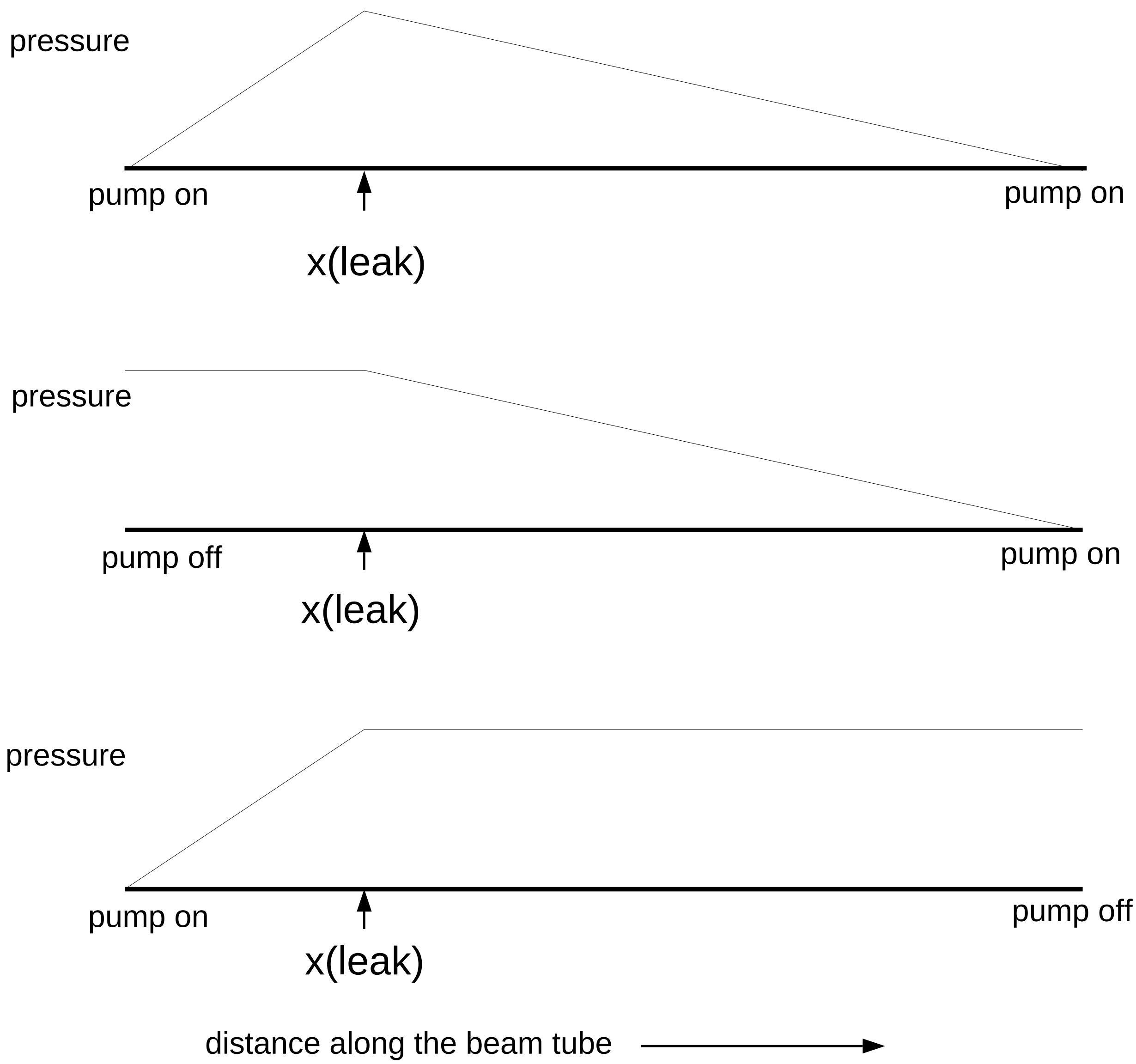
›› Typical: $5000 < T_0 < 10000$ K

›› Time dependence

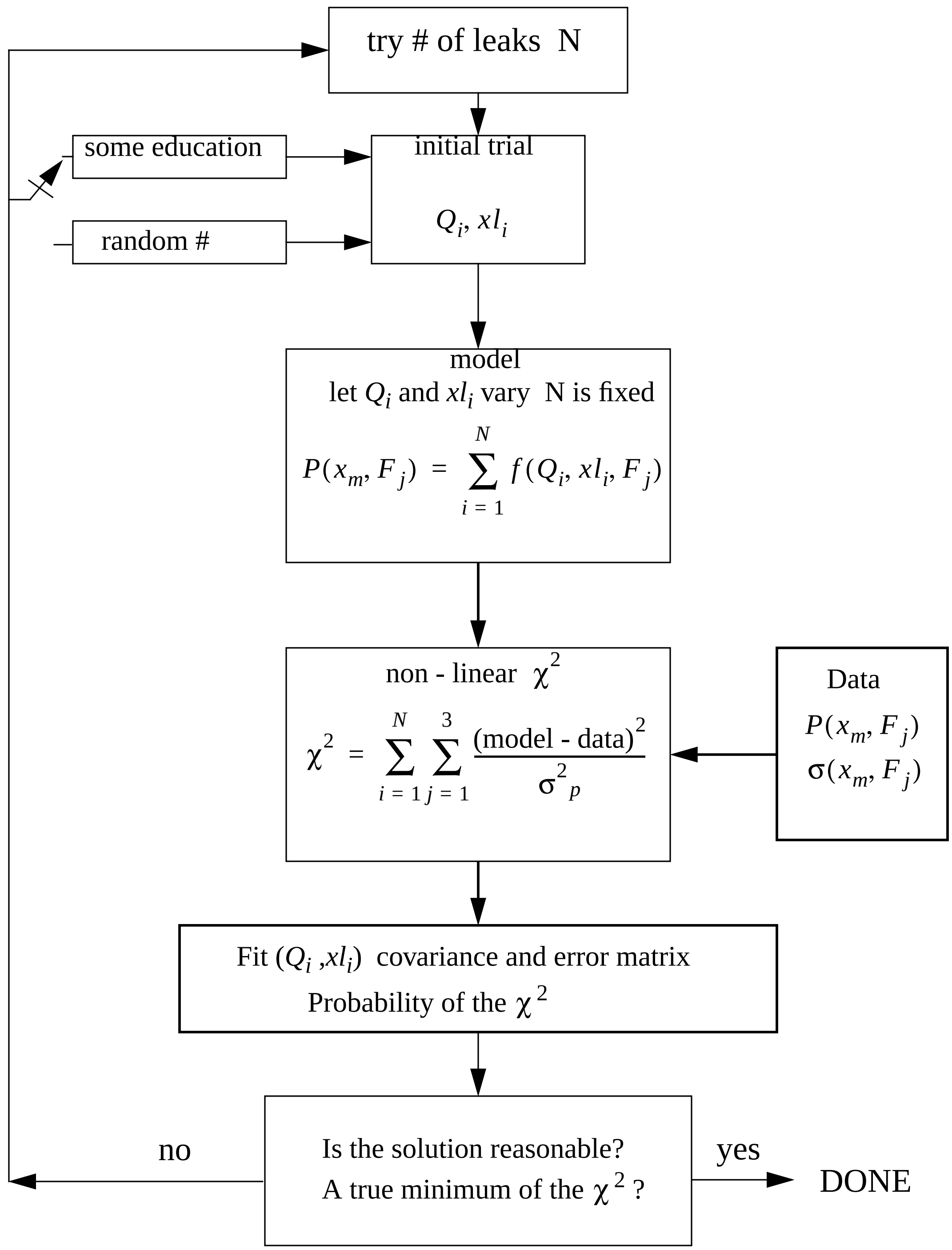
– 1 /t surface adsorption with distribution of binding site energies

– $(1/t)^{0.5}$ diffusion followed by evaporation


LITERATURE
MOLECULAR CRACKING FRACTIONS
α
VARIABLE
FIXED
CALIBRATION GASES
CHOOSE GASES IN MODEL
MODEL
AMU = Σα GAS
OUTPUT MODEL ESTIMATE
(AMU (DATA) - AMU (MODEL))2
RGA SPECTRUM DATA
χ2



Leak pressure profiles in tube



Leak localization algorithm

Beam Tube Cleaning

- Cleaning steps
  - ›› Hot water and detergent - Mirachem 500 spray wash
    - – 30/1 water/Mirachem - 500
    - – 1 cc/ cm^2
  - ›› Steam rinse
    - – 2 cc/ cm^2
    - – 7 - 8.5 atmospheres pressure
    - – 58 - 65 C surface temperature of steel
  - ›› Applied by rotating wand that traverses the tube longitudinally at 20 cm / minute
- Surface analysis
  - ›› Fourier Transform Infrared Spectroscopy FTIR
    - – Sample taken by pouring 2 - isopropanol in strip down tube
    - – Analysis made in professional testing laboratory


LB.

Beam Tube Cleaning

›› Auger electron spectroscopy

– Sample strips placed in tube

– Analysis made in surface measurement lab after cleaning

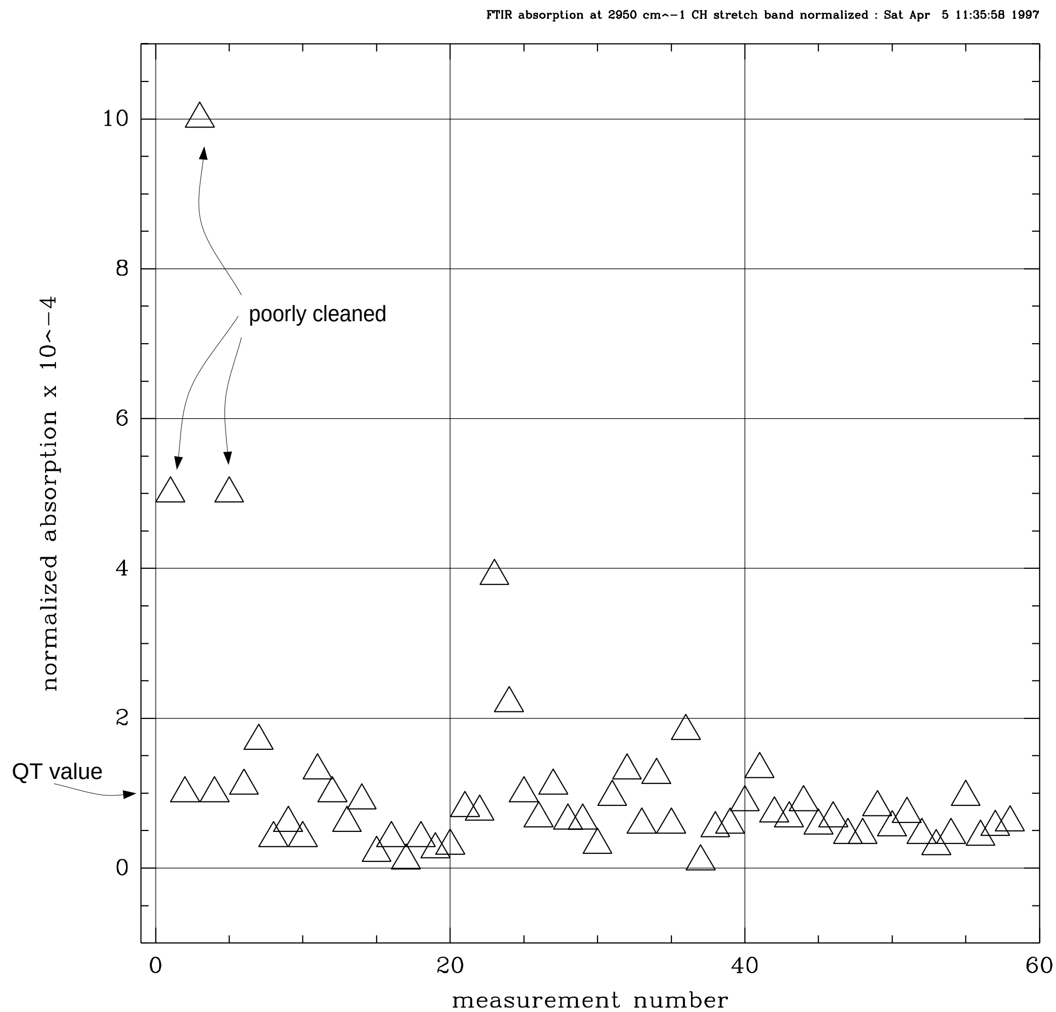
– Sensitive to elemental carbon

– Useful to determine state of rinse by measurement of sodium and calcium

››Water drop adhesion tests

– Qualitative but can be made on location

– Useful in diagnosis of oil layers (poor adhesion) and incomplete rinse of detergent (super adhesion and wetting).



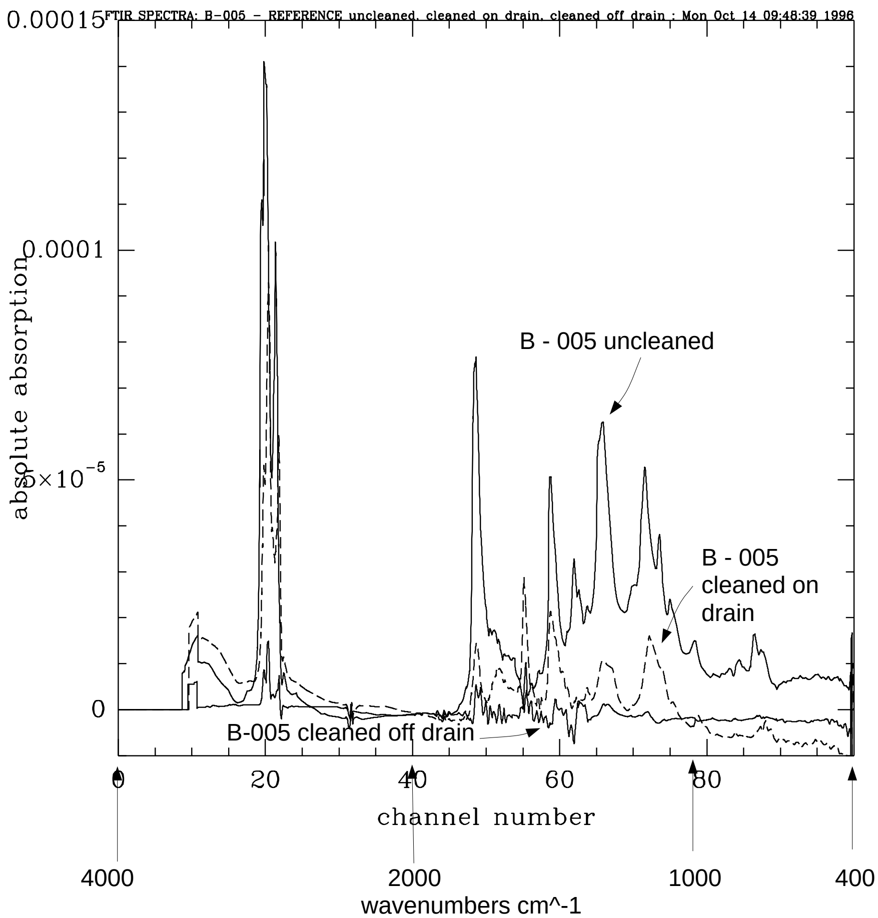
Normalized absorption z at 2950 cm^{-1}

$$z = \frac{(\ln(I/I_0)_{\text{sample}} - \ln(I/I_0)_{\text{reference}}) \times \text{KBr area} \times \text{sample volume in tube}}{\text{sample volume evaporated on KBr} \times \text{area of tube exposed}}$$

Typical values:

Area of tube exposed = 2 x 10^4 cm^2
Sample volume in tube = 2 liters
Sample evaporated = 200 cc
KBr area = 0.6 cm^2

$z \approx 1 \times 10^{-4}$ corresponds to 0.1 monolayer of 100 amu hydrocarbon



Spectra of tube B-005 uncleaned, and cleaned with sample taken along and off the drain line. The off drain sample is more characteristic of the average wall condition. The spectra have had the reference spectrum of the isopropanol subtracted, hence the negative values of the absorption.

Table 1: Auger analysis 270 ev Carbon line given in terms of 10^3 counts in 1.64 minutes vs A^+ milling time

tube # or surface	*condition*	*0 min*	*1 min*	*2 min*	*3 min*	*4 min*
22B	uncl	57.4	24.3	16.5	11.8	10.8
22B	cl	26.1	8.1	6.5	4.4	5.1
B-005	uncl	59.5	17.6	10.6	8.3	7.1±1.0
B-005	cl 1	24.3	5.2	2.3	1.0±1.0	0.0±1.0
B-005	cl 2	21.9	6.7	2.1	1.0±1.0	0.0±1.0
Oxidized	super cl	35.1	22.1	3.0	2.7±1.0	2.4±1.0
smooth	super cl	27.9	2.9	0.0±1.0		
rough	oily	61.9	64.9	63.2	62.3	62.3

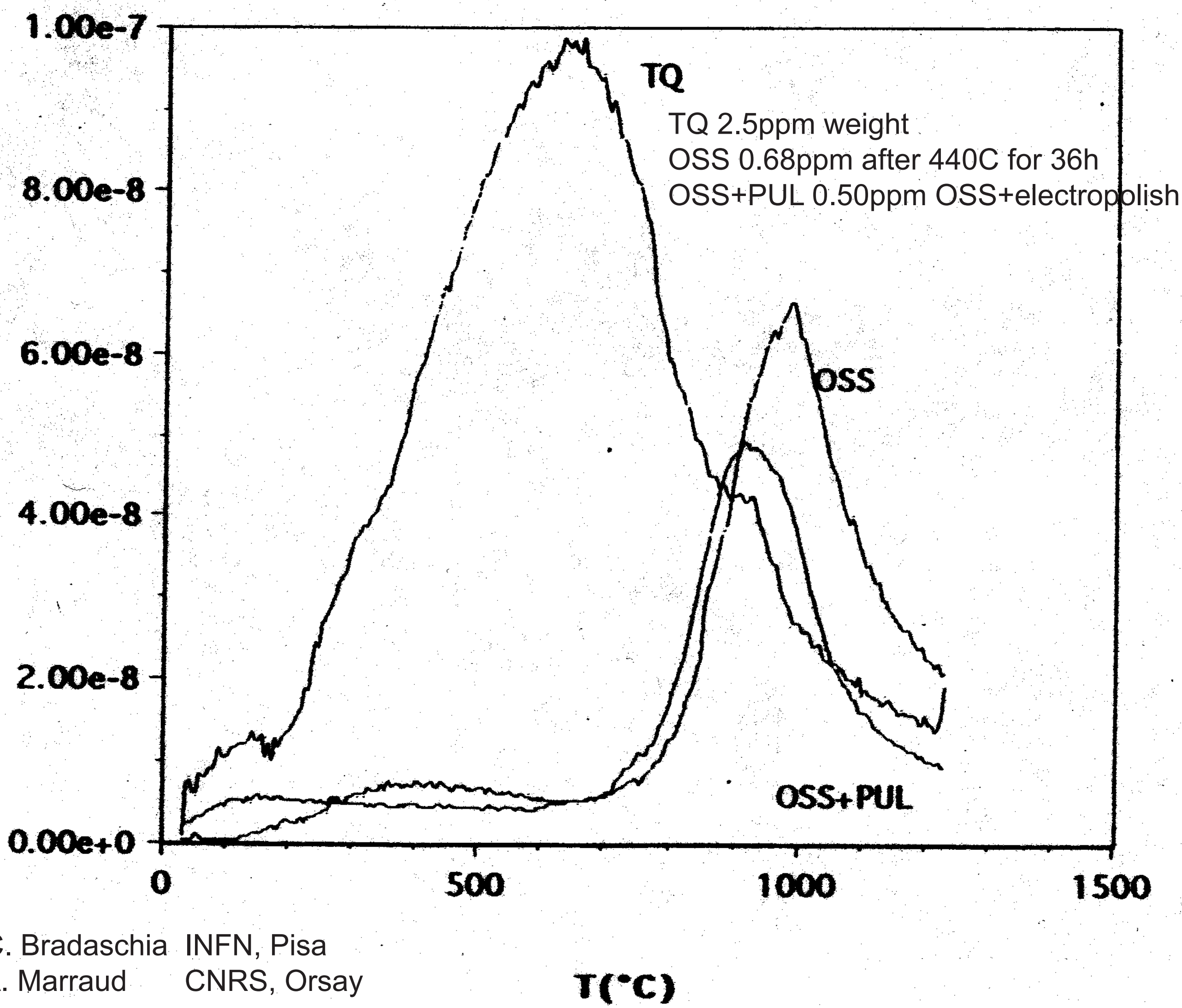
Conditions:

Incident electron energy = 5kV
Incident electron current = 100nA
Ion milling energy = 2kV
Ion current density = 10μ A/cm^2

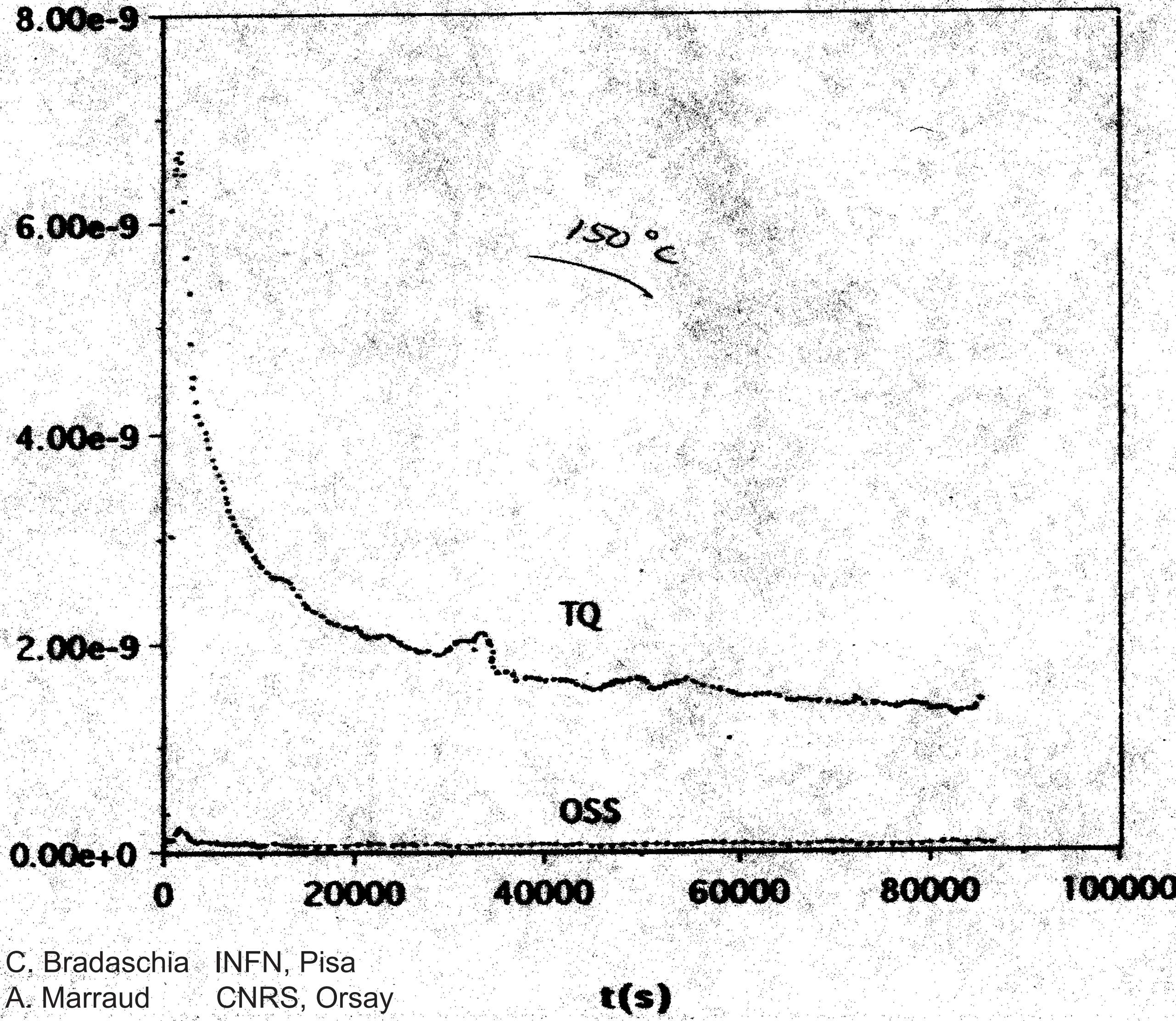
5 x 10^4 counts of 270 ev electrons in 1.64 sec of acquisition time corresponds to 1 monolayer of carbon bearing molecule

Hydrogen Reduction

- Dry air bake at 454C for 36 hours
  - Reduced 1 micron reflectivity of 304 L
  - Max temperature to minimize Carbide formation
- Mechanism:
  - tight (20000K) and loose (5000K) H binding sites
  - reduce density of loosely bound H and J(300K)
  - surface important for recombination (Myers)
  - Oxide layer not a significant factor
- Avoid reintroduction in welding
  - Dry purge gas until weld is cool
  - Clean weld rod



C. Bradaschia INFN, Pisa
A. Marraud CNRS, Orsay



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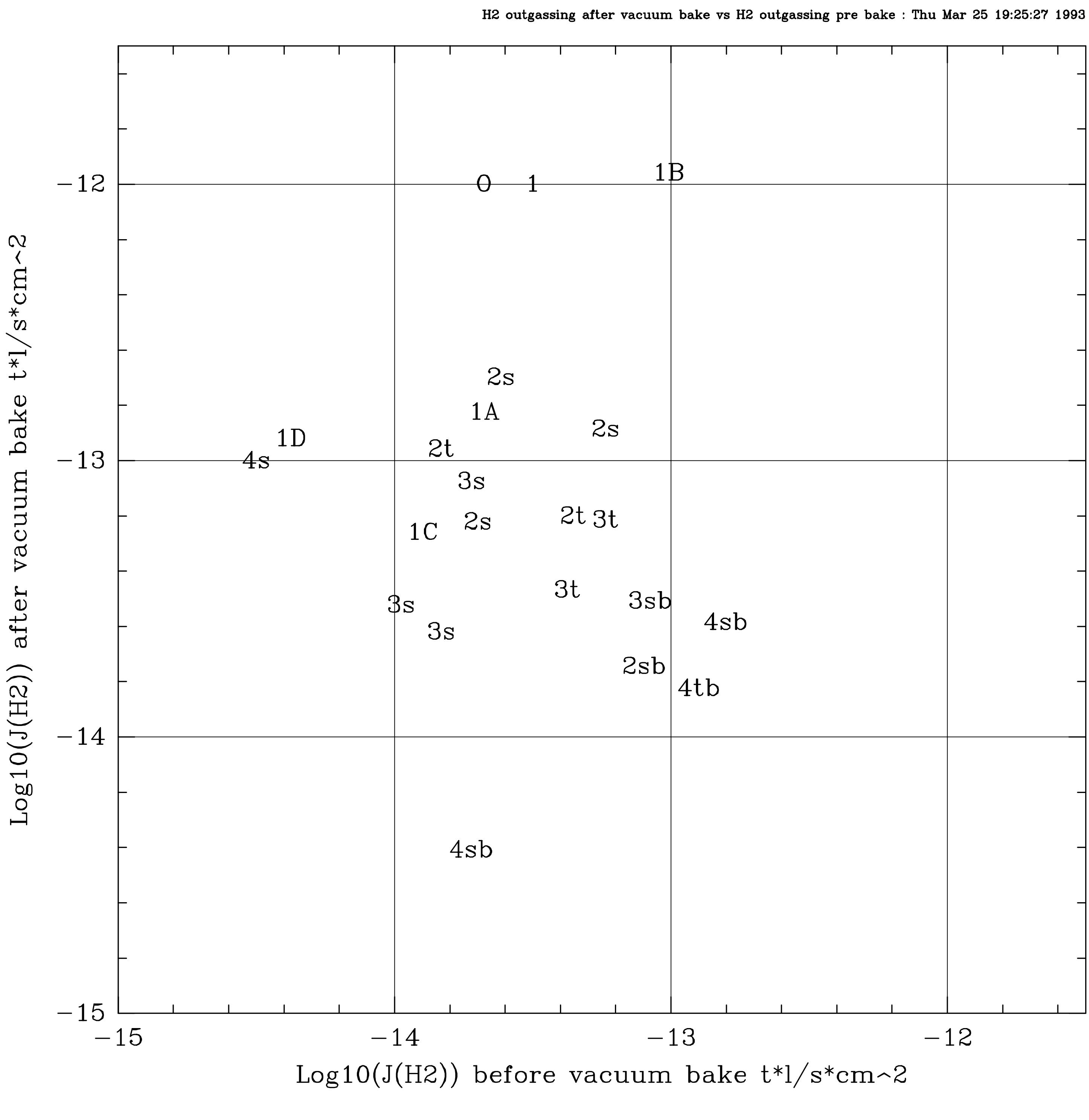
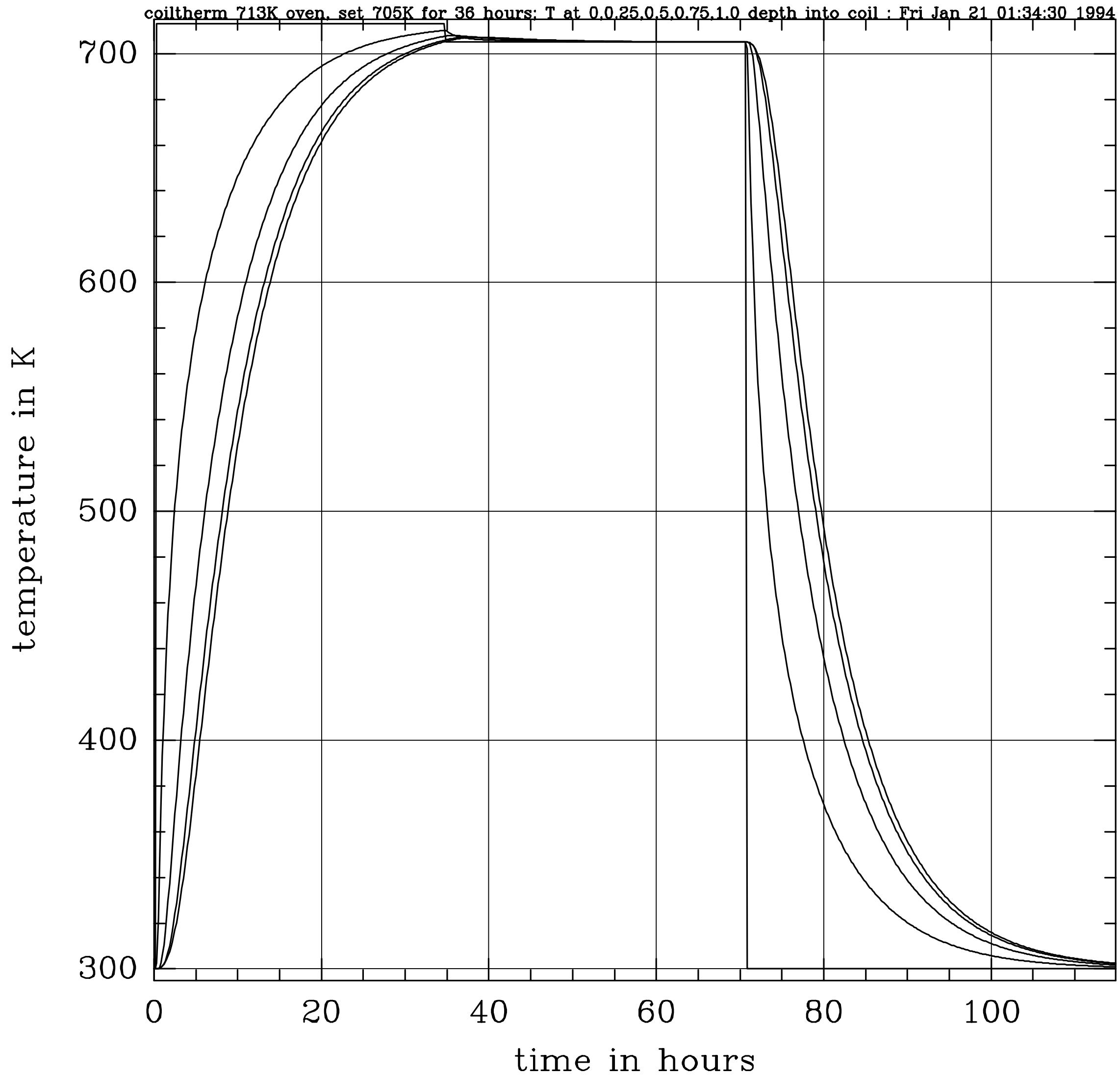
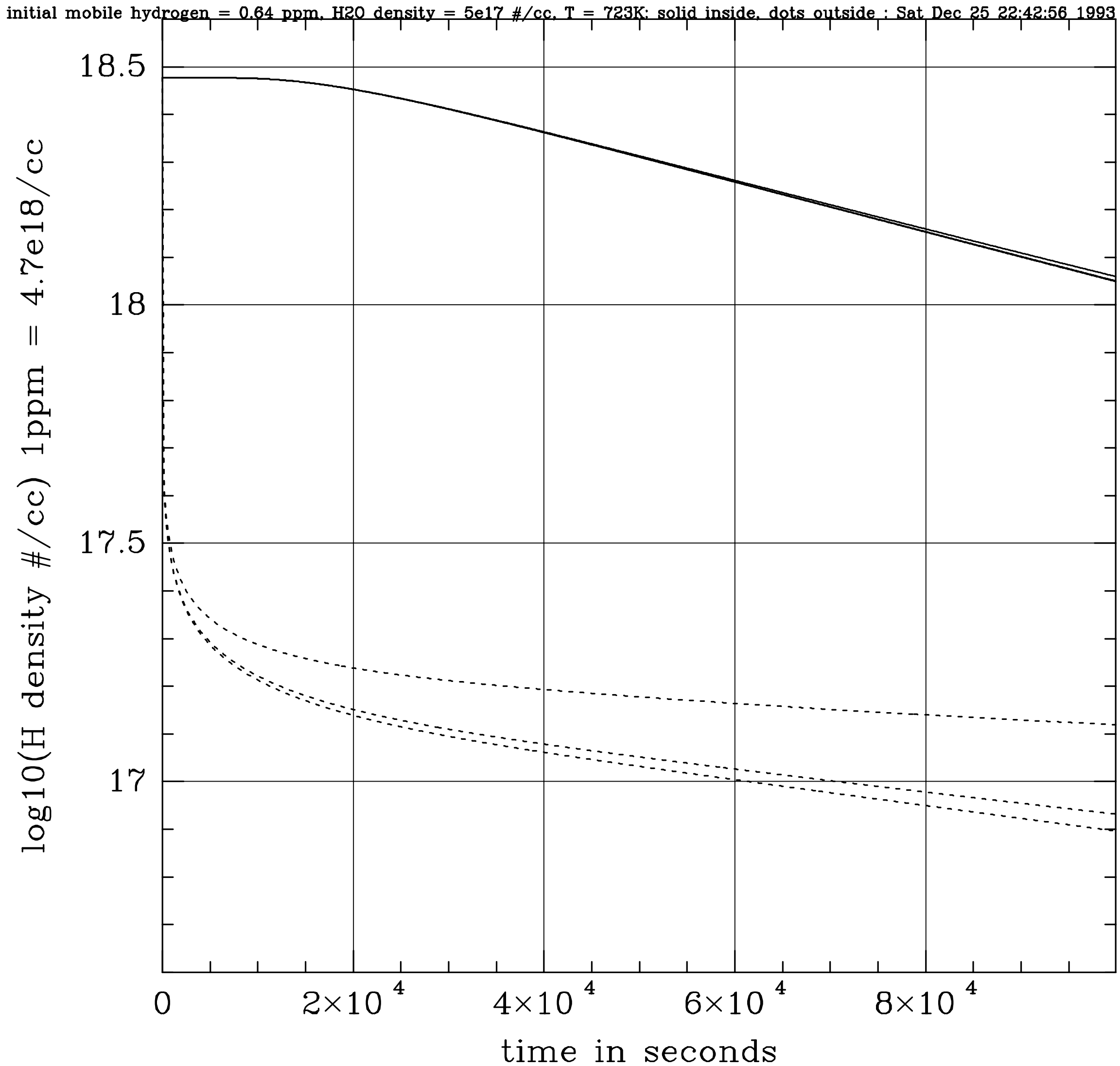
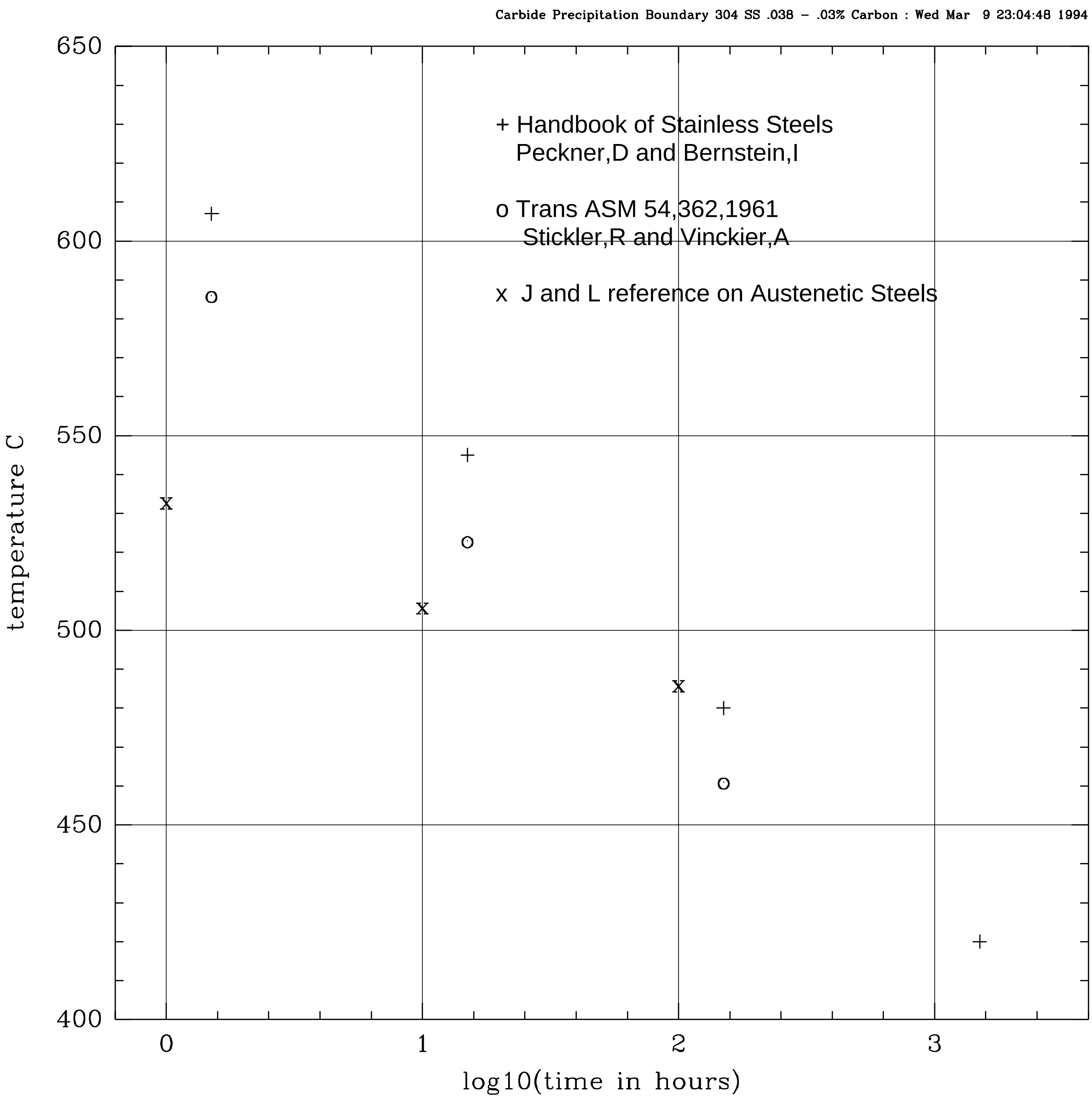

H2 outgassing after vacuum bake vs H2 outgassing pre bake : Thu Mar 25 19:25:27 1993
Log10(J(H2)) after vacuum bake t*l/s*cm^2
Log10(J(H2)) before vacuum bake t*l/s*cm^2
−12
−13
−14
−15
−15
−14
−13
−12
0
1
1B
2s
1A
2s
1D
4s
2t
3s
2t
3t
2s
1C
3t
3sb
4sb
3s
3s
2sb
4tb
4sb


coiltherm 713K oven, set 705K for 36 hours; T at 0,0.25,0.5,0.75,1.0 depth into coil : Fri Jan 21 01:34:30 1994
700
600
500
400
300
temperature in K
0
20
40
60
80
100
time in hours


initial mobile hydrogen = 0.64 ppm, H20 density = 5e17 #/cc, T = 723K: solid inside, dots outside : Sat Dec 25 22:42:56 1993
18.5
18
17.5
17
log10(H density #/cc) 1ppm = 4.7e18/cc
0
2×10 4
4×10 4
6×10 4
8×10 4
time in seconds

Chromium Carbide formation boundary temperature vs time at temperature
From several sources



Heuristic Statistical Mechanics Model

Dubinin-Radushkevich (DR) equilibrium surface coverage:

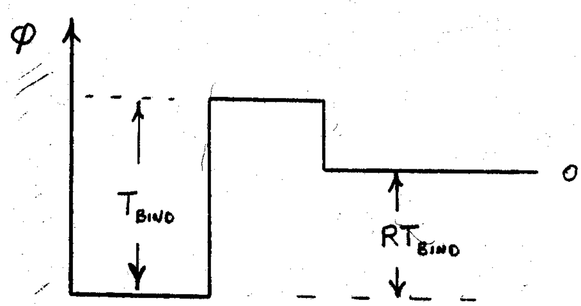
$$\frac{\sigma}{\sigma_m} = e^{-(T/T_0)^2 ln^2(P/P_0)}$$

DR site distribution function:

$$\theta(T_{bind}) = \left(2T_{bind}/{T_0}^2\right) e^{-(T_{bind}/T_0)^2}$$

$$\int_0^\infty \theta(T_{bind}) \delta T_{bind} = 1$$

Heuristic surface potential:



Emission time:

$$\tau_{emit}(T_{bind}) = \tau_0 e^{T_{bind}/T}$$

Adsorption time:

$$\tau_{ads} = \frac{4n\sigma_0}{\alpha \rho v_{th}(1 + (1-R)T_{bind}/T) e^{-(1-R)T_{bind}/T}}$$

Detailed balance per site:

$$\frac{dP(T_{bind}, t)}{dt} = -\frac{P(T_{bind}, t)}{\tau_{emit}} + \frac{(1 - P(T_{bind}, t))}{\tau_{ads}}$$

Integration:

$$P(T_{bind}, t) \;=\; P(T_{bind}, 0)e^{-t/\tau} \;+\; P_{equil}(T_{bind})(1 \;-\; e^{-t/\tau})$$

where

$$\tau = \frac{\tau_{emit}\tau_{ads}}{(\tau_{emit} \;+\; \tau_{ads})}$$

and

$$P_{equil}(T_{bind}) \;=\; \frac{\tau_{emit}}{(\tau_{emit} \;+\; \tau_{ads})}.$$

Incremental outgassing rate of band of sites:

$$dJ_{out}(t) = n\sigma_0 \; \theta(T_{bind})(\frac{dP(T_{bind}, t)}{dt}) \; \delta T_{bind}$$

Aside: for $P(T_{bind}, 0) \;=\; 1$ and $\tau_{ads} \rightarrow \infty$

$$J_{out}(t, T) = \left(\frac{2n\sigma_0 T}{tT_0}\right) \int_0^a bln(y/a)e^{-(bln(y/a))^2} e^{-y} dy$$

where

$$b = T/T_0 \qquad a = t/\tau_0$$

Computational algorithm (waterbakesm.f)

Step time:

$$\Delta t/\tau_s = f \quad \tau_s = V/F$$

Probability computation over 1024 binding energies $0 \rightarrow 3T_0$

$$P(T_{bind}, t_{j+1}) = P(T_{bind}, t_j)\, e^{-f\tau_s/\tau_j} + P_{equil}(T_{bind}, t_j)\,(1 - e^{-f\tau_s/\tau_j})$$

Surface coverage:

$$\sigma(t_{j+1}) = n\sigma_0 \sum_0^{3T_0} \theta(T_{bind}) P(T_{bind}, t_{j+1}).$$

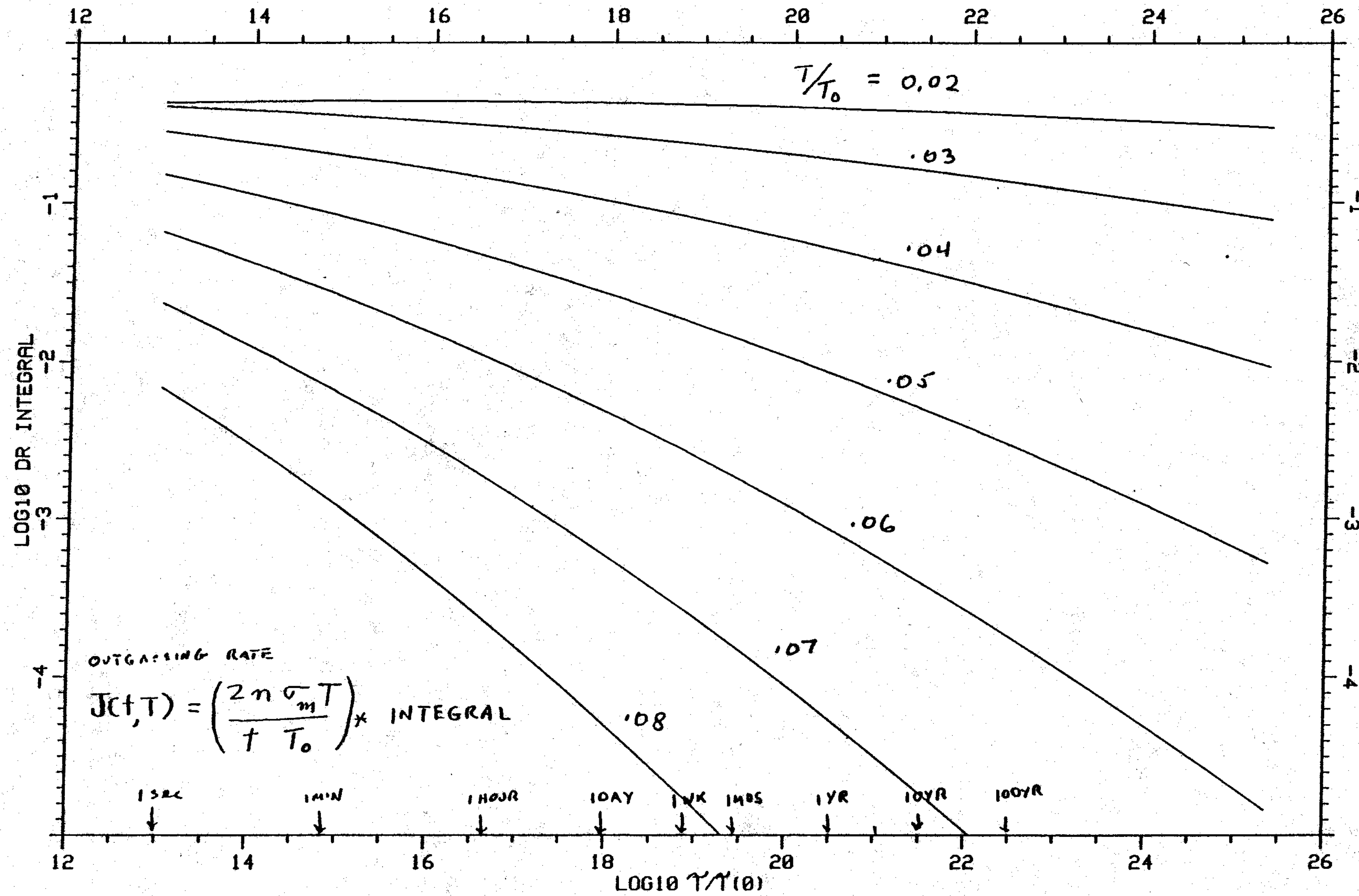
Outgassing rate:

$$J(t_{j+1}) = \frac{(\sigma(t_{j+1}) - \sigma(t_j))}{f\tau_s}$$

Pressure:

$$p(t_{j+1}) = p(t_j)\, e^{-f} + (\frac{J(t_j)A}{F})(1 - e^{-f})$$

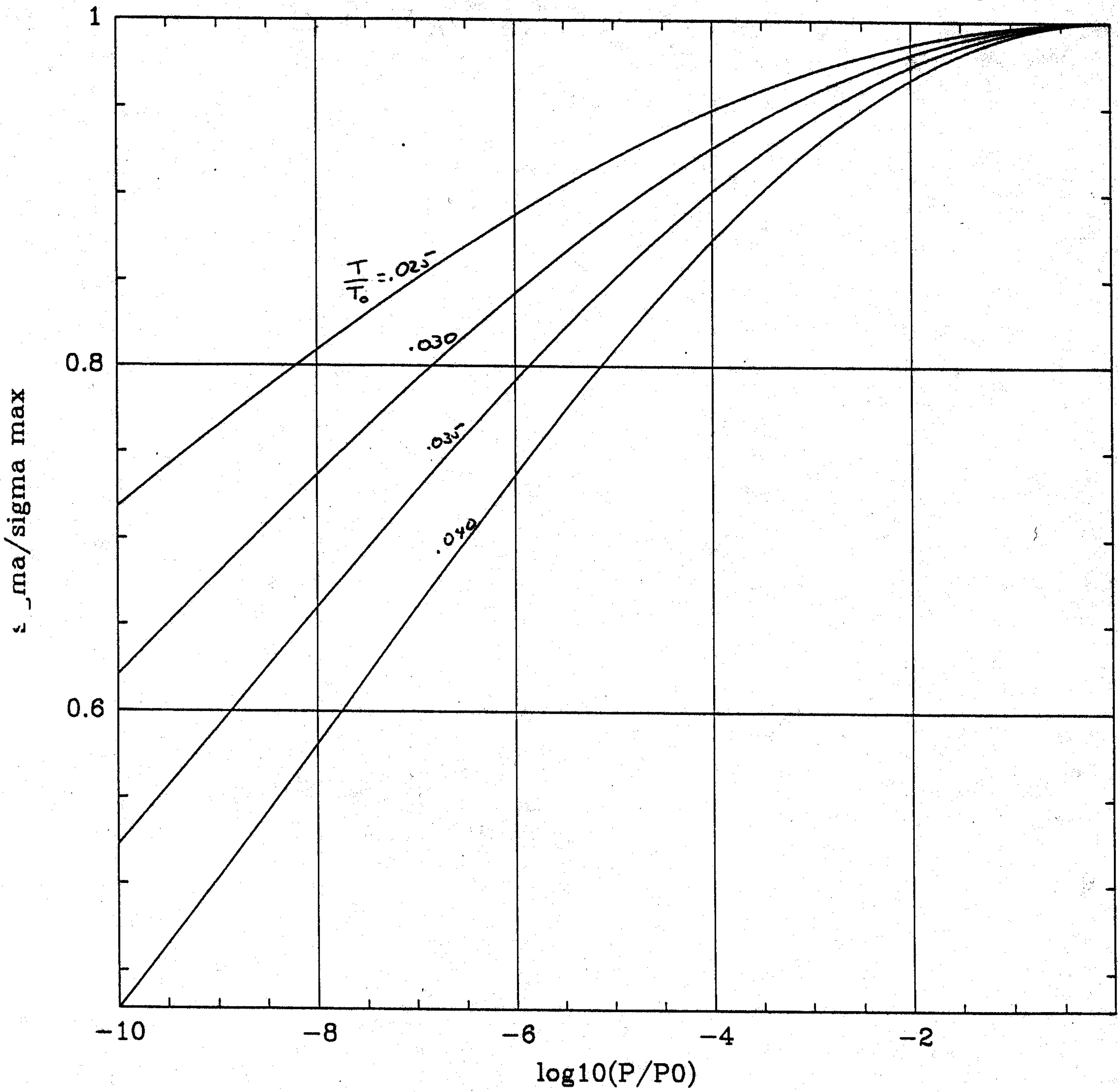
GO BACK AND DO IT AGAIN (new time and temperatures)



DR INTEGRAL VS NORMALIZED PUMPING TIME

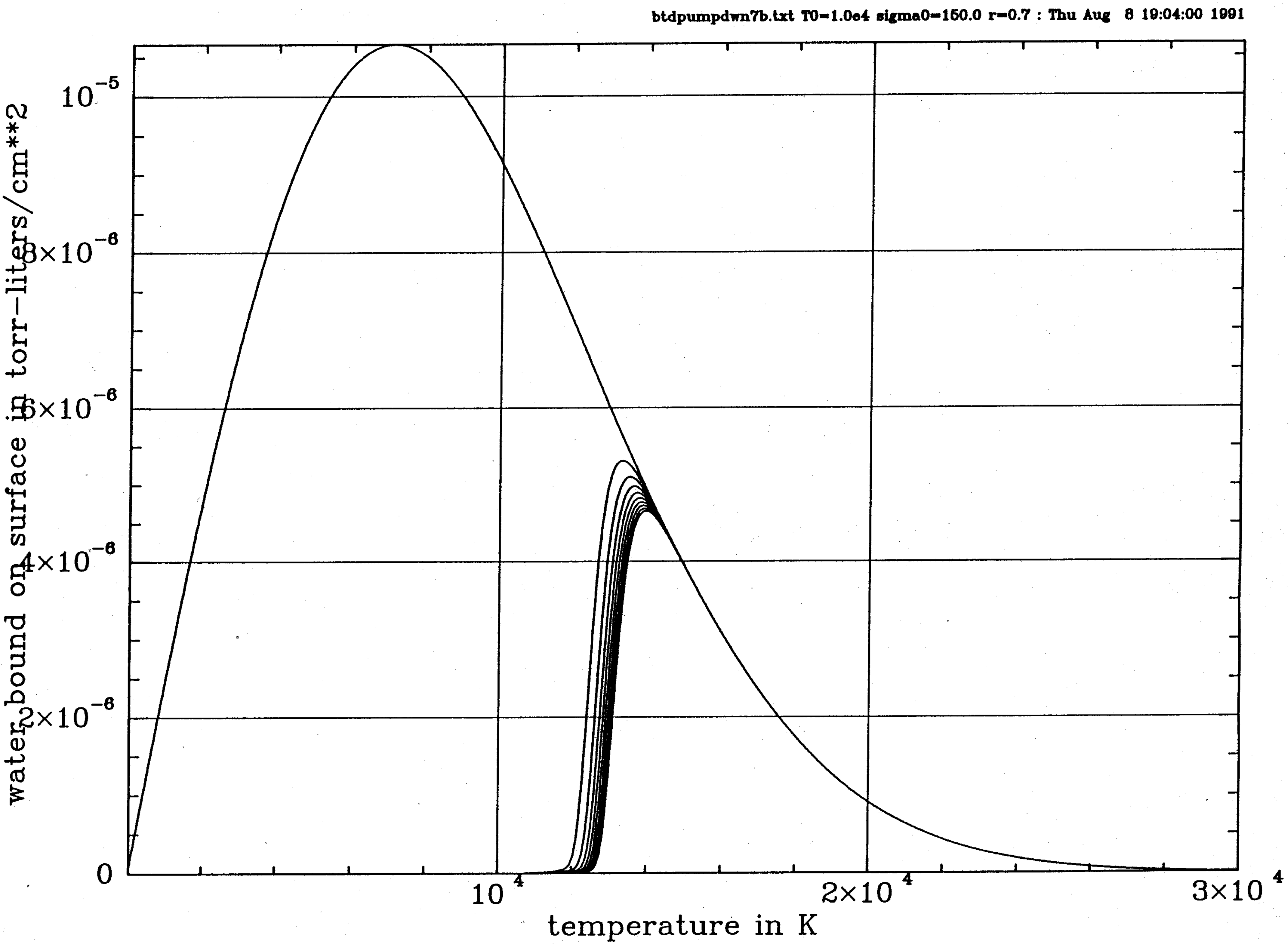
ASSUME $\tau_0 = 10^{-13}$ sec

dr isotherms: T/T0 = .025,.030,.035,.040 : Sat Sep 18 01:05:47 1993

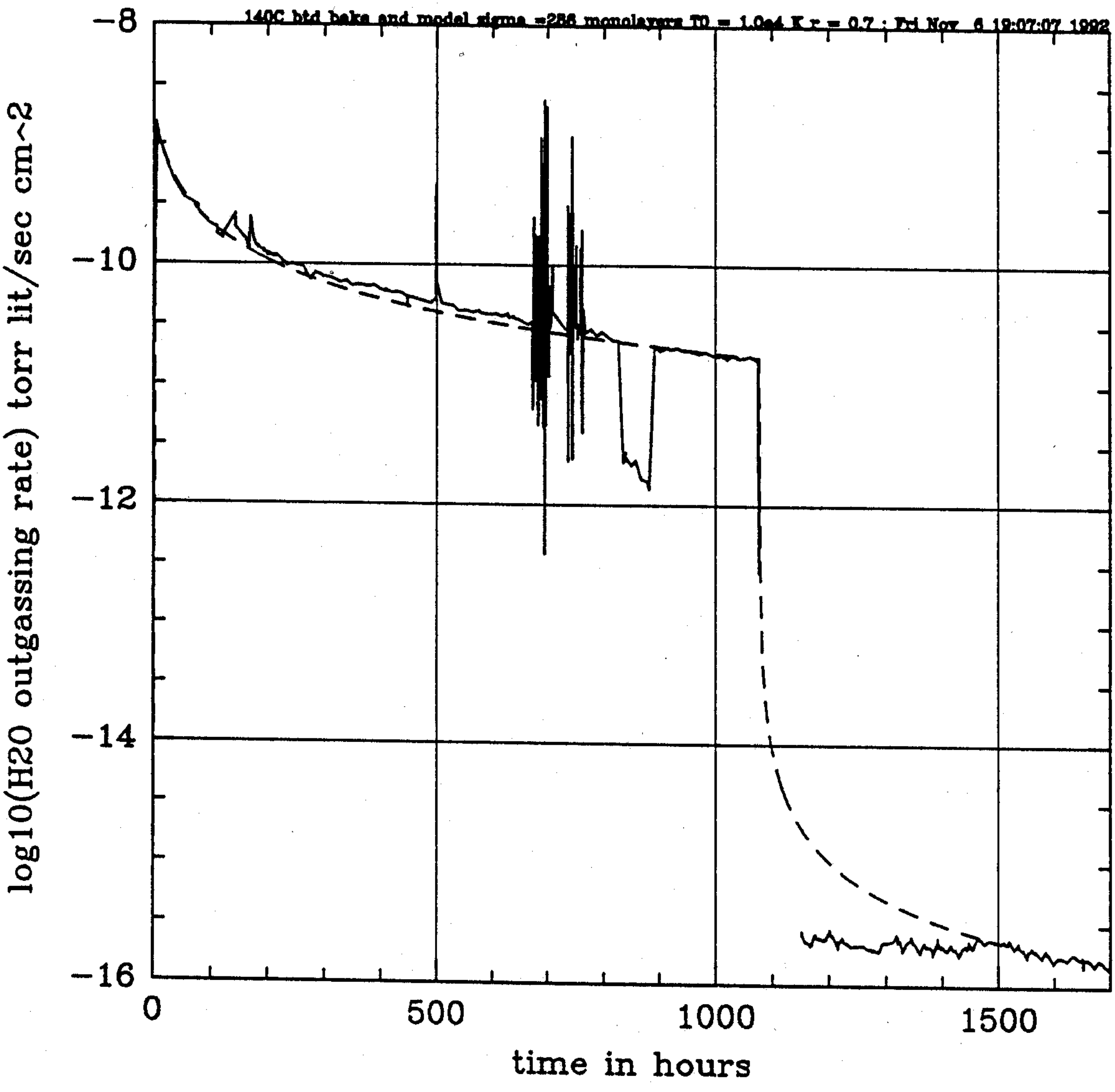


$$\frac{\sigma}{\sigma_m} = e^{-\left(\frac{T}{T_0}\right)^2 \ln^2 (P/P_0)}$$

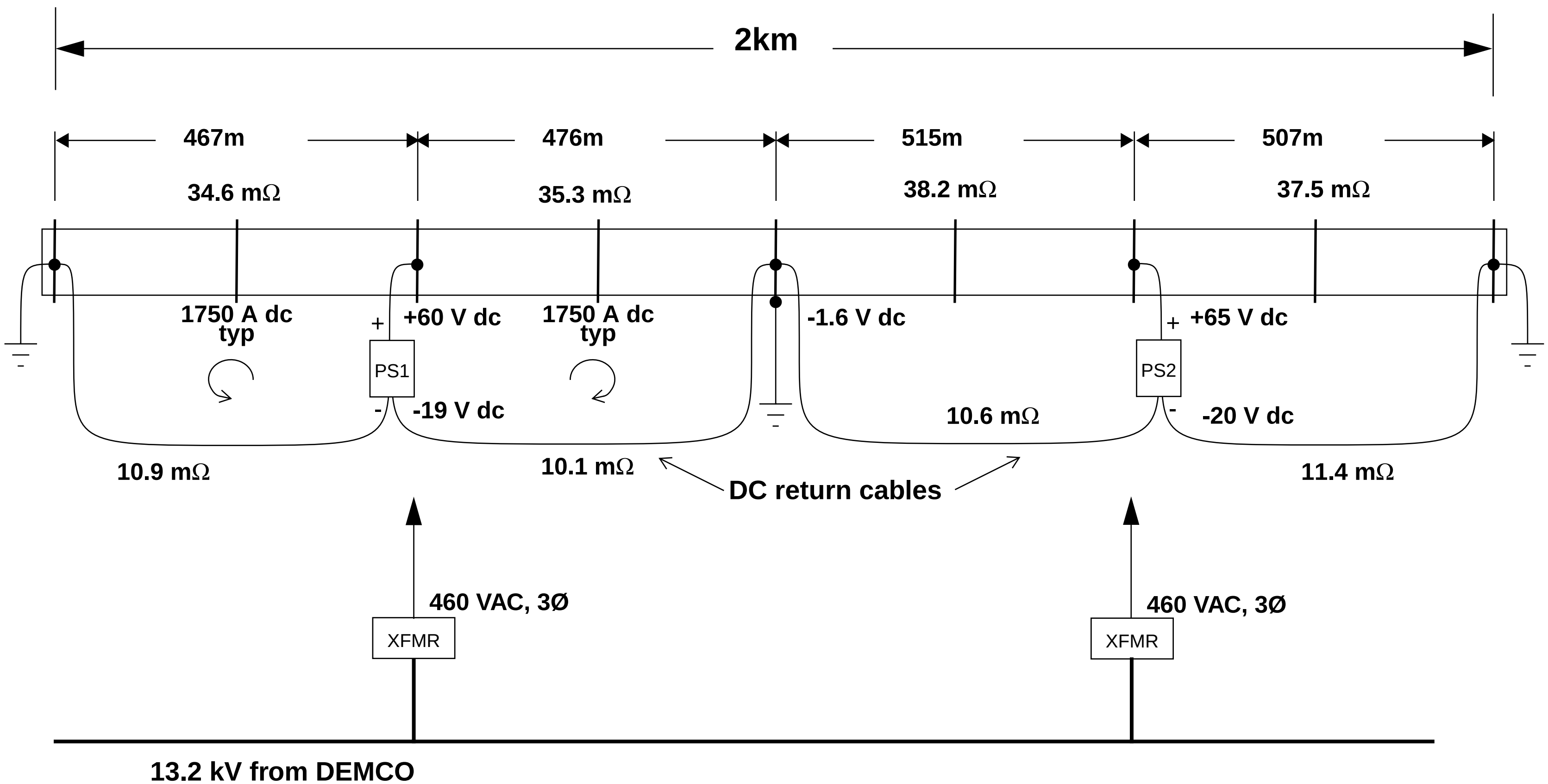
EQUILIBRIUM WITH SURFACE



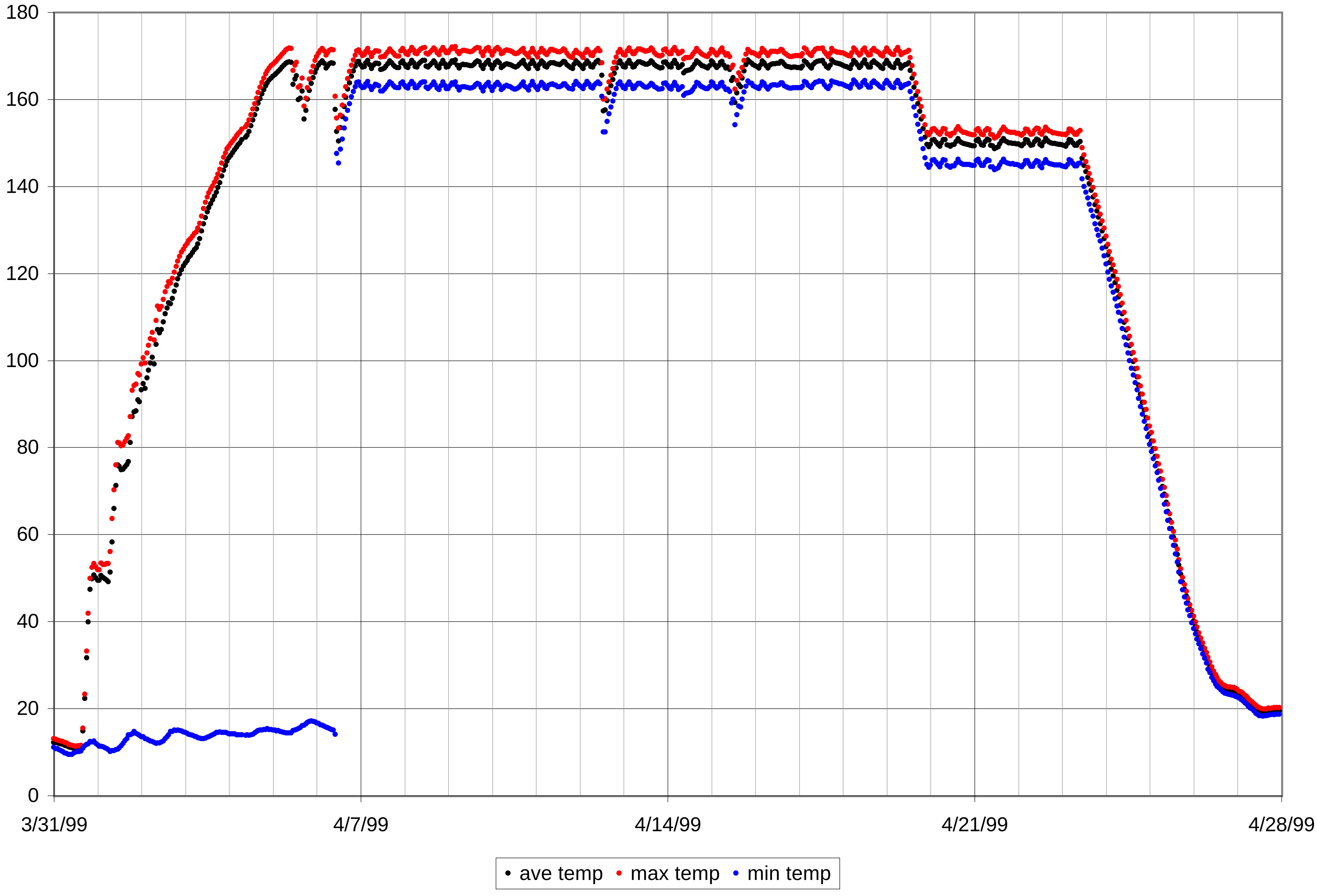
btdpumpdwn7b.txt T0=1.0e4 sigma0=150.0 r=0.7 : Thu Aug 8 19:04:00 1991
water bound on surface in torr-liters/cm**2
10^{-5}
8×10^{-6}
6×10^{-6}
4×10^{-6}
2×10^{-6}
0
10^4
2×10^4
3×10^4
temperature in K

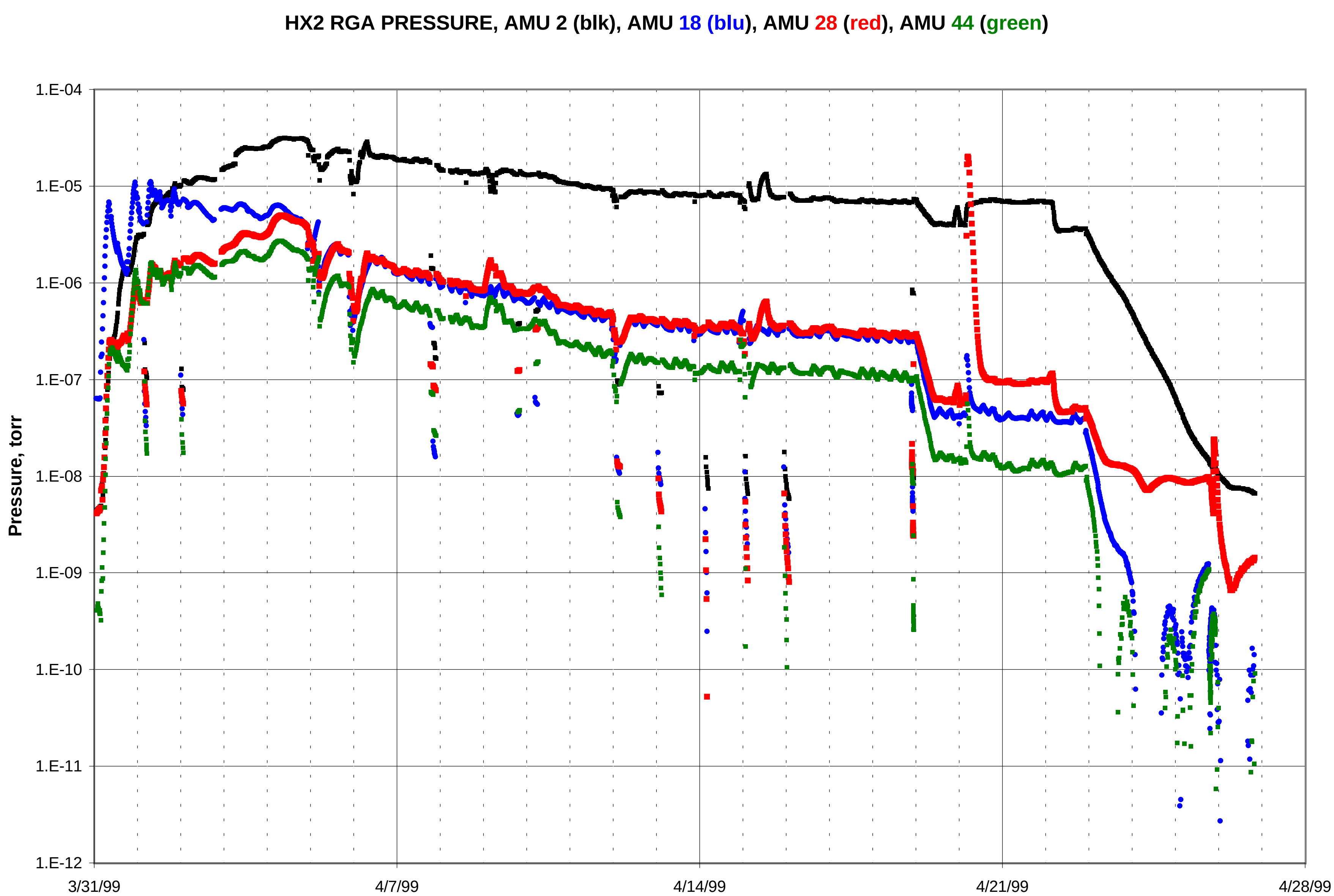

140C btd bake and model sigma =286 monolayers T0 = 1.0e4 K r = 0.7 : Fri Nov 6 19:07:07 1992
-8
-10
-12
-14
-16
log10(H20 outgassing rate) torr lit/sec cm^2
0
500
1000
1500
time in hours

BEAM TUBE BAKEOUT ELECTRICAL HEATING POWER



Legend: XFMR Power Transformer PS Low voltage, high current DC power supply

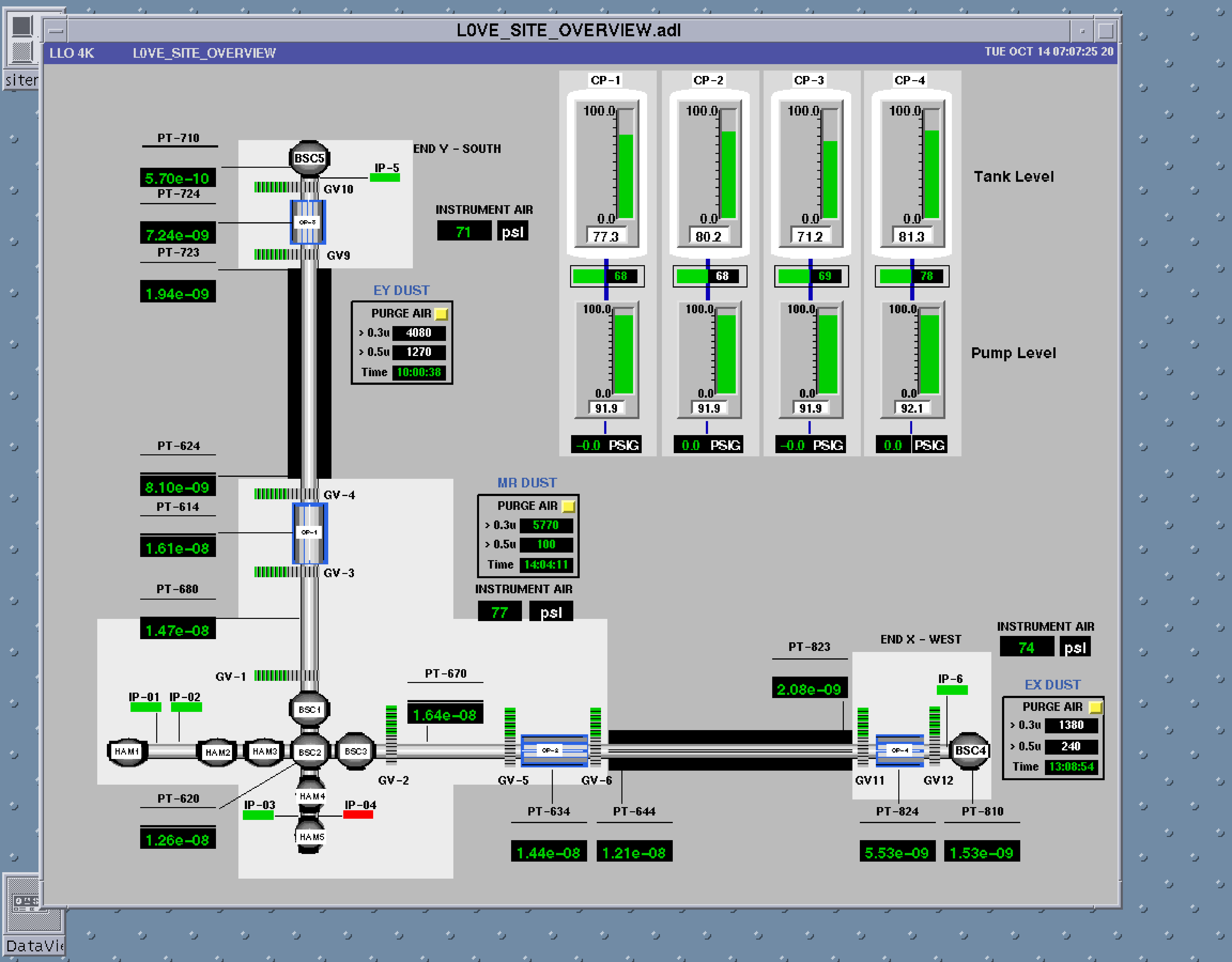

180
160
140
120
100
80
60
40
20
0
3/31/99
4/7/99
4/14/99
4/21/99
4/28/99
ave temp
max temp
min temp


HX2 RGA PRESSURE, AMU 2 (blk), AMU 18 (blu), AMU 28 (red), AMU 44 (green)
Pressure, torr
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
3/31/99
4/7/99
4/14/99
4/21/99
4/28/99

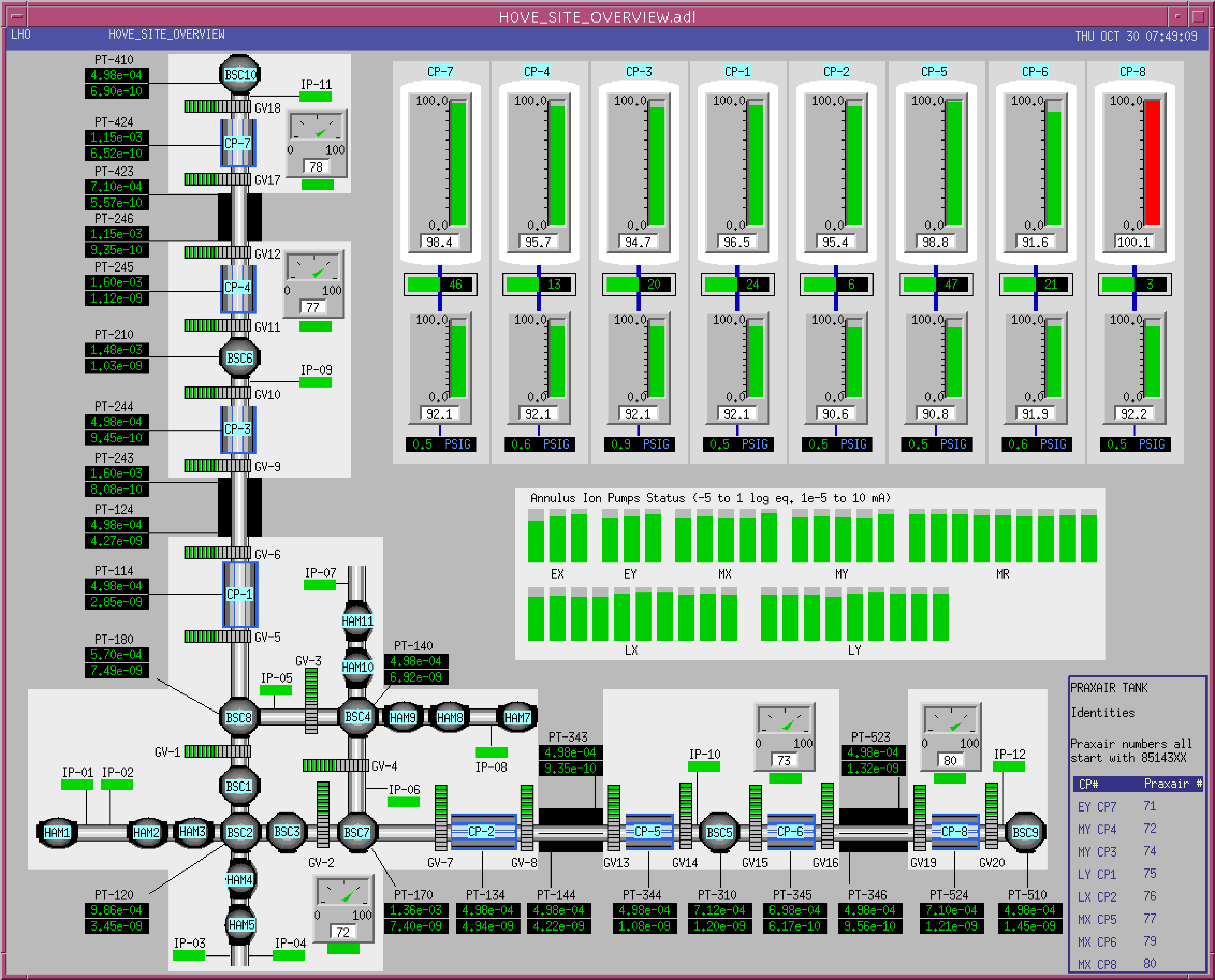
2 km module post bake outgassing and leak rate
Outgassing rate of selected gases in torr liters/sec/cm^2@ 23 C

molecule	Goal*	HY2	HY1	HX1	HX2	LY2	LY1	LX1	LX2	
H_2	4.7	4.8	6.3	5.2	4.6	2.6	3.4	6.6	4.3	$x10^{-14}$
CH_4	4800	< 90	< 22	< 0.9	< 10	< 24	< 3.9	< 3	< 4.0	$x10^{-19}$
H_2O	1500	< 4	< 20	< 1.8	< 0.8	< 3	< 0.9	< 0.6	< 10	$x10^{-18}$
CO	650	< 14	< 9	< 5.7	< 2	< 5	< 10	< 8	< 5	$x10^{-18}$
CO_2	2200	< 40	< 18	< 2.9	< 8.5	< 10	< 6	1.1	< 8	$x10^{-19}$
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	< 1.9	< 3.6	< 1.1	< 1.1	$x10^{-19}$
$H_nC_pO_q$	50-2 #	< 15	< 8.5	< 5.3	< 0.4	< 20	< 25	< 1.9	< 4.3	$x10^{-19}$
air leak torr-liters/sec	10	< 2	< 1	< 0.4	< 1.6	< 10	23	< 3.5	< 0.7	$x10^{-10}$

* Goal : maximum outgassing rate to achieve equivalent to 10^{-9} torr H_2 with 2000 liter/sec pumps at only stations
# Goal for hydrocarbons depends on mass of parent molecule; range corresponds to 100 - 300 AMU



LOVE_SITE_OVERVIEW.adl
LLO 4K
LOVE_SITE_OVERVIEW
TUE OCT 14 07:07:25 20
CP-1
CP-2
CP-3
CP-4
100.0
0.0
77.3
80.2
71.2
81.3
68
68
69
78
91.9
91.9
91.9
92.1
-0.0 PSIG
0.0 PSIG
-0.0 PSIG
0.0 PSIG
Tank Level
Pump Level
PT-710
5.70e-10
PT-724
7.24e-09
PT-723
1.94e-09
BSC5
IP-5
GV10
GV9
END Y - SOUTH
INSTRUMENT AIR
71
psi
EY DUST
PURGE AIR
> 0.3u
4080
> 0.5u
1270
Time
10:00:38
PT-624
8.10e-09
PT-614
1.61e-08
GV-4
GV-3
PT-680
1.47e-08
MR DUST
PURGE AIR
> 0.3u
5770
> 0.5u
100
Time
14:04:11
INSTRUMENT AIR
77
psi
GV-1
IP-01
IP-02
BSC1
HAM1
HAM2
HAM3
BSC2
BSC3
HAM4
HAM5
GV-2
PT-670
1.64e-08
PT-620
1.26e-08
IP-03
IP-04
GV-5
GV-6
PT-634
1.44e-08
PT-644
1.21e-08
PT-823
2.08e-09
END X - WEST
INSTRUMENT AIR
74
psi
IP-6
BSC4
GV11
GV12
PT-824
5.53e-09
PT-810
1.53e-09
EX DUST
PURGE AIR
> 0.3u
1380
> 0.5u
240
Time
13:08:54
siter
DataVi


HOVE_SITE_OVERVIEW.adl
LHO
HOVE_SITE_OVERVIEW
THU OCT 30 07:49:09
PT-410
4.98e-04
6.90e-10
PT-424
1.15e-03
6.52e-10
PT-423
7.10e-04
5.57e-10
PT-246
1.15e-03
9.35e-10
PT-245
1.60e-03
1.12e-09
PT-210
1.48e-03
1.03e-09
PT-244
4.98e-04
9.45e-10
PT-243
1.60e-03
8.08e-10
PT-124
4.98e-04
4.27e-09
PT-114
4.98e-04
2.85e-09
PT-180
5.70e-04
7.49e-09
PT-120
9.86e-04
3.45e-09
BSC10
IP-11
GV18
CP-7
0
100
78
GV17
GV12
CP-4
0
100
77
GV11
BSC6
IP-09
GV10
CP-3
GV-9
GV-6
CP-1
IP-07
HAM11
GV-5
HAM10
PT-140
4.98e-04
6.92e-09
GV-3
IP-05
BSC8
BSC4
HAM9
HAM8
HAM7
GV-1
GV-4
IP-08
IP-01
IP-02
BSC1
IP-06
HAM1
HAM2
HAM3
BSC2
BSC3
BSC7
CP-2
CP-5
BSC5
CP-6
CP-8
BSC9
GV-2
GV-7
GV-8
GV13
GV14
GV15
GV16
GV19
GV20
HAM4
HAM5
0
100
72
IP-03
IP-04
PT-170
1.36e-03
7.40e-09
PT-134
4.98e-04
4.94e-09
PT-144
4.98e-04
4.22e-09
PT-343
4.98e-04
9.35e-10
PT-344
4.98e-04
1.08e-09
IP-10
0
100
73
PT-310
7.12e-04
1.20e-09
PT-345
6.98e-04
6.17e-10
PT-523
4.98e-04
1.32e-09
PT-346
4.98e-04
9.56e-10
0
100
80
IP-12
PT-524
7.10e-04
1.21e-09
PT-510
4.98e-04
1.45e-09
CP-7
100.0
0.0
98.4
46
100.0
0.0
92.1
0.5 PSIG
CP-4
100.0
0.0
95.7
13
100.0
0.0
92.1
0.6 PSIG
CP-3
100.0
0.0
94.7
20
100.0
0.0
92.1
0.9 PSIG
CP-1
100.0
0.0
96.5
24
100.0
0.0
92.1
0.5 PSIG
CP-2
100.0
0.0
95.4
6
100.0
0.0
90.6
0.5 PSIG
CP-5
100.0
0.0
98.8
47
100.0
0.0
90.8
0.5 PSIG
CP-6
100.0
0.0
91.6
21
100.0
0.0
91.9
0.6 PSIG
CP-8
100.0
0.0
100.1
3
100.0
0.0
92.2
0.5 PSIG
Annulus Ion Pumps Status (-5 to 1 log eq. 1e-5 to 10 mA)
EX
EY
MX
MY
MR
LX
LY
PRAXAIR TANK
Identities
Praxair numbers all
start with 85143XX
CP# Praxair #
EY CP7 71
MY CP4 72
MY CP3 74
LY CP1 75
LX CP2 76
MX CP5 77
MX CP6 79
MX CP8 80