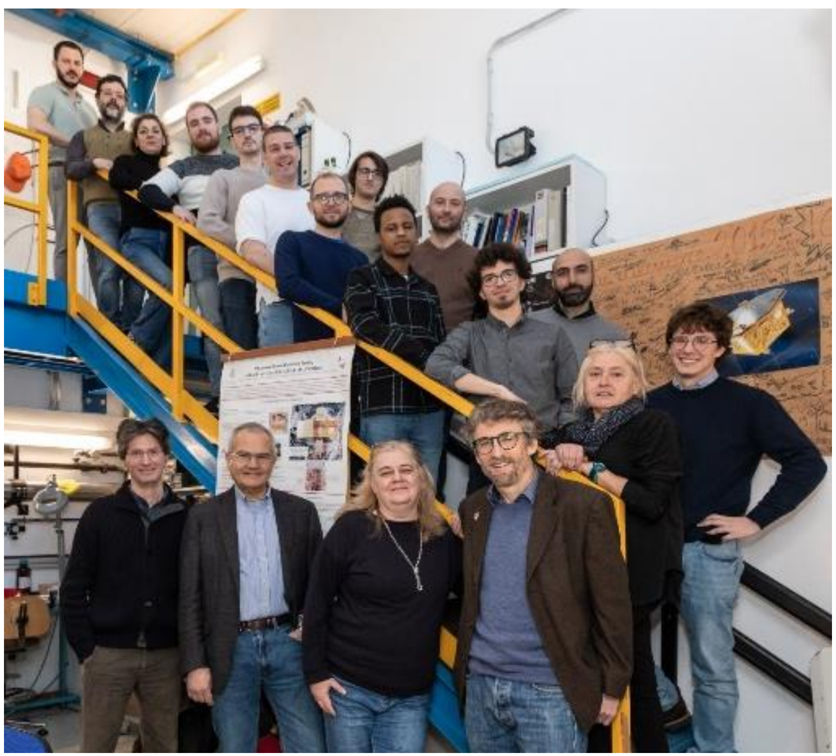
The gravitational reference system from LPF to LISA phase B2:

LPF ops logbook observations and subsequent evolution of the LISA GRS



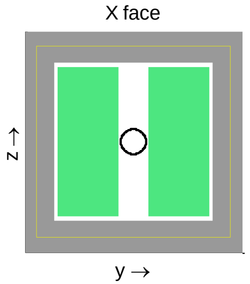
Bill Weber
LISA GRS PI team

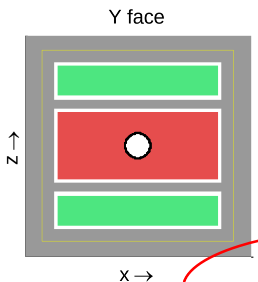
Barcellona, 20251203

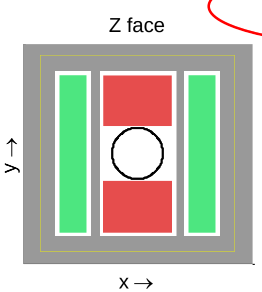
UNIVERSITÀ DI TRENTO
INFN
ASI Agenzia Spaziale Italiana

LISA test mass – electrode geometry 2025: as designed 2002 and tested 2016

from Dolesi / Weber presentation (2002)

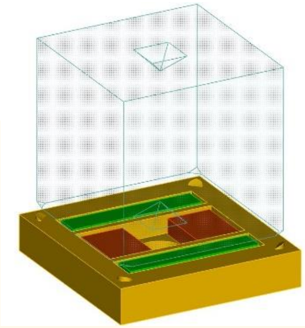






4 mm X-gap

46 mm, 2 kg Au-Pt TM



```
EDU» trento_yzin_z('din',4,'dx',4,'dy',2.9,'dz',3.5,'win',16,'mass',46,...
'cagehole',12,'double_inz','plt','xyz');

Modified Trento Design (2 sensing electrodes on every face, YZ injection)
Assume Trento bridge: capacitance noise = 4.3674e-007 pF V / rtHz

   DESIGN
X faces (mass face 46 x 46 mm
   Two sensing electrodes:  14.5 x 36 mm , gap 4 mm,  Rphi 10.75 mm (6 mm laser hole)

...

 Sensitivities (nm or nrad/rtHz):;
                    x         y         z        phi        th        eta
                   0.88965;    0.9;    1.4784;    82.7579;   57.8778;   96.9437;

 Neg Electrostatic Stiffness (nano / s^2):
                wx^2       wy^2        wz^2        wphi^2       wth^2       weta^2
LTP Total;     56.4967;     2358.58;     2716.4987;      1599.5227;        2859.9274;     2457.0655;
LTP Specs;       950;        950;         2850;       3850;        3850;        3850;
LTP Act freqs (nano/s^2); 1.3;          2.2;          3.7;         16;          27;        23;

LISA Specs;       250;        250;         550;         550;      550;     550
 LISA Act freqs (nano/s^2);  0.1;         0.1;        0.3;          0.5;         1;          1;


Bortoluzzi Bottom Line: Mass Mass 1.9467 kg, inner housing dimensions: 54 x 51.8 x 53 mm
```

LTP / SMART-2

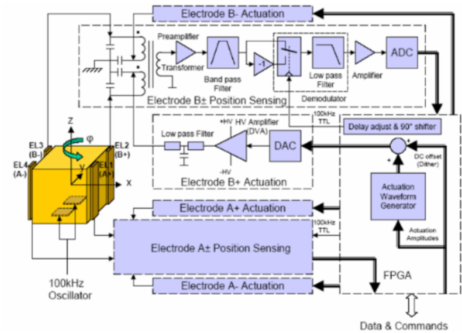
LISA

What is the biggest TM with the biggest gaps that we can launch?

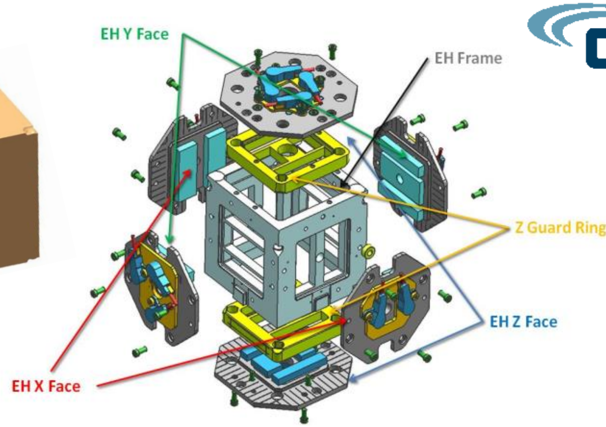
How big are the remaining forces – electrostatic, thermal, molecules, ecc – in this configuration?

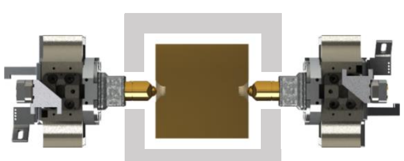
→ torsion pendulum, then LISA Pathfinder in orbit test

FEE sensing / actuation electronics (ETHZ)

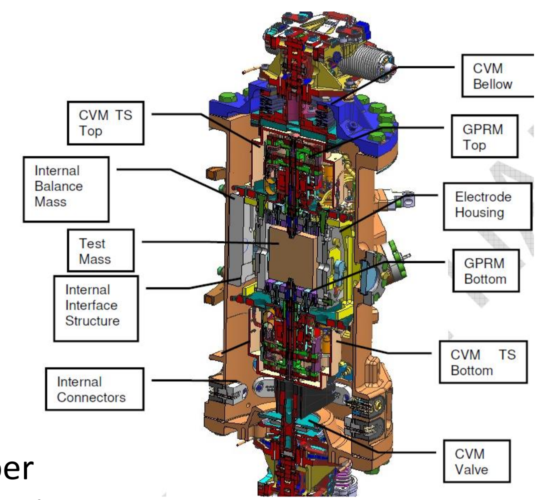


UV charge management device (ICL)





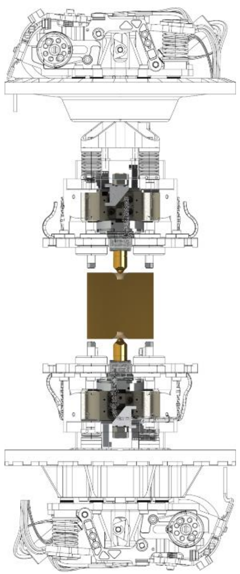
Grabbing positioning release mechanism (GPRM) (RUAG)

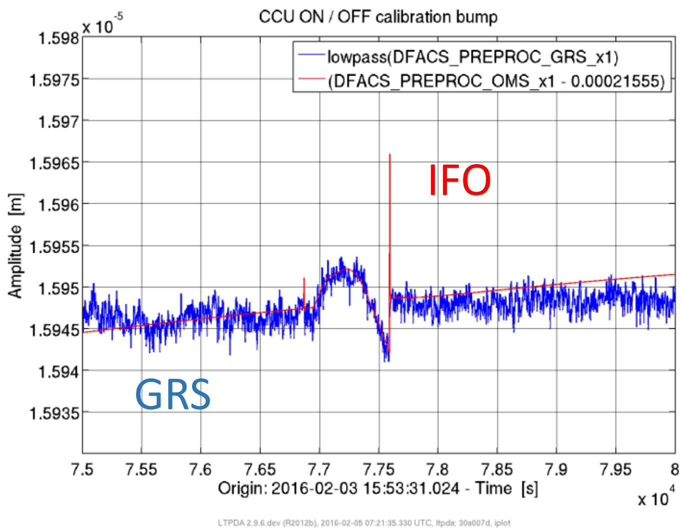


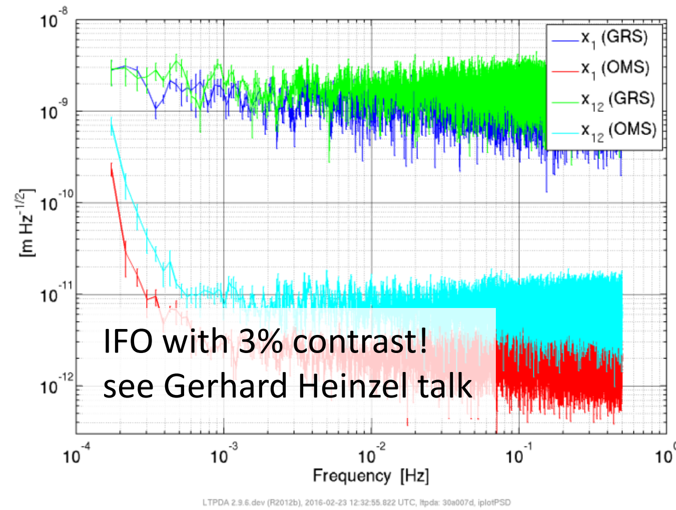
- Ti vacuum chamber
- gravitational balancing
- Single-shot launch lock caging / venting (RUAG)

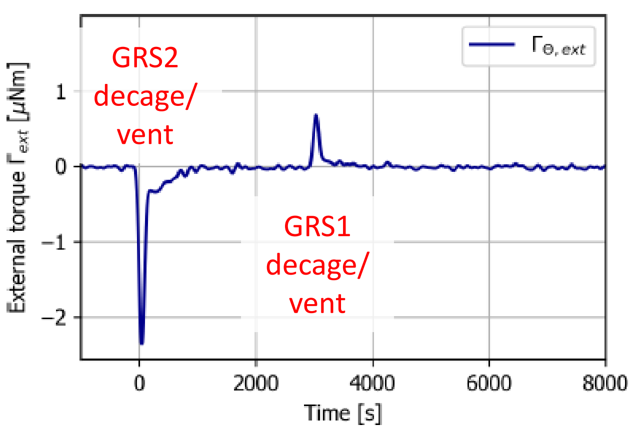
20160203 TM decaging, vent and grabbed TM sensing

See Luigi Ferraioli (ETH) talk for FEE!







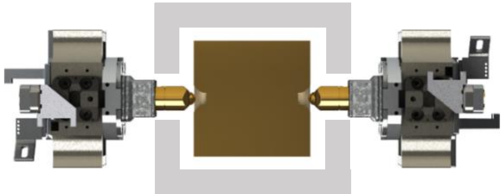


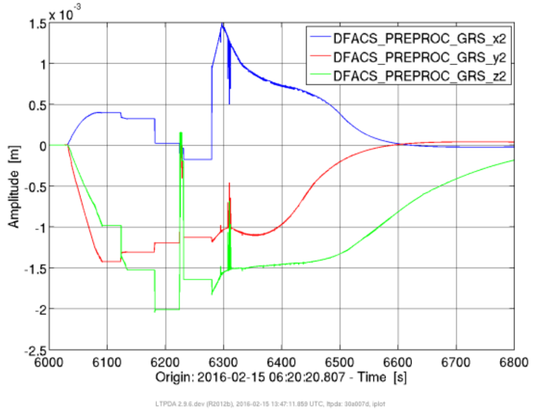
parasitic performance tests "pre-release"

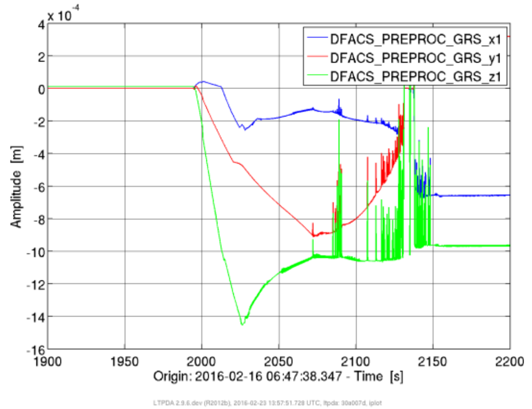
- GRS and IFO see the same test mass motion!
- GRS nm/Hz$^{1/2}$ sensing with 4 mm gaps works
- SC rolls when GRS vents gas to space
  - consistent with internal outgassing (not leak)

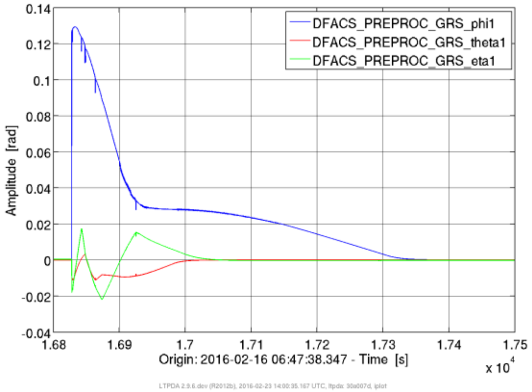
- LPF GRS not designed for TM alignment when caged or grabbed
  - same for LISA
  - one-shot cage / vent mechanism rebuild for LISA
  - provided by ASI

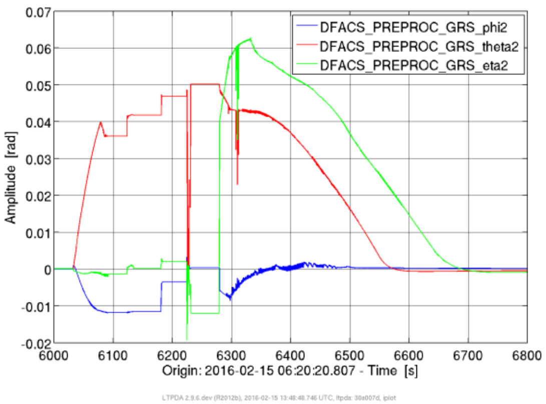
20260215-16: release of TM2 and TM1

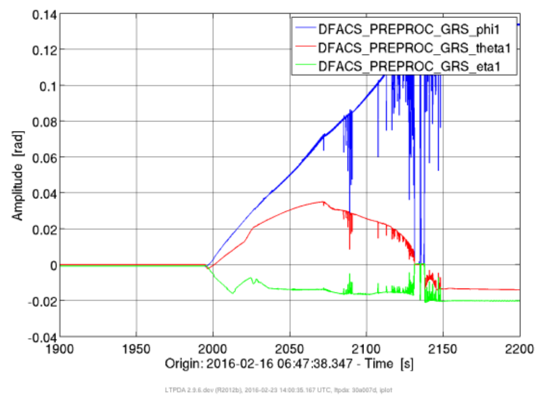


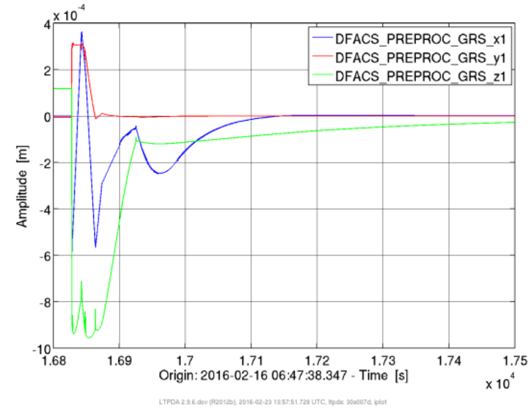










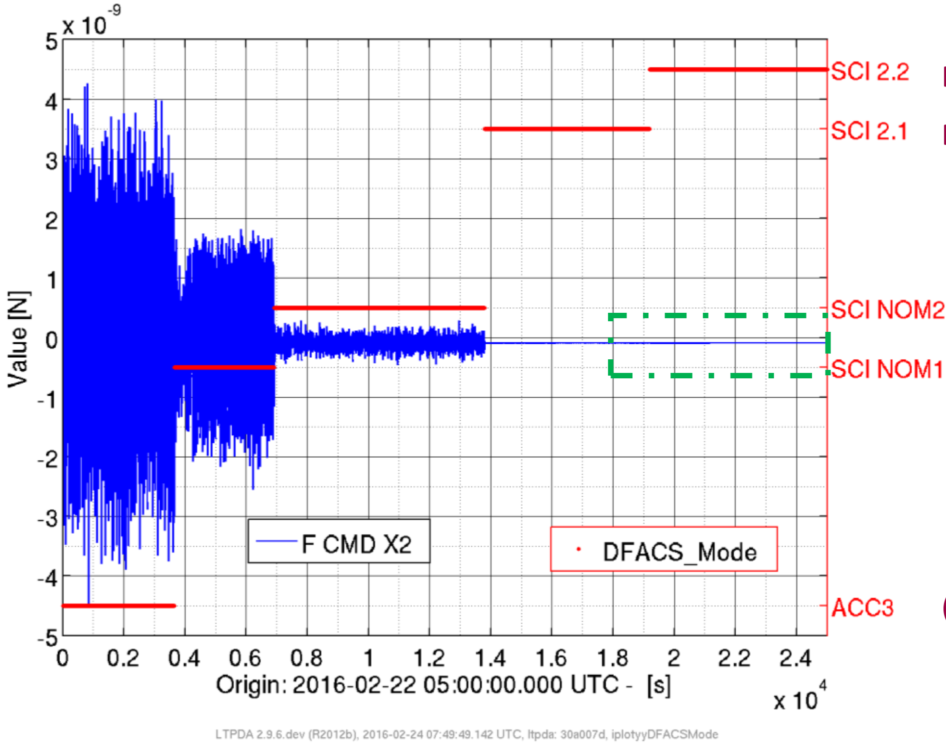


TM2 release

TM1 release ... first and second tries

- release always “successful” (we released and controlled the TM)
- often excess velocities (up to 50 mm/s) and control by bouncing
  - extensive end of mission tests (50 TM1, 50 TM2 releases)

20160222 Start of drag-free control, DC force levels



BW 0.5 mHz

BW 10 mHz

TM1 drag-free

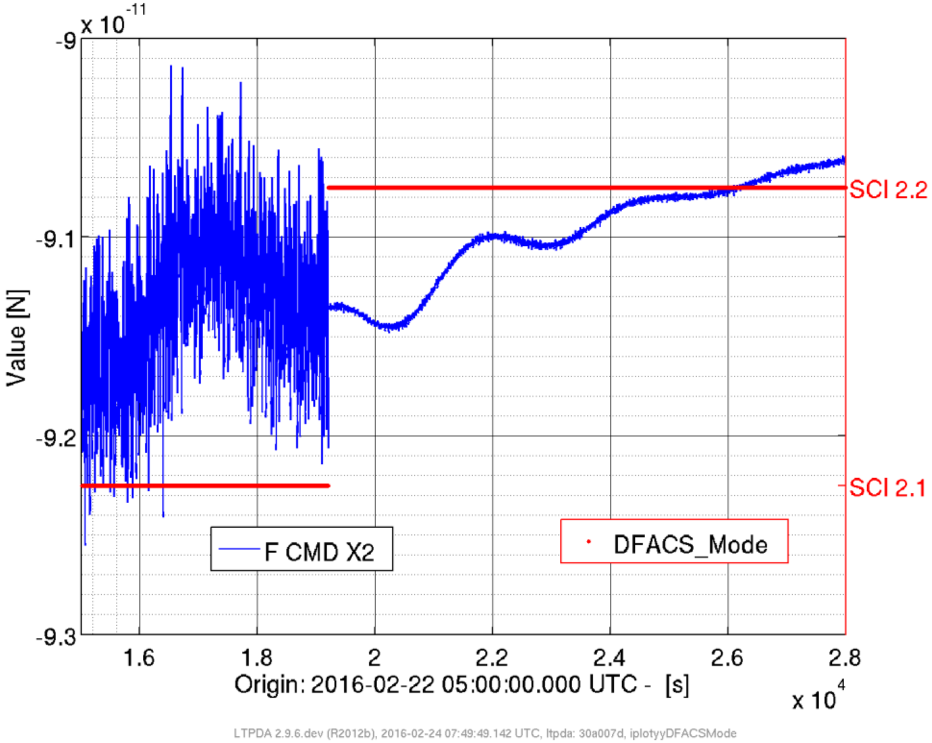
FEE HR

FEE WR

(both TM forced to SC)

Notable improvement from accelerometer mode to drag-free mode

20160222 Start of drag-free control, DC force levels



$|F_{X2}| < 100$ pN!

$\Delta g_x < 50$ pm/s^2 !!!

			MAX ALLOWED
Δg_x^{DC}	45.0 ± 0.2	pm/s^2	500
Δg_y^{DC}	503.5 ± 0.3	pm/s^2	1050
Δg_z^{DC}	5.2 ± 0.2	pm/s^2	1850
$\gamma_{1\phi}^{DC}$	0.990 ± 0.001	nrad/s^2	8
$\gamma_{1\theta}^{DC}$	-0.5653 ± 0.0001	nrad/s^2	11.5
$\gamma_{1\eta}^{DC}$	2.7338 ± 0.0007	nrad/s^2	13.5
$\gamma_{2\phi}^{DC}$	-0.032 ± 0.001	nrad/s^2	8
$\gamma_{2\theta}^{DC}$	-0.1379 ± 0.0002	nrad/s^2	11.5
$\gamma_{2\eta}^{DC}$	-1.3125 ± 0.0006	nrad/s^2	13.5

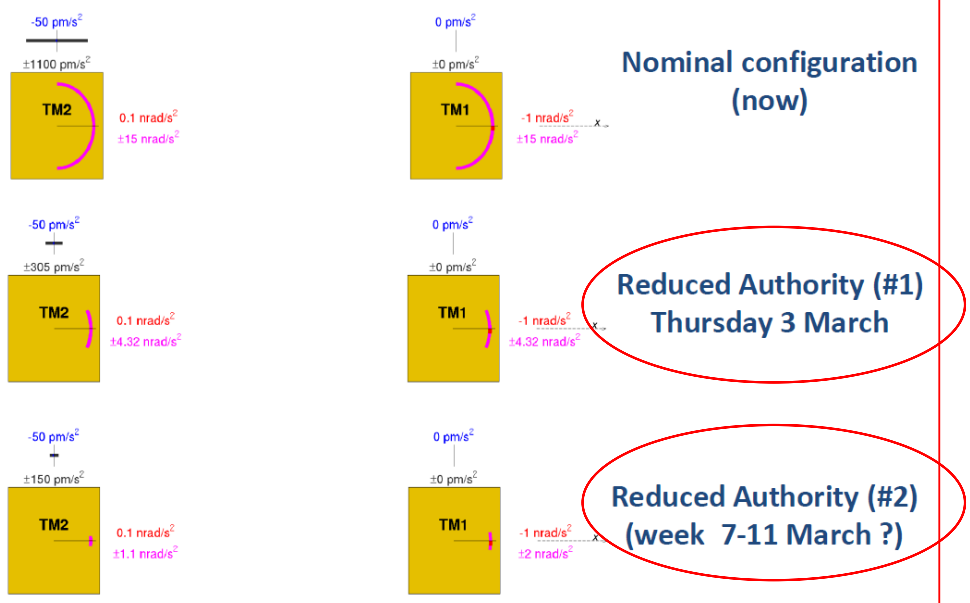
- we're in drag-free!

- all 9 DC force DOF well in specs!
- agreement with model even better
  - spacecraft gravitational balancing
  - GRS gravitational balancing

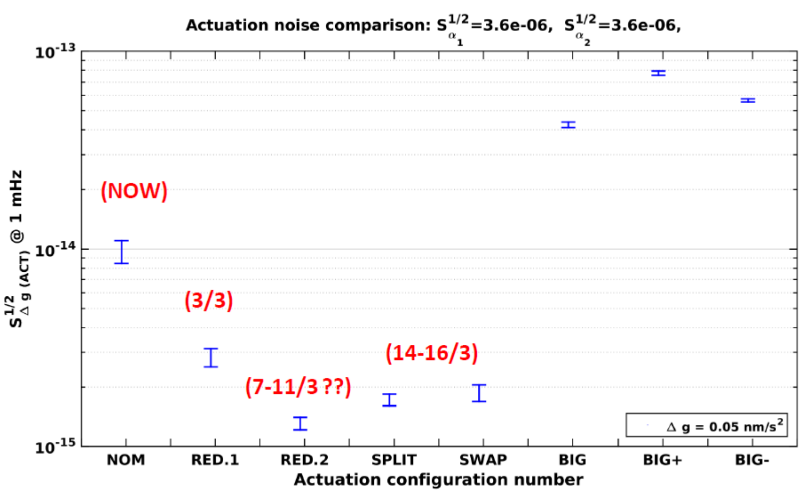
End commissioning, late Feb 2016

- lobbying to lower the actuation authorities
- our model and ground tests predicted decreasing in Δg noise with lower force / torque authorities

Actuation stability noise: configurations for first 2 weeks



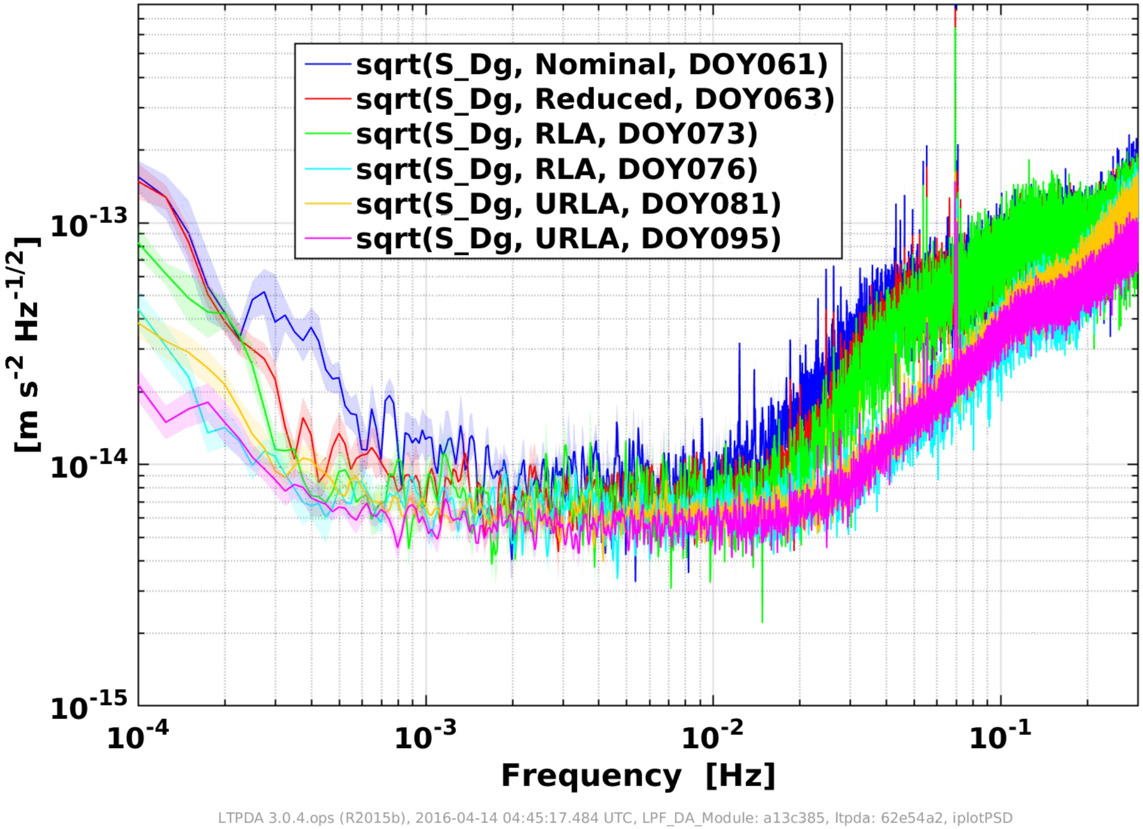
Prediction of actuation noise contribution from ground FEE tests



- authorities were reduced (by start of science)
- slightly different numbers
- reduced authorities rebaptized:
  - “reduced”
  - “ridiculously low authority”
  - “ultra ridiculously low authority”

- limiting factor was TM1 ϕ torque (1 nrad/s^2)

March – April 2016: lowering noise levels (actuation and gas damping)



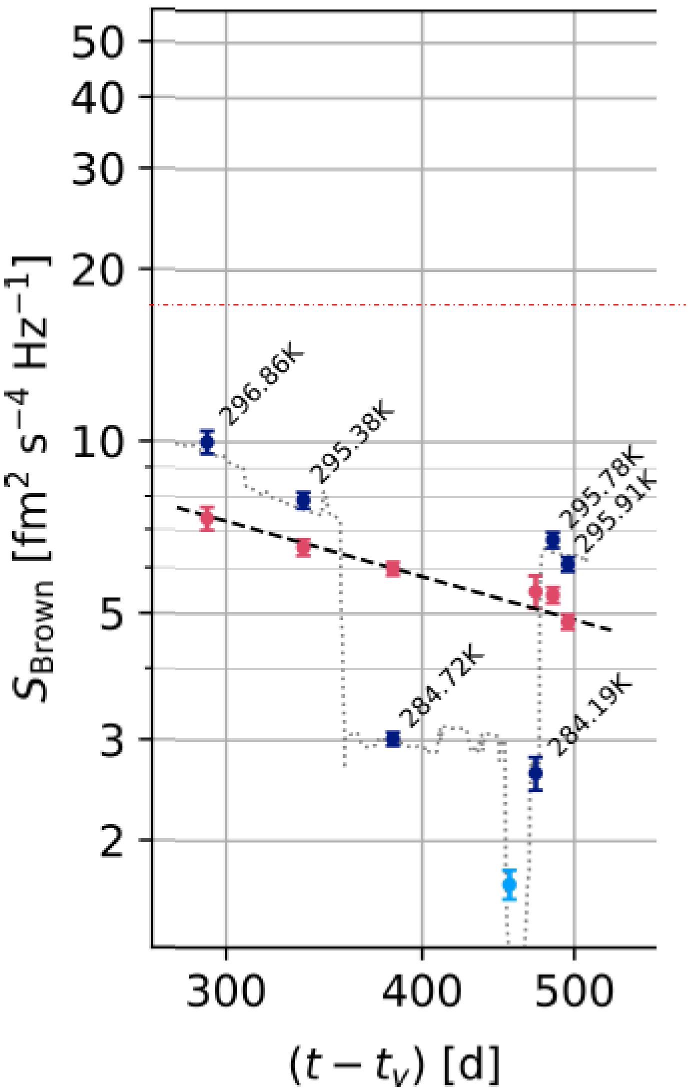
low frequency improvement with lowering authorities

- thanks to gravitational balance (and everything else working...)

several mHz improvement with vent to space

- fog slowly burning off ... what is underneath?

A year and a half later ... gas damping brownian noise



the mHz noise – and thus ***p*** – are still decreasing

lower T from 295 K to 285 K: cut noise power in half

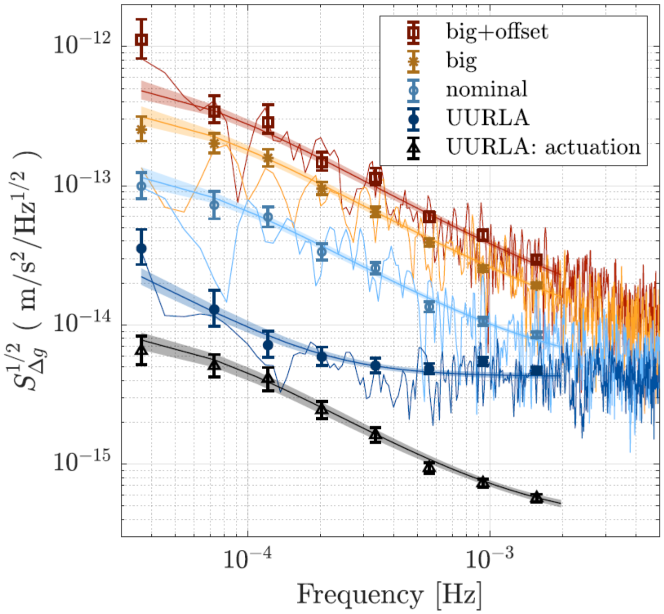
- compatible with water evaporation

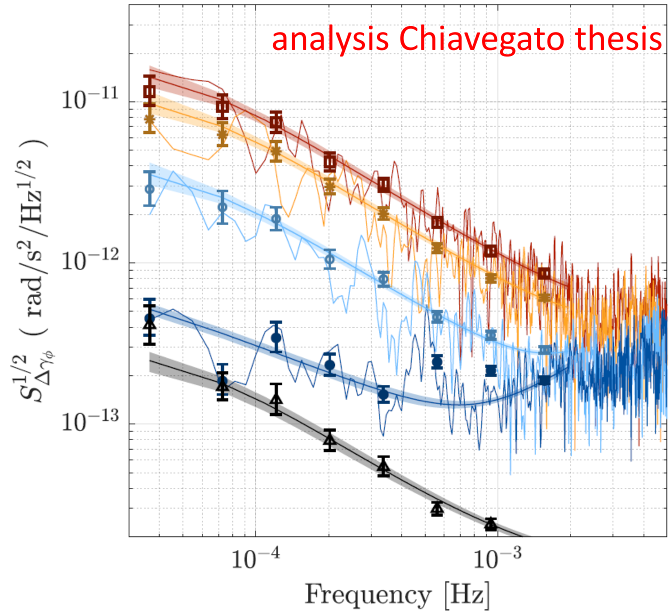
“between the glitches” at 0° C ... noise decreases further

- all other mHz force noise sources – GRS and otherwise – are small

❖ matching or improving upon LPF residual gas pressure improves LISA instrument sensitivity at several mHz

20160516-0525: actuation stability test campaign

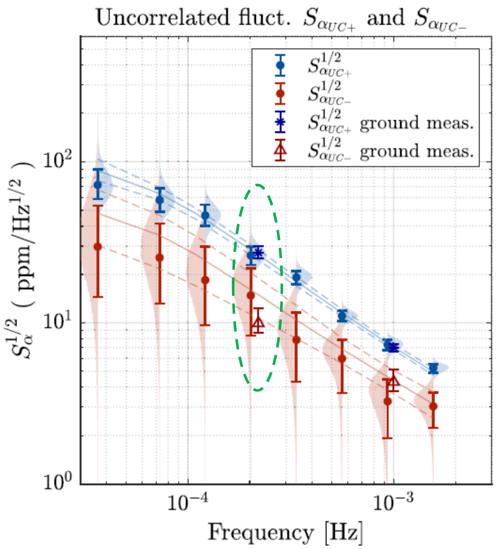


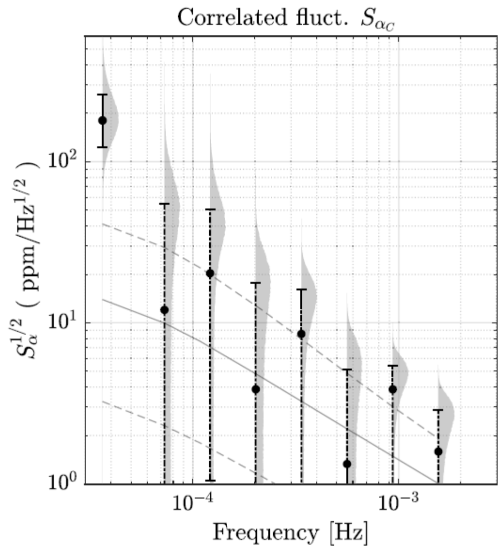


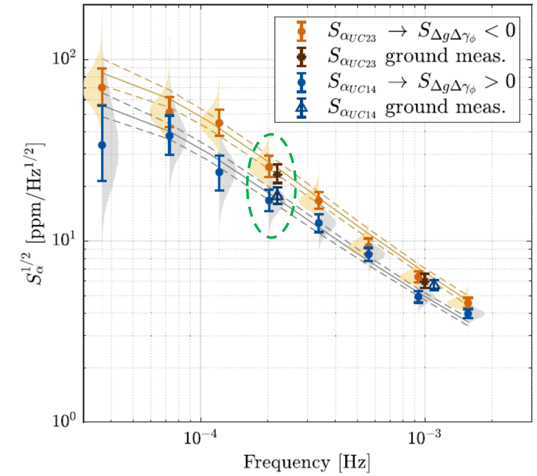
- actuation gain model works!
  - force noise scales with forces / torques
    - limit DC forces and torques (ϕ) for LISA
  - the measured acceleration noise from actuation is as we estimate from applied forces and ground measurements

- actuation is the biggest known source of LPF low frequency noise
  - it does not however dominate the LPF 0.1 mHz noise floor (20-40% of noise power)
    - it would have if the LPF x/ϕ gravitational balancing had not been so good
    - by a factor 50 (power) with "NOMINAL" force authorities

20160516-0525: actuation stability test campaign

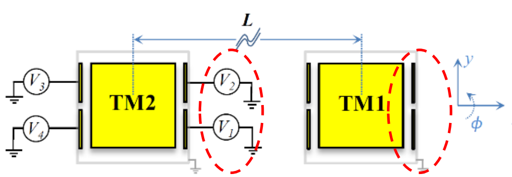






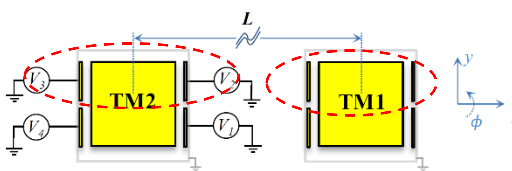
actuation noise in-flight consistent with that on ground – electrode by electrode!

- dominated by uncorrelated electrode amp gains (not reference voltage)



- +X forcing electrodes statistically noisier than –X electrodes

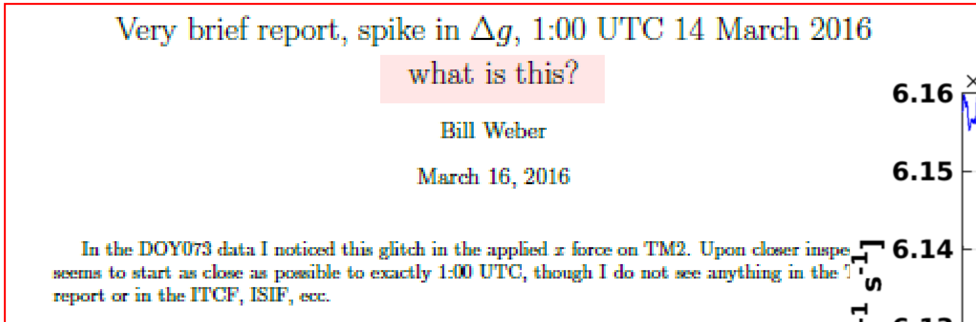
- electrodes 2/3 statistically noisier than electrodes ¼



testing on ground matters:

- for LISA test both at FEE level and with torsion pendulum (force noise)

20160314 01:00 ... (my) first glitch



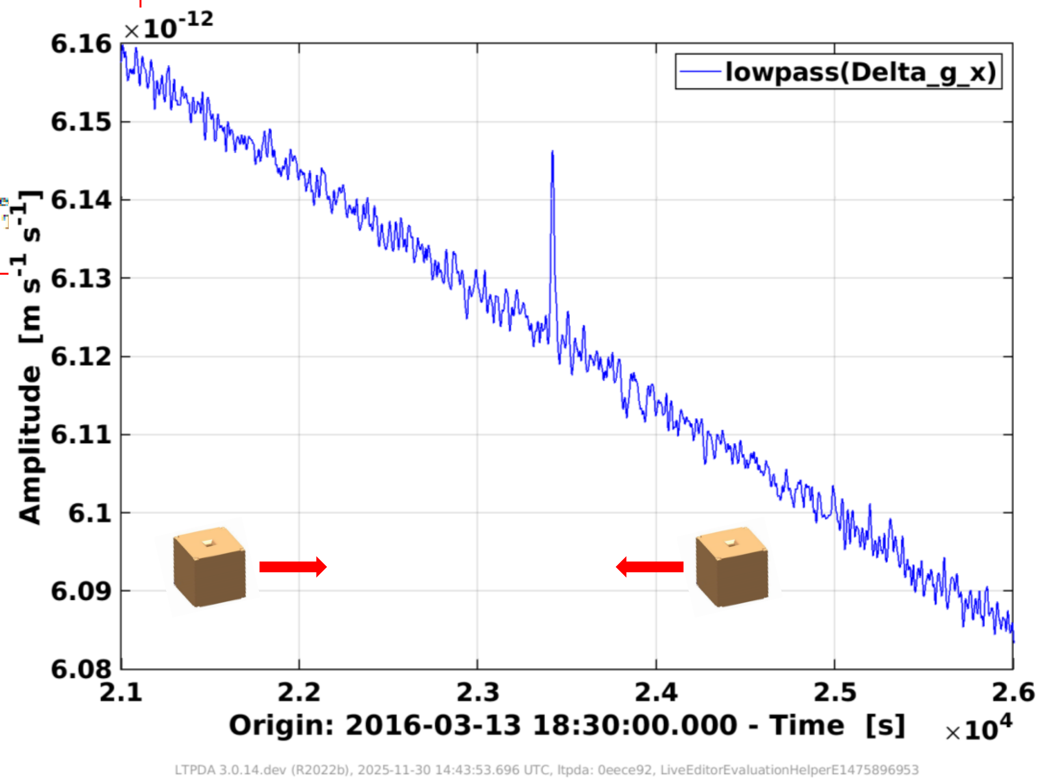
Very brief report, spike in Δg, 1:00 UTC 14 March 2016
what is this?

Bill Weber

March 16, 2016

In the DOY073 data I noticed this glitch in the applied x force on TM2. Upon closer inspe
seems to start as close as possible to exactly 1:00 UTC, though I do not see anything in the T
report or in the ITCF, ISIF, ecc.

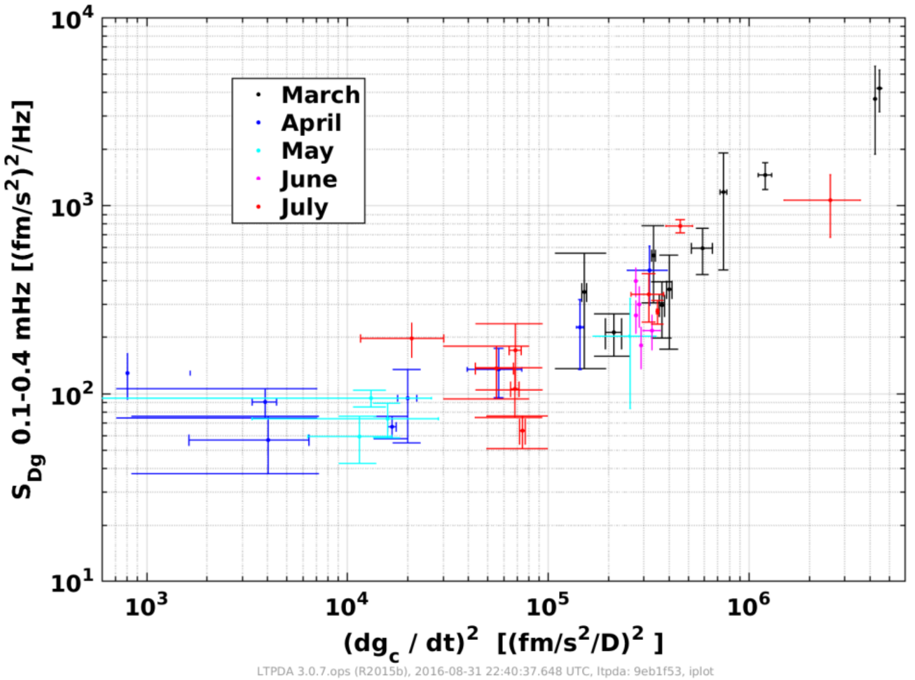
- during an early noise run ... in "ridiculously low authority" (RLA)
- fast, $\tau < 20$ s
- modest impulse, $\Delta v \approx 0.4$ pm/s

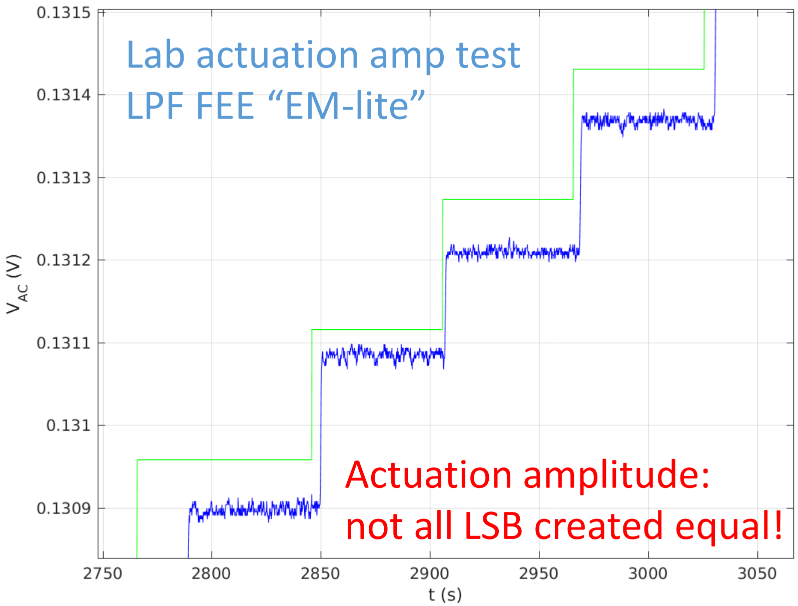


- a population of force impulse events, of order 1 per day
- mostly minutes and order 1 pm/s^2, mostly positive (towards IFO)
- some hours and up to hundreds of pm/s^2
- not trivial to discriminate from "burst GW events"

see Lorenzo Sala talk

Summer 2016 :
watching the low frequency noise increase ... with d∆g/dt



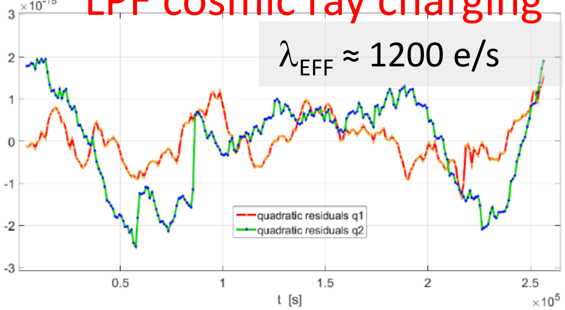


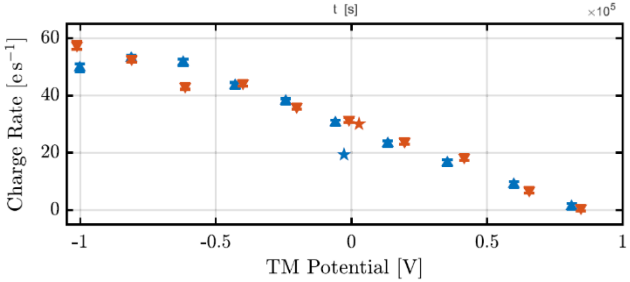
The reason: actuation non-linearities, see Luigi Ferraioli FEE talk!

- correctable (in software) for LPF
- design LISA FEE to avoid this “roundoff” error
- have a ground truth FEE + GRS operative during LISA operations

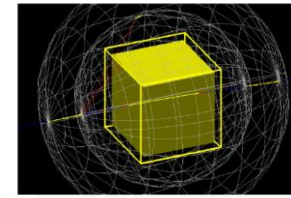
Stray electrostatic forces and mitigation for LISA

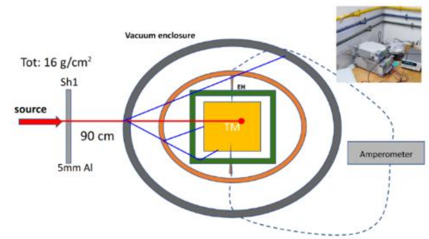
LPF cosmic ray charging





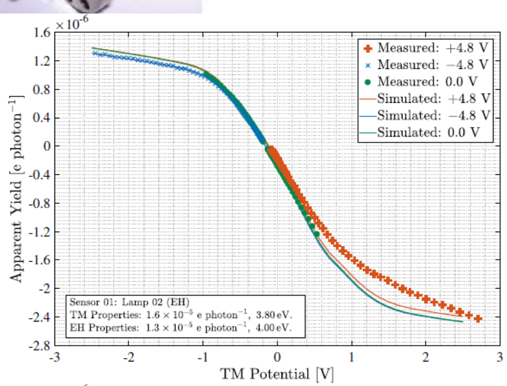
ESA "test mass charging toolkit" simulation (OHB/Urbino/UTN)



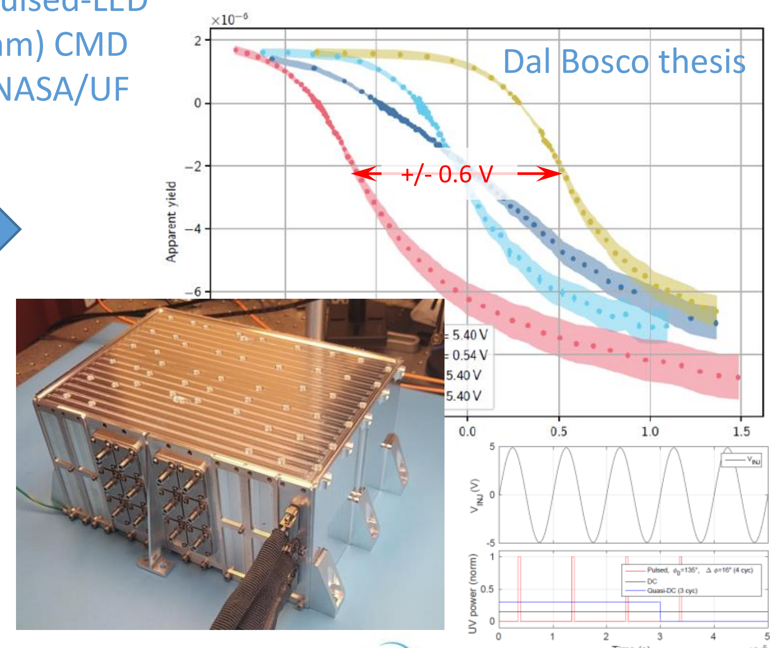


Trento proton beam experiment

254 nm Hg lamp-based CMD (Imperial College)



LISA pulsed-LED (250 nm) CMD from NASA/UF



LISA GPRM

LISA requires greater autonomy

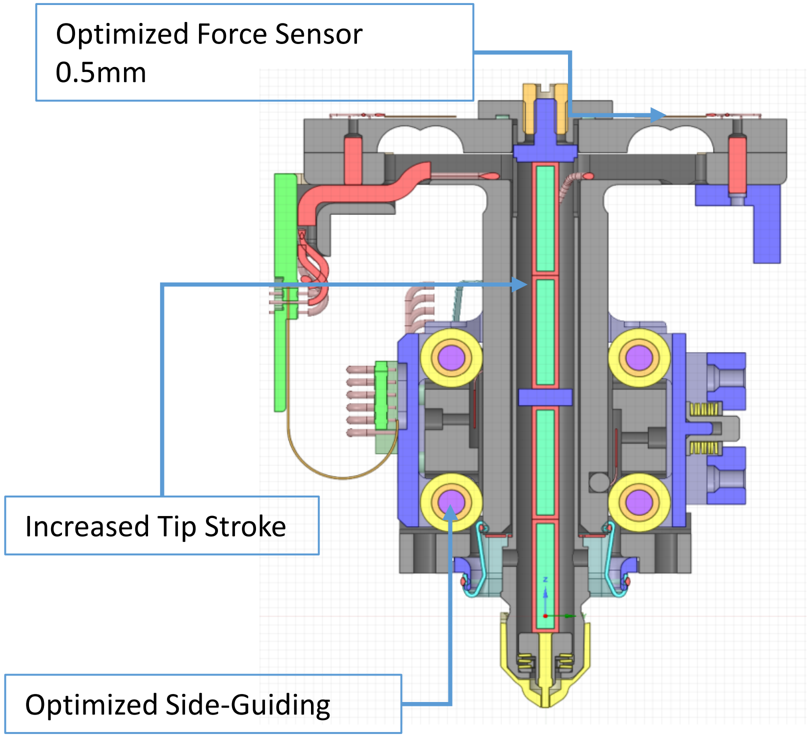
- 6 TM (not 2)
- 6 minute roundtrip light time (not 10 s)

LPF excess velocities due to "secondary" collisions, lateral motion / misalignments

LISA design improvements

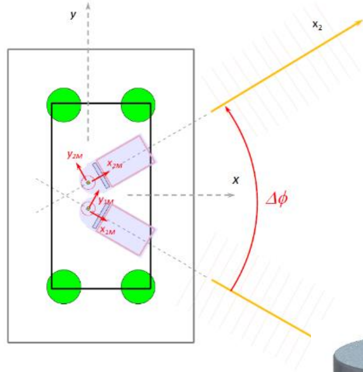
- two cold redundant piezo stacks, each with 27 μm stroke (up from 16 μm)
- improved "roller-roller" guiding
- improved force sensing
- improved testing for lateral motion

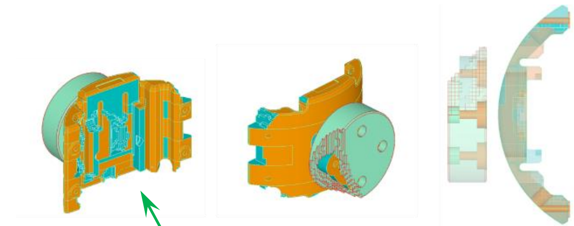
❖ requirements 15 μm/s and 500 μrad/s
❖ DFACS should be ready to handle bounces as contingency

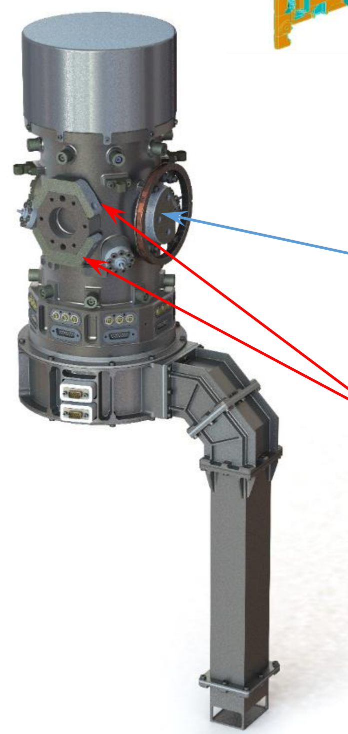


GRS gravitational balancing and DC forces in LISA

LISA DC force requirements
- Δg_x $\Delta g_{y\,,}$ $\Delta g_z < 500$ pm/s^2
- $\gamma_\phi < 1$ nrad/s^2
- γ_θ , $\gamma_\eta < 3$ nrad/s^2



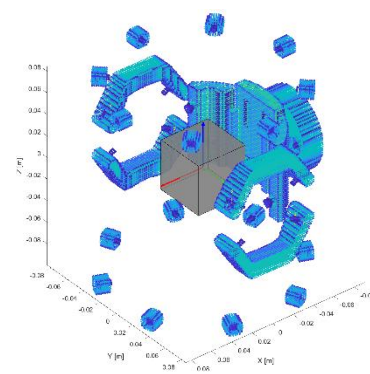




LPF-like IBM

LISA EBM-x (10 nm/s2)

LISA EBM-y envelope



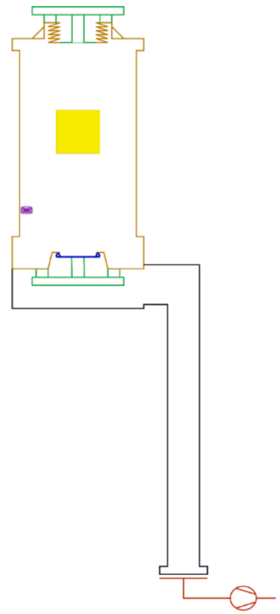
Additional requirements on SC "common mode" and MOSA DC forces

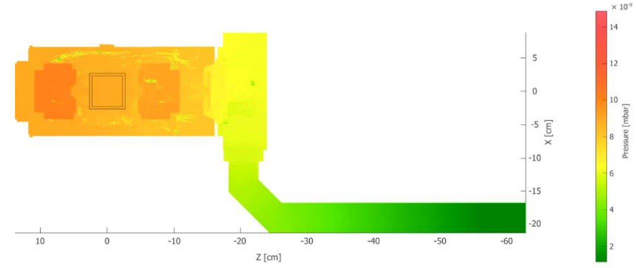
GRS gravitational balance authority request
- 35 nm/s^2
- limited / zero on y, z

GRS residual error allocations < 100 pm/s^2

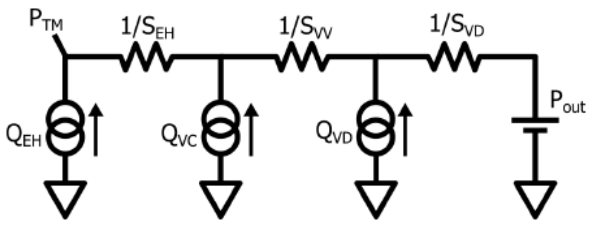
LISA GRS vacuum system and strategies

Requirement 2 µPa from day 1 science ops:
- similar to LPF end of operations





hermetic vent duct with ground vac IF
- pumped on ground, up to 2 weeks pre-launch
- drastic reduction in water permeation

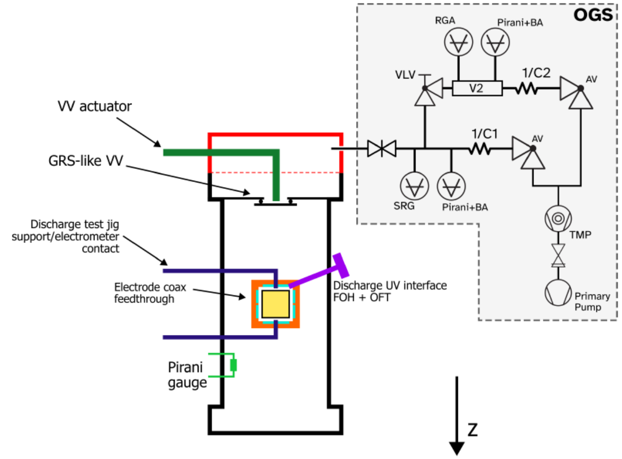


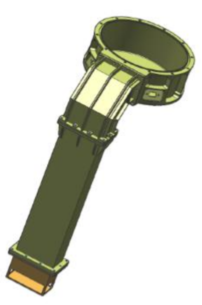
larger conductance to space
- 40 L/s for water (up from 20 L/s)

$$P_{TM} = P_{OUT} + Q_{VC}\frac{1}{S_{EFF-VC}} + Q_{VD}\frac{1}{S_{EFF-VD}}$$

better modelling and sample testing
- 200 g of plastic inside GRS VC

early, better system level testing
- direct VC, VD outgassing measurements
- refine bakeout (coupled with discharge test)
- long term storage monitoring (Pirani in VC)



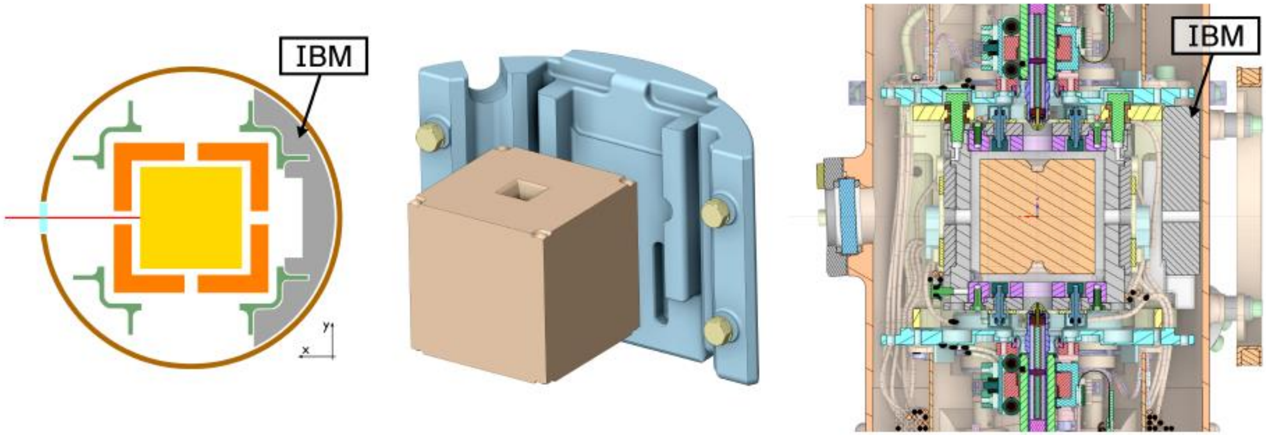


LISA CONSORTIUM

ASI UNIVERSITÀ DI TRENTO INFN

No smoking gun for glitches ... strongest candidate is population of "gas burst" event

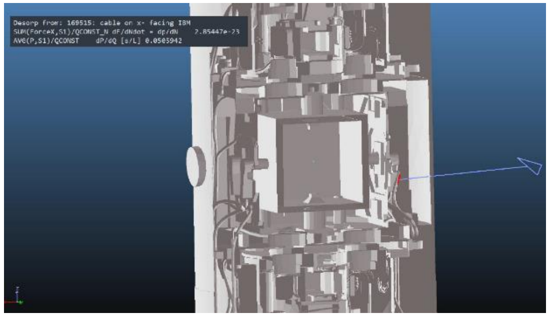
- entering through EH holes, mostly towards IFO – away from IBM – and no torque



Can we test the "gas burst" hypothesis for glitches?

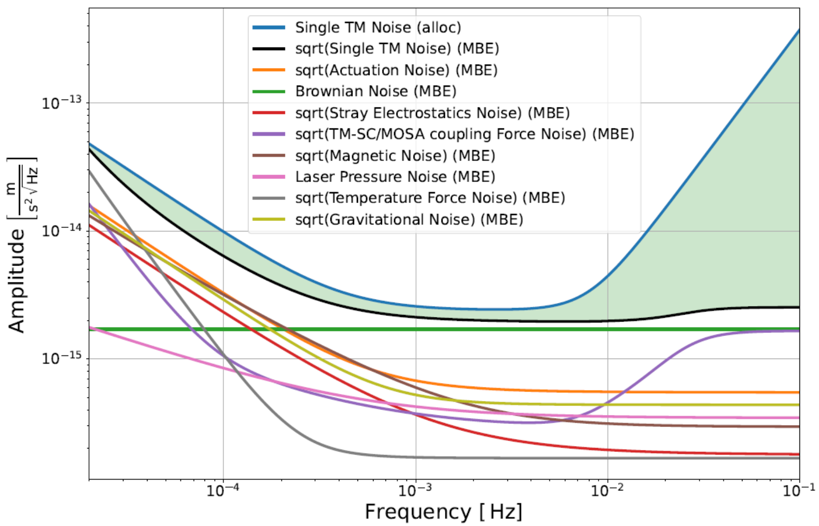
Could we improve the flow paths to limit forces on TM?

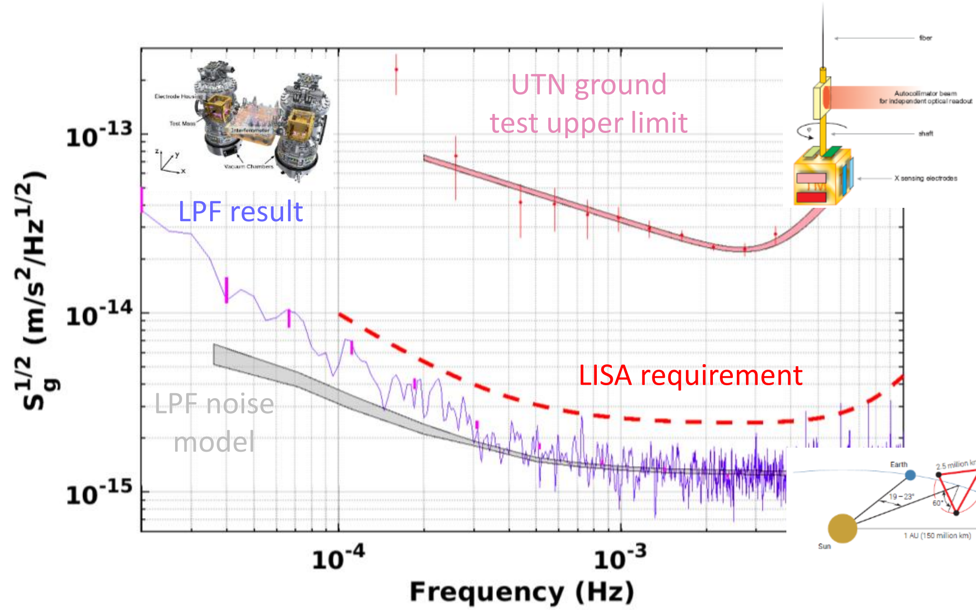
- typical glitch of order 10^{11} molecules, peak flow of 10^{-11} mBar L/s – for glitch coming from IBM cavity
- total outgassing from GRS order 10^{-7} mBar L/s
- but most material in GRS does not make glitches
- can we detect with pressure gauge / outgas test?



Currently under molecular flow (MOLFLOW) analysis ...

Summary: experimental situation for free-falling TM in LISA





- LISA Pathfinder left us with a detailed, experimentally anchored force noise budget
  - but it doesn't explain everything
  - we can't test to LISA limit on ground
  - but we can mitigate key risks (we think)

- next 2-3 years critical for testing and consolidating GRS on ground

Thank you!