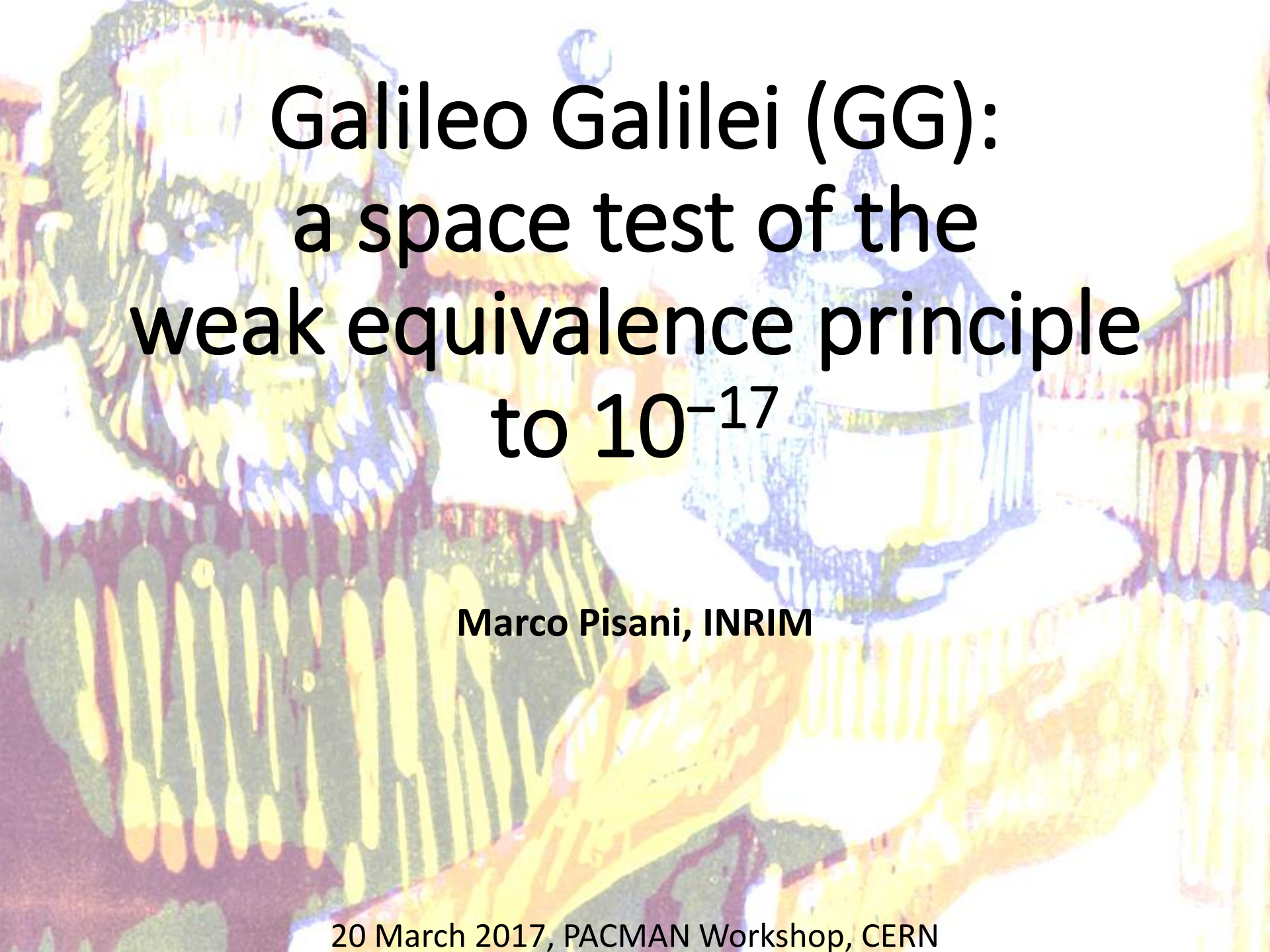


Galileo Galilei (GG): a space test of the weak equivalence principle to 10^{-17}

Marco Pisani, INRIM

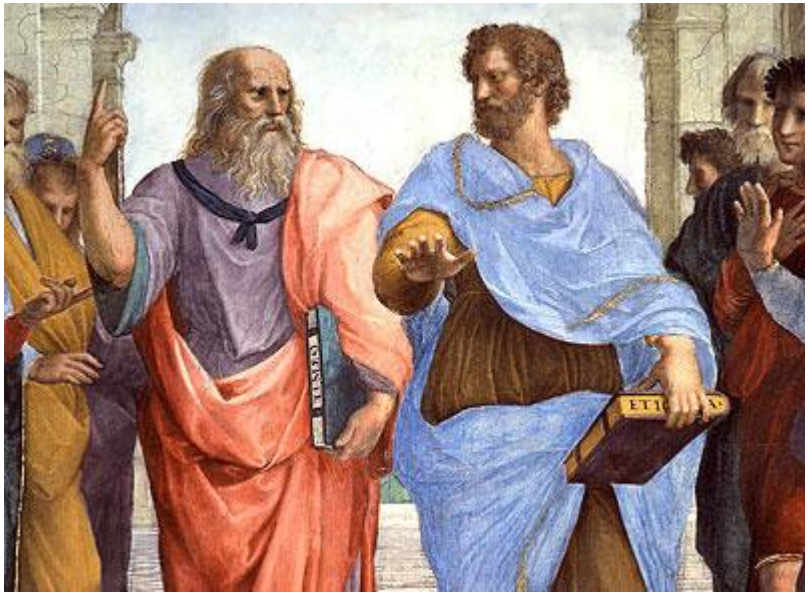
20 March 2017, PACMAN Workshop, CERN

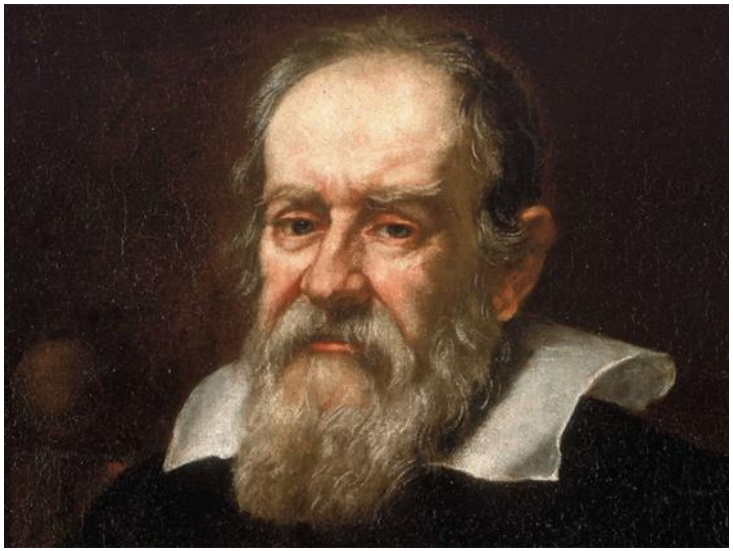
Summary

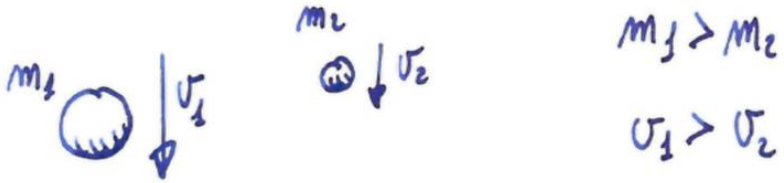
- **What is EP**
- **Why to measure EP**
- **How to measure EP**
- **GG experiment**

Galileo vs Aristoteles

- Aristoteles stated that a heavy body falls “faster” than a light body
- This intuitive conviction lasted for centuries until Galileo’s experiments







Theoretical demonstration (thought experiment)

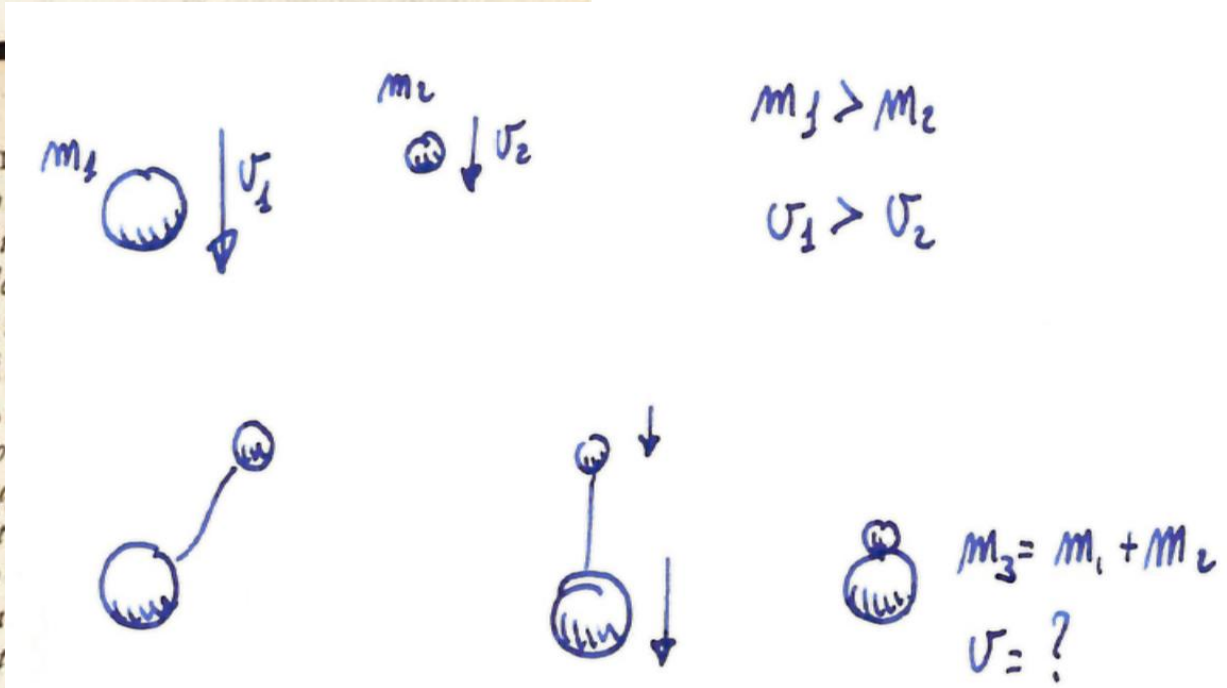
Salu. *Quando dunque noi haueſſimo due mobili, le naturali velo-*

64 DIA

velocità de i quelli fuſſero
gneſſimo il più tardo col p
parte ritardato, & il tard
Non concorrete voi meco

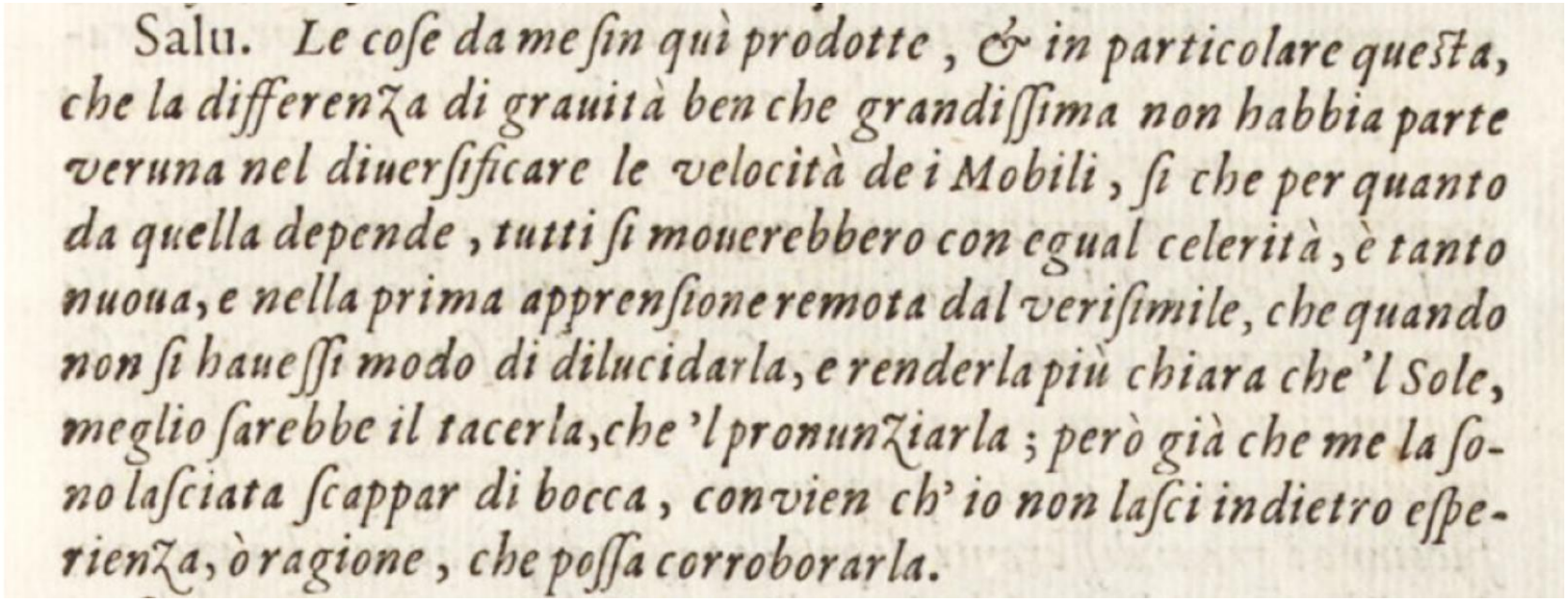
Simp. *Parmi che così*

Salu. *Mà ſe queſto è,*
ſi muoua per eſempio con o
quattro, adunque congiu
loro ſi moverà con velocit
congiunte inſieme fanno
che ſi moueua con otto gra
ſi muoue men velocement
ſuppoſizione. Vedete dun
ſi muoua più velocemente del men graue, io vi concludo il più graue muouerſi men velocemente.



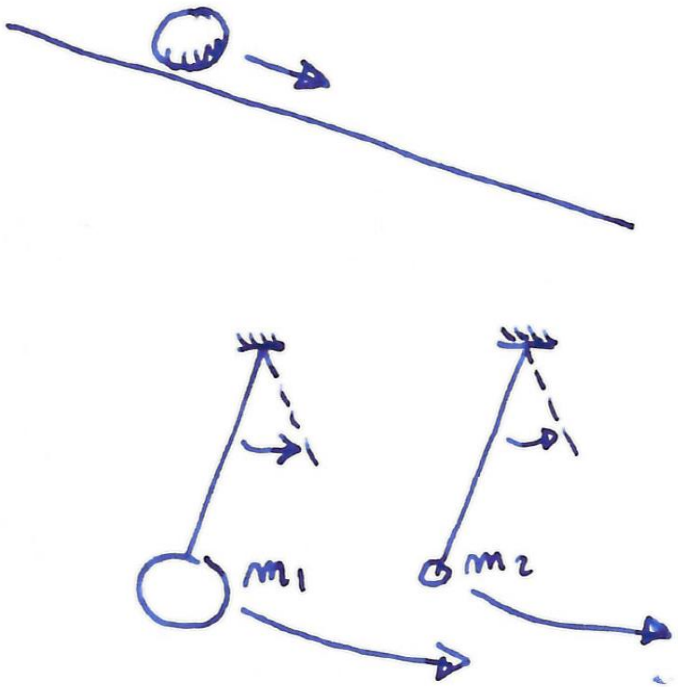
A real experiment is needed

- The consequences of this statement are so dramatic that if I am not able to demonstrate it in a manner «as clear as the Sun» it is better to shut up.



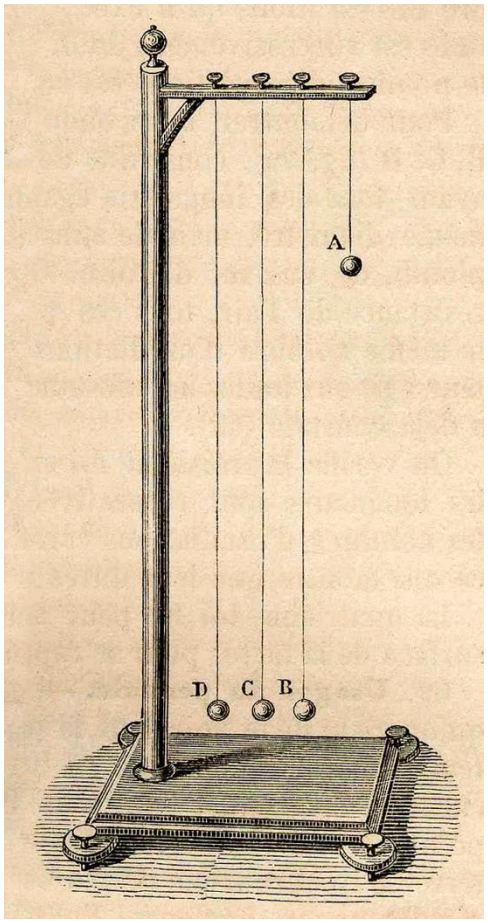
Salu. *Le cose da me sin quì prodotte, & in particolare questa, che la differenza di grauità ben che grandissima non habbia parte veruna nel diuersificare le velocità de i Mobili, si che per quanto da quella depende, tutti si mouerebbero con egual celerità, è tanto nuoua, e nella prima apprensione remota dal verisimile, che quando non si hauessi modo di dilucidarla, e renderla più chiara che 'l Sole, meglio sarebbe il tacerla, che 'l pronunziarla; però già che me la sono lasciata scappar di bocca, conuien ch' io non lasci indietro esperienza, ò ragione, che possa corroborarla.*

Real experiments, 1590

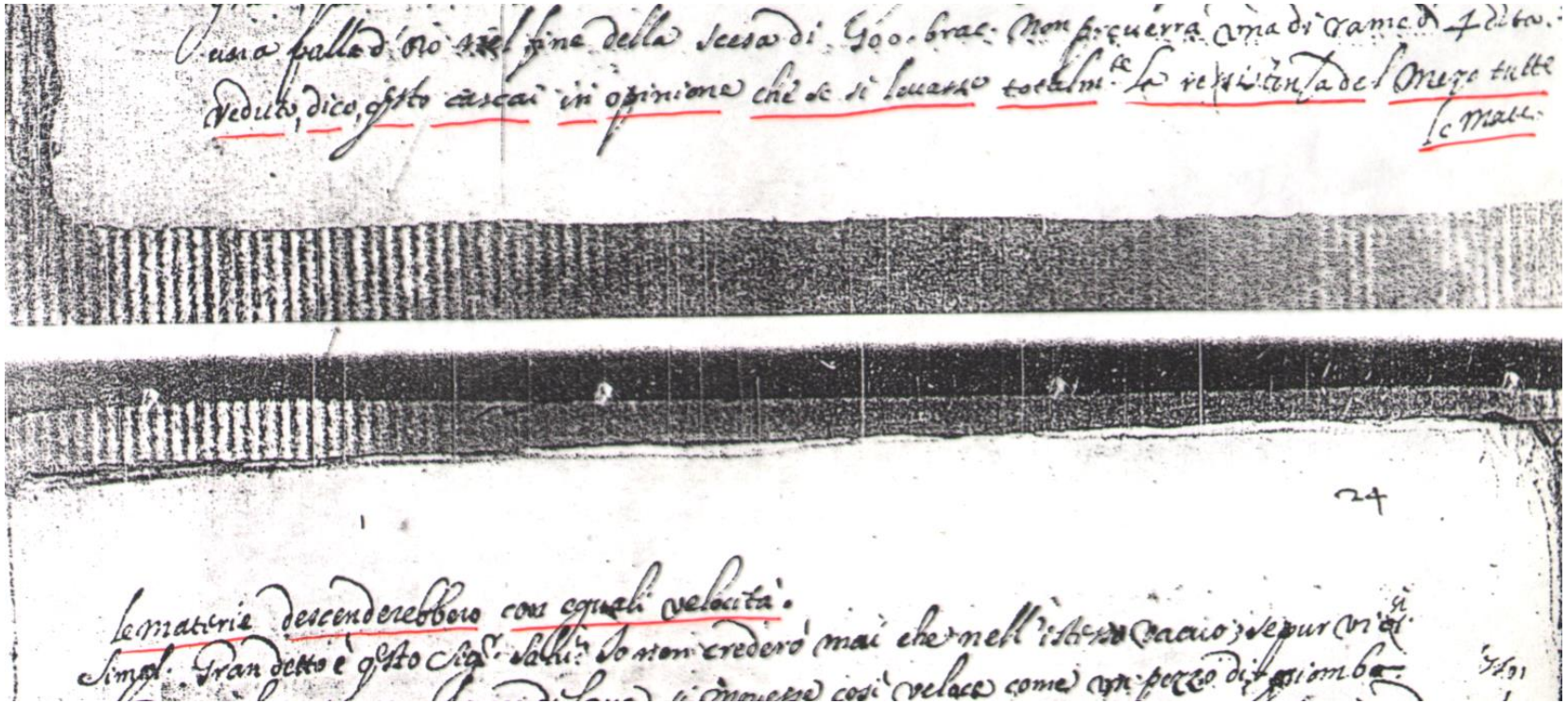


- Galileo expressed experimentally that the acceleration of a test mass due to gravitation is independent of the amount of mass being accelerated

Real experiments



Universality of Free Fall (UFF)

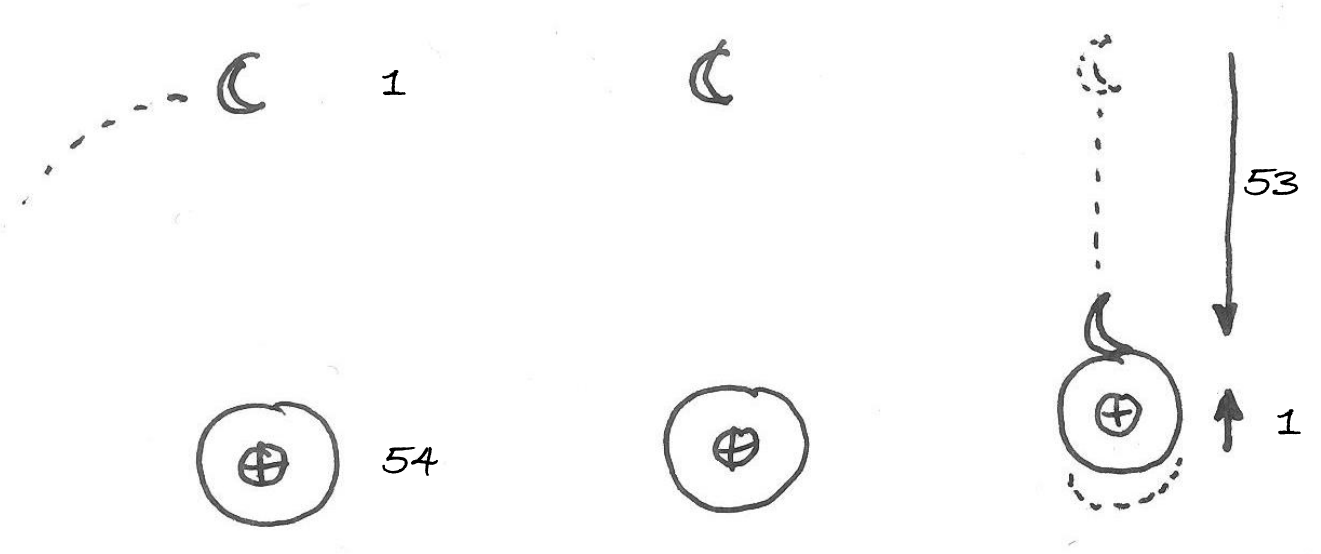


"...veduto, dico, questo cascai in opinione che se si levasse totalmente la resistenza del mezzo tutte le sostanze descenderebbero con eguali velocità."

«… seen this, my convincement is that, if we could completely eliminate the opposition of the medium, all substances would fall at the same speed»

Kepler thought experiment: Concept of inertia, 1609

- If two stones were placed in any part of the world near each other, and beyond the sphere of influence of a third cognate body, these stones, like two magnetic needles, would come together in the intermediate point, each approaching the other by a space proportional to the comparative mass of the other. If the moon and earth were not retained in their orbits by their animal force or some other equivalent, the earth would mount to the moon by a fifty-fourth part of their distance, and the moon fall towards the earth through the other fifty-three parts, and they would there meet, assuming, however, that the substance of both is of the same density. *"Astronomia Nova", 1609*



Newton: the Equivalence Principle, 1686

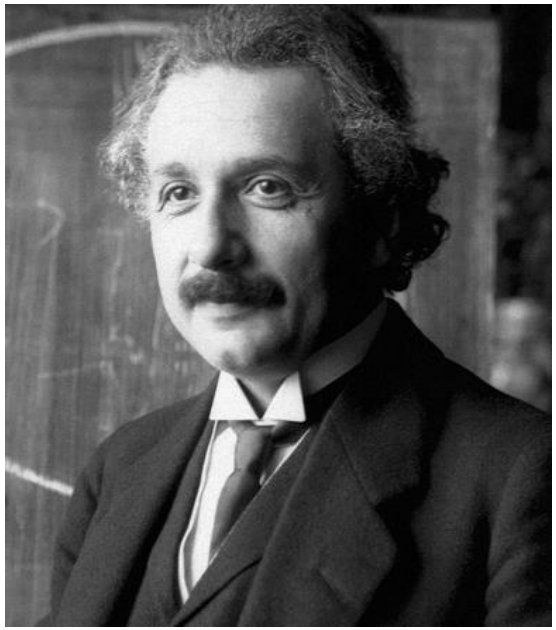
- the law of the equality of the inertial and gravitational mass is equivalent to the assertion that the acceleration imparted to a body by a gravitational field is independent of the nature of the body. For Newton's equation of motion in a gravitational field, written out in full, it is:

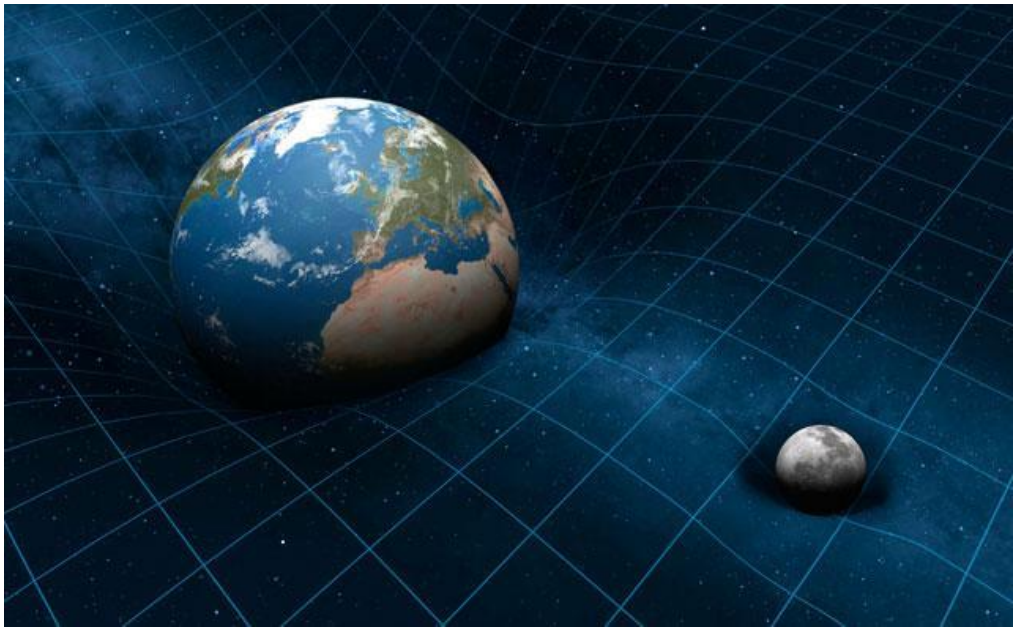
$$F = m_i\, a = m_g\, g \quad \rightarrow m_i = m_g$$

(Inertial mass) (Acceleration) = (Gravitational mass) (Intensity of the gravitational field)

Einstein

- we [...] assume the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system. — 1907
- and starting from that “happiest thought of his life” he formulated the GR theory in 1915





Why to prove the UFF/WEP principle with great accuracy?

- GR rests on the "fact of Nature" that in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition (UFF/WEP) and Einstein was well aware that experimental evidence is crucial
- In "The foundation of the General Theory of Relativity" (1916) About the need for an extension of the postulate of relativity, Einstein wrote: ..."This view is made possible for us by the teaching of experience as to the existence of a field of force, namely the gravitational field, which possesses the remarkable property of imparting the same acceleration to all bodies". Footnote: "Eötvös has proved experimentally that the gravitational field has this property in great accuracy." This footnote was not added in the English translation; it is there in the original paper in German!

Why to prove the UFF/WEP principle with great accuracy?

- GR and the Standard Model cannot be reconciled with each other
- Because of UFF/WEP, gravity couples in the same way to all forms of mass-energy, and such universal coupling makes it different from all known forces described by the SM
- Most of the mass of the Universe is not understood
- A violation would make a revolution in Physics: Is GR to be amended? Is a new force of Nature at play?
- A null result after such deep probing will get rid of all theories which, in their attempts to solve the current impasse, predict violations of UFF/WEP. They will simply become less and less credible. ... Similarly to what happened after Michelson-Morley experiment!

Experiments to test the UFF/WEP

The physical observable of an experiment testing UFF-WEP is the differential acceleration Δa of two test masses one relative to the other as they fall in the gravitational field of a source body (the Earth in the case of GG) with an average acceleration a (*the driving signal*). The fractional differential acceleration

$$\eta = \frac{\Delta a}{a} \tag{1}$$

is known as the Eötvös parameter and quantifies the violation of equivalence (it is exactly zero if no violation occurs). In terms of the inertial and gravitational mass of the bodies being tested it is written as $\eta = 2[(m_g/m_i)_\alpha - (m_g/m_i)_\beta]/[(m_g/m_i)_\alpha + (m_g/m_i)_\beta]$ where α and β indicate their different composition, m_i and m_g their respective inertial and gravitational mass. We know since 1905 that the total mass-energy of a body is the sum of many terms corresponding to the energy of all the conceivable interactions and components: $m = \Sigma_k m_k$, hence η is generalized to:

$$\eta_k = \frac{2[(m_g/m_i)_{\alpha_k} - (m_g/m_i)_{\beta_k}]}{(m_g/m_i)_{\alpha_k} + (m_g/m_i)_{\beta_k}} \tag{2}$$

where a non-zero value of η_k would define the violation of equivalence between the inertial and gravitational mass-energy of the *k-th* type. For UFF-WEP to hold, all of them must be exactly zero. This is the remarkable universal coupling of gravity to all different forms of mass-energy in all bodies that was mentioned earlier. After completion of a new experiment testing Au and Al in

UFF-EP tests

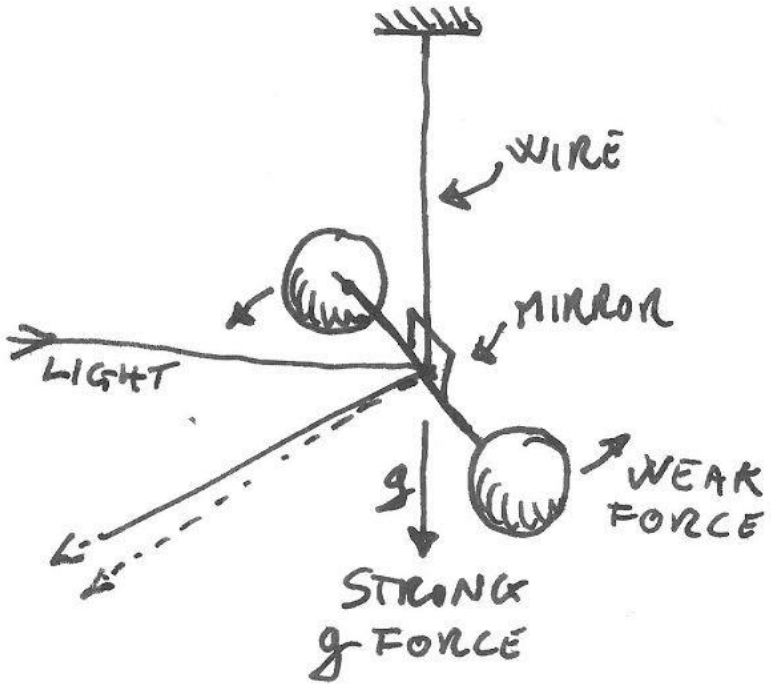
Year	Investigator	Sensitivity	Method
500?	Philoponus	"small"	Drop Tower
1585	Stevin	5×10^{-2}	Drop Tower
1590?	Galileo	2×10^{-2}	Pendulum, Drop Tower
1686	Newton	10^{-3}	Pendulum
1832	Bessel	2×10^{-5}	Pendulum
1910	Southerns	5×10^{-6}	Pendulum
1918	Zeeman	3×10^{-8}	Torsion Balance
1922	Eötvös	5×10^{-9}	Torsion Balance
1923	Potter	3×10^{-6}	Pendulum
1935	Renner	2×10^{-9}	Torsion Balance
1964	Dicke, Roll, Krotkov	3×10^{-11}	Torsion Balance, Sun
1972	Braginsky, Panov	10^{-12}	Torsion Balance, Sun
1976	Shapiro, et al	10^{-12}	Lunar Laser Ranging
1981	Keiser, Faller	4×10^{-11}	Fluid Support
1987	Niebauer, et al	10^{-10}	Drop Tower
1989	Stubbs, et al	10^{-11}	Torsion Balance
1990	Adelberger, Eric G.; et	10^{-12}	Torsion Balance, rotating
1999	Baessler, et al.	5×10^{-14}	Torsion Balance
2016	MICROSCOPE	10^{-16}	Earth Orbit
Future	GG	1×10^{-17}	Earth Orbit, Spinning
Future	Falling atoms	1×10^{-7}	Drop experiment

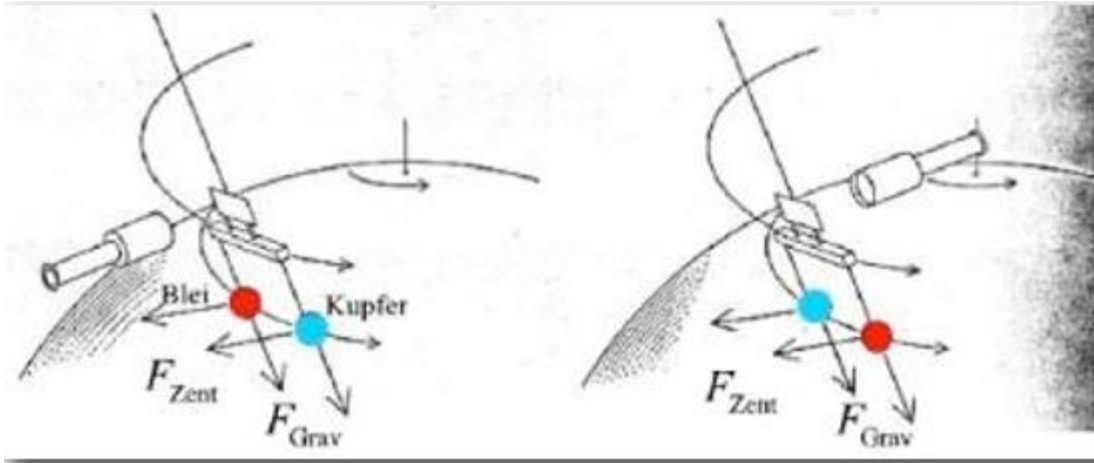
Most relevant experiments

- Pendulum, drop tower (mass dropping, Galileo, Newton, others)
- Torsion balance (Eotvos)
- Braginsky, Torsion balance in the field of Sun
- Mass dropping + interferometer
- Atom dropping
- Rotating torsion balance 1000 s (Adelberger)
- Lunar Laser Ranging

Eötvös, 1906, 10^{-9}

- He exploited the torsion balance (or torsion pendulum) technique
- The gravity effect is cancelled and the torsional sensitivity is huge
- Eötvös made compared the effect of the gravitational field on the masses (of different composition) with the centrifugal force due to the rotation of the Earth





Dicke, Braginsky, 1964, 10^{-11}

- Torsion balance in the field of the Sun
- He used as test masses aluminum and gold being very different in density but mostly in neutron/proton, binding energy and electron relativistic energy

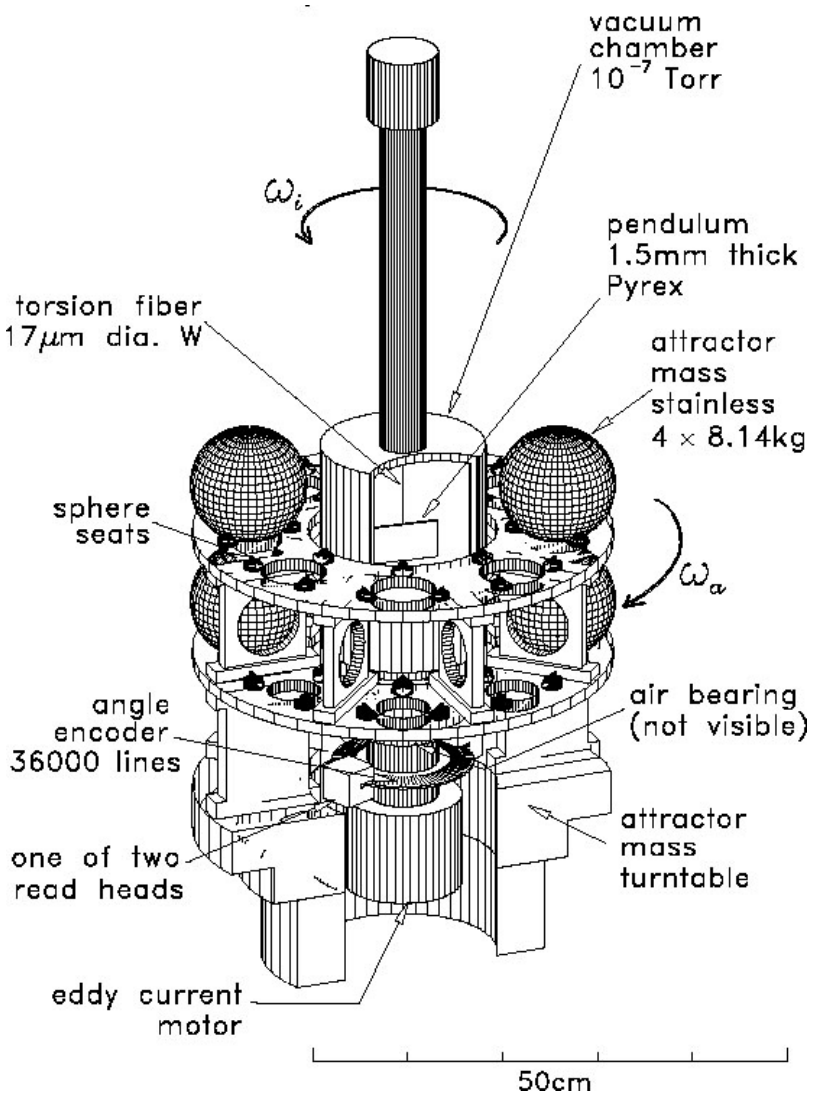
Niebauer, 1987, 10^{-10}

$$\eta = \frac{\Delta a}{a}$$

- Drop tower with interferometric readout.
- The speed of the masses can be determined with exceptional percision, but…
- The indetermination of the initial release conditions coupled with the gravity gradient is the main error source
- A similar limitation will affect atoms dropping experiments (today at 10^{-8})

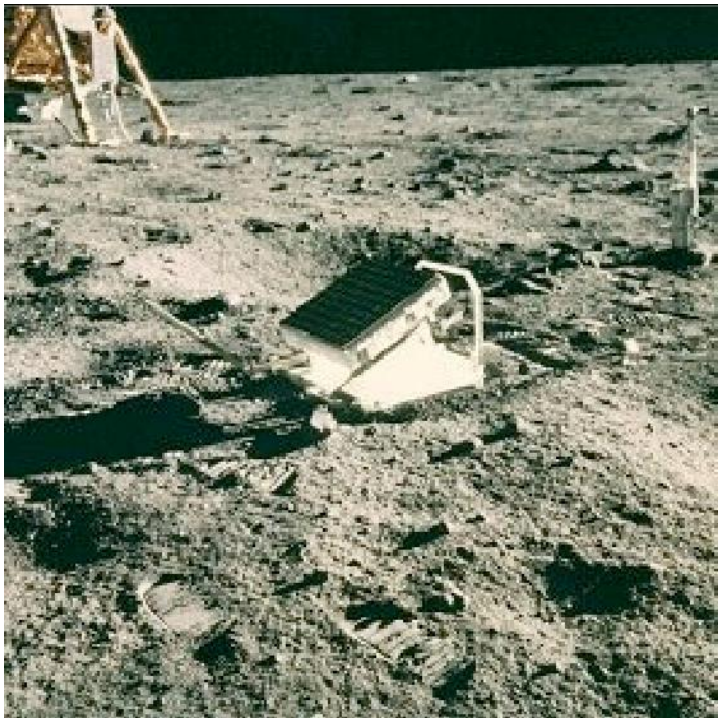
Adelberger, 1990, 10^{-12}

- A slowly rotating torsion balance is exploited to modulate the driving signals
- The signal is modulated at the frequency 1/4h
- Today the EOT-WASH group reached 10^{-13} at present the best result



Lunar Laser Ranging, 70s →, 10^{-13}

- Since the Apollo 11 mission in 1969 the distance between Earth and Moon is accurately measured (centimeters in the 70s and millimeters today).
- Their behavior in the Sun's gravity field of two bodies with different densities would unveil WEP violation

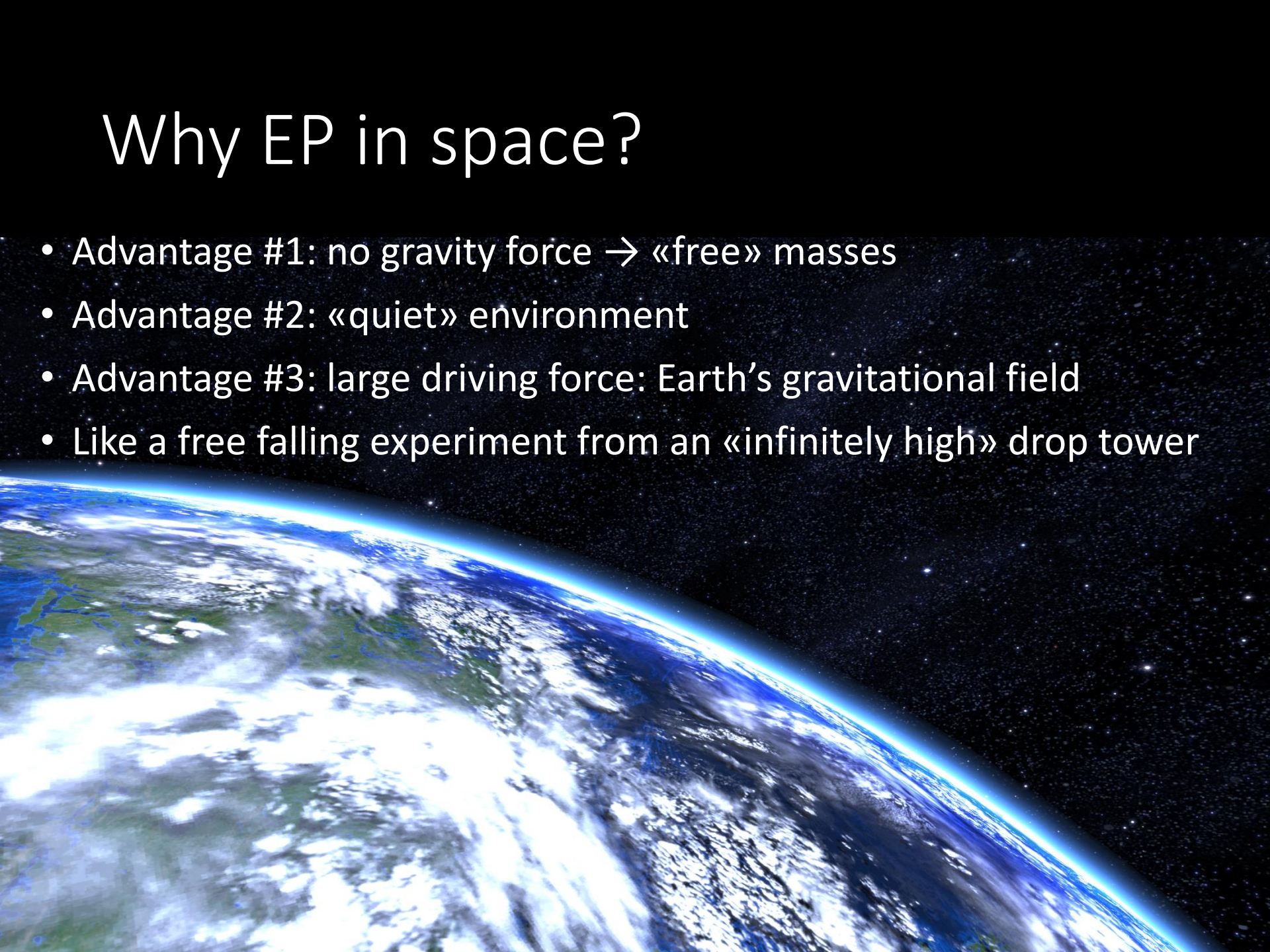


Astrometric space missions

- Future Astrometric space missions could look for WEP by accurately measure the orbits of planets in the gravitational field of the Sun.
- Astrometric Gravitation Probe (AGP) measuring the orbits of Jupiter and Mercury with μarcsecond resolution
- BepiColombo orbiting around Mercury

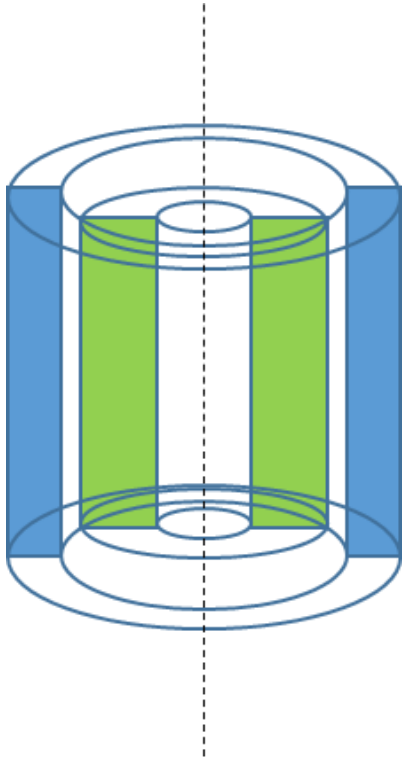
Why EP in space?

- Advantage #1: no gravity force → «free» masses
- Advantage #2: «quiet» environment
- Advantage #3: large driving force: Earth's gravitational field
- Like a free falling experiment from an «infinitely high» drop tower



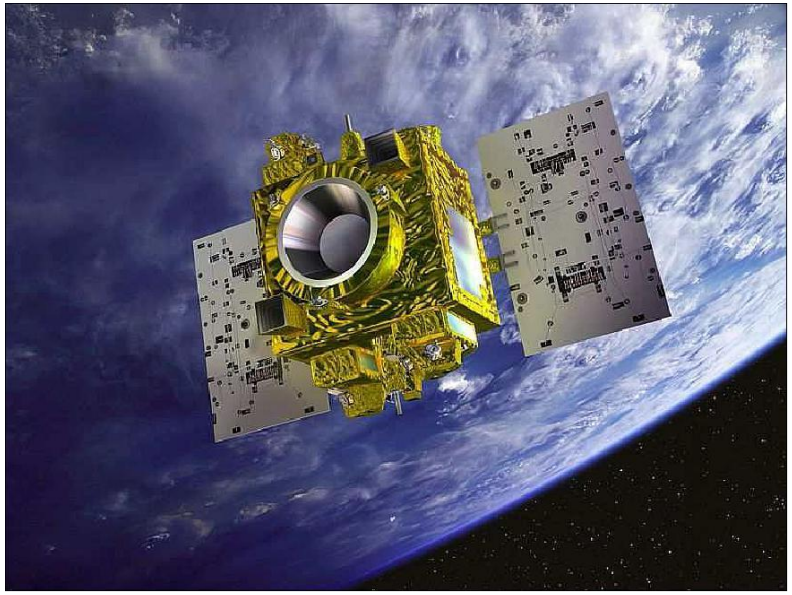
How EP in space?

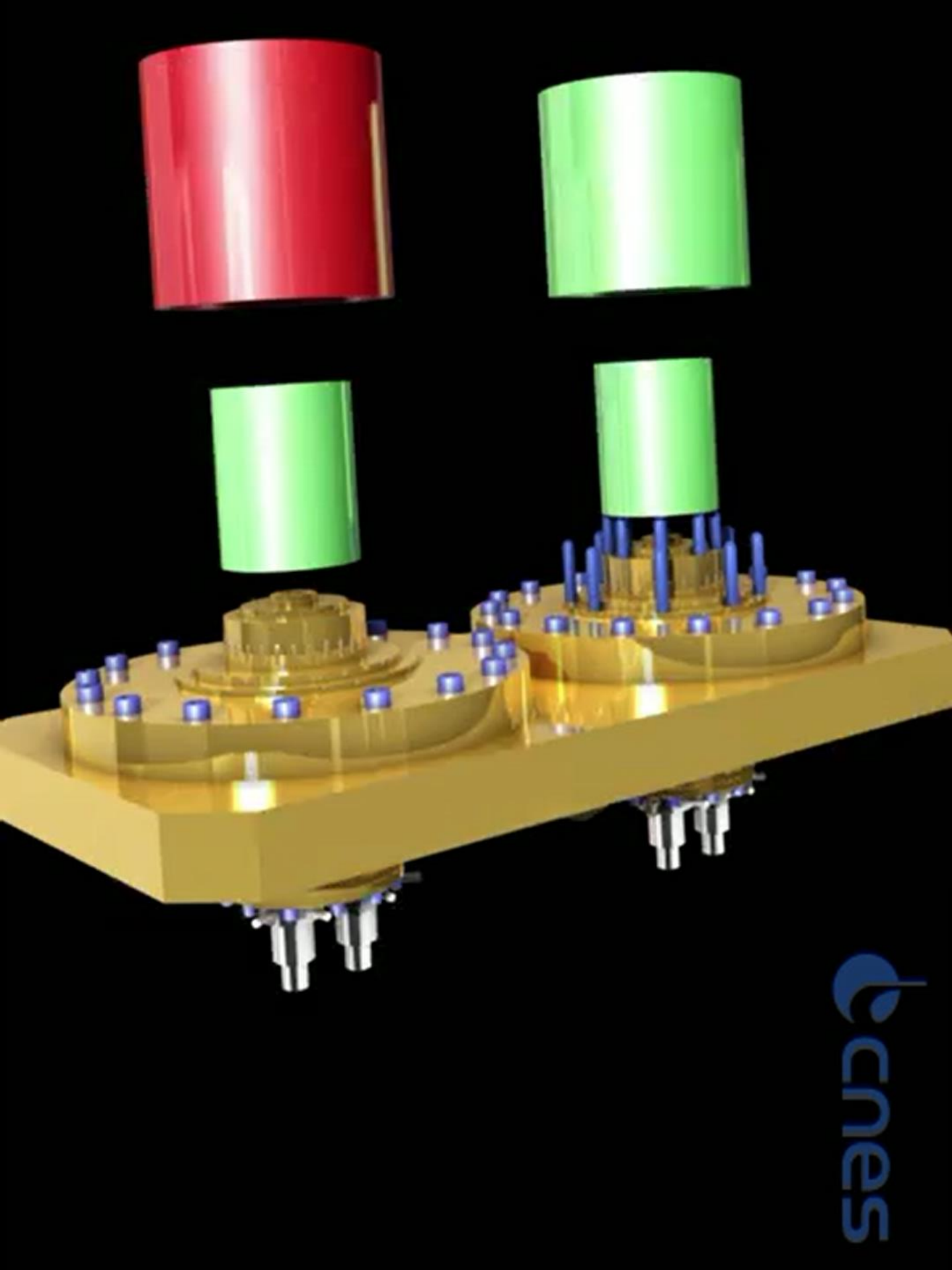
- Test masses: coaxial cylinders to eliminate tidal effects (gravity gradients)
- The relative displacements of the two masses due to a violation of the EP is measured
- The signature signal is modulated by changing the relative orientation of the sensing axis wrt the force source

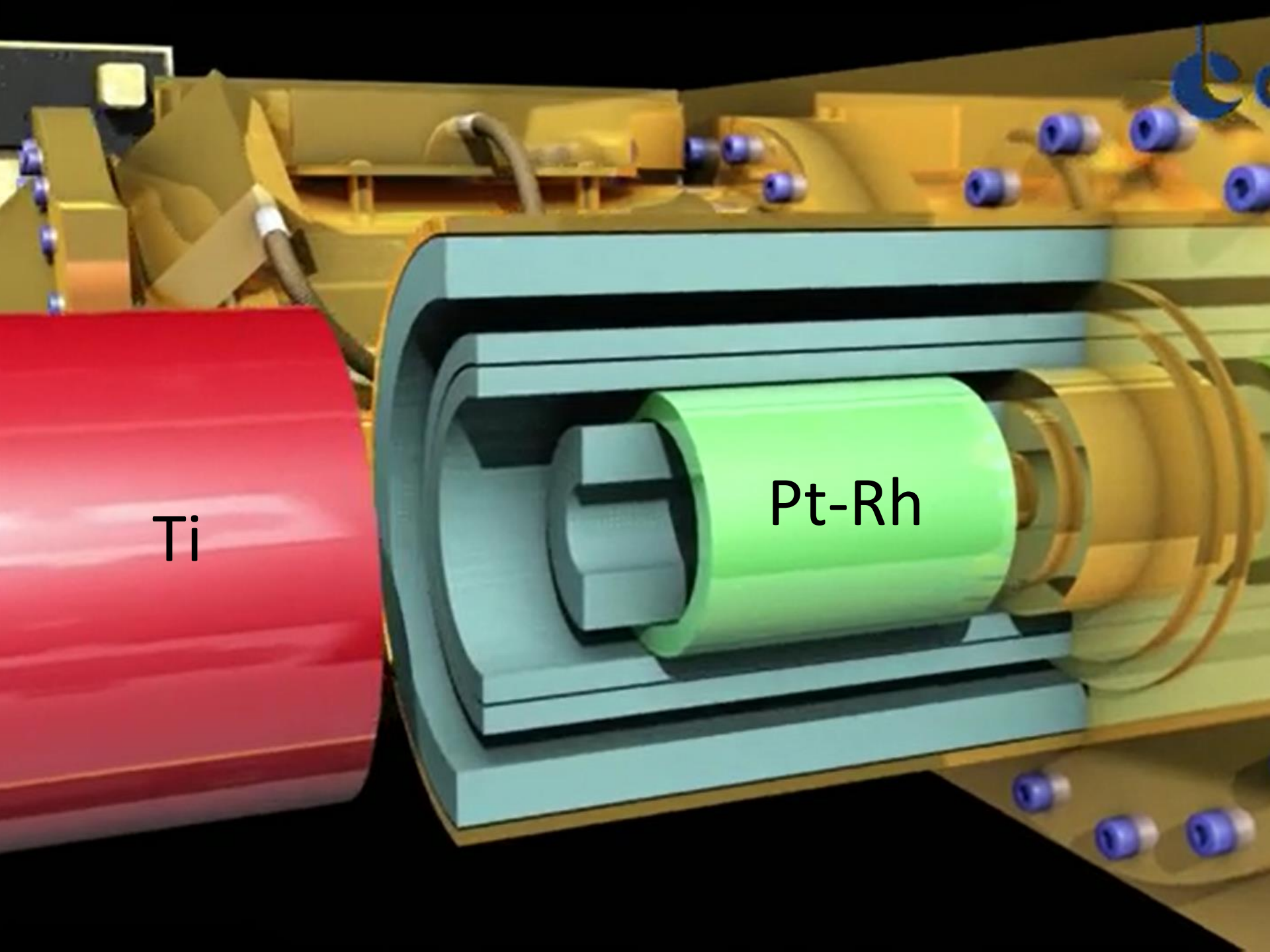


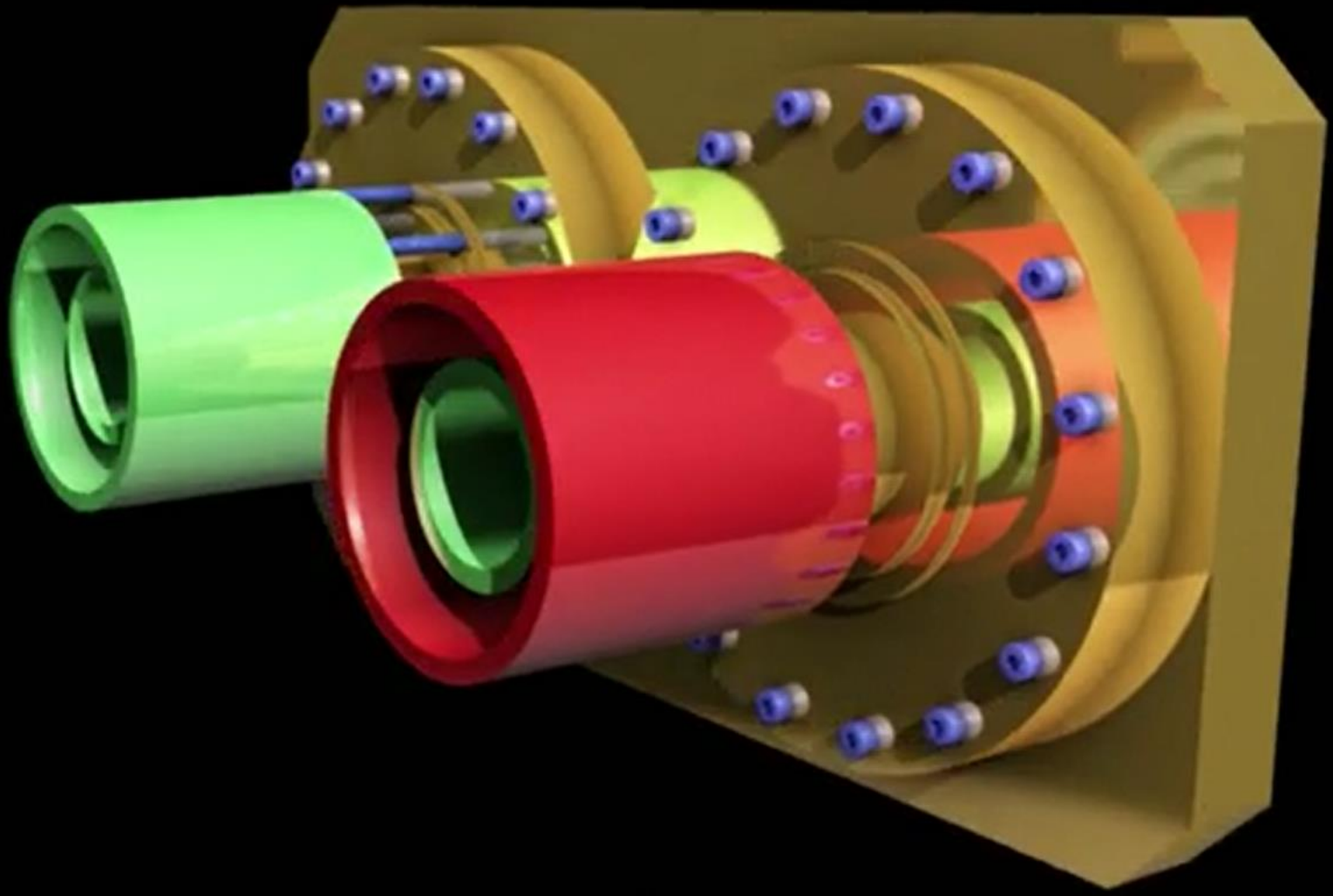
Microscope (CNES), now operating

- 4 masses: 3 of platinum-rhodium alloy and another mass of titanium alloy
- Launched on 25 April 2016
- Orbit: 700 km, sun synchronous
- Orbit period: ≈ 6000 s

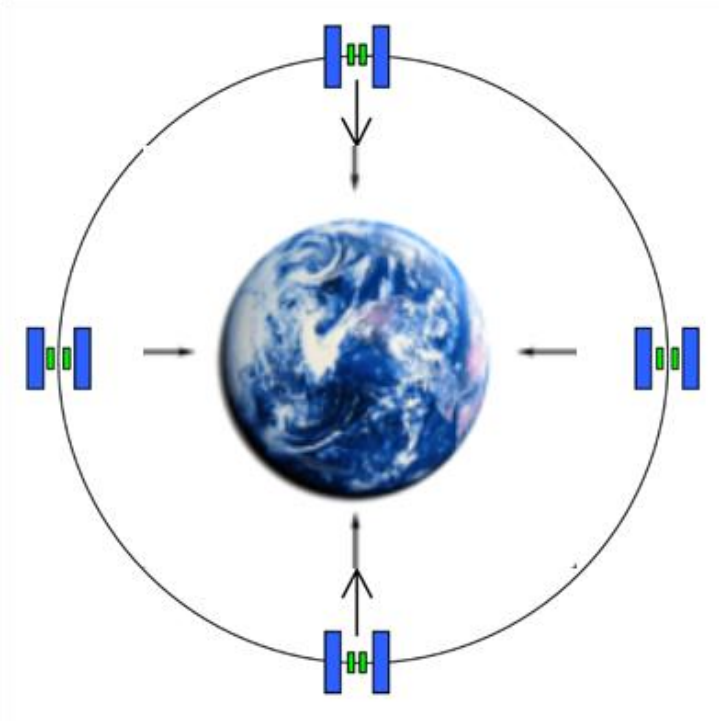



cnes

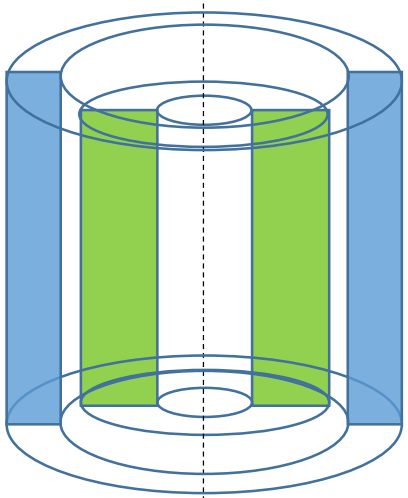

Ti
Pt-Rh



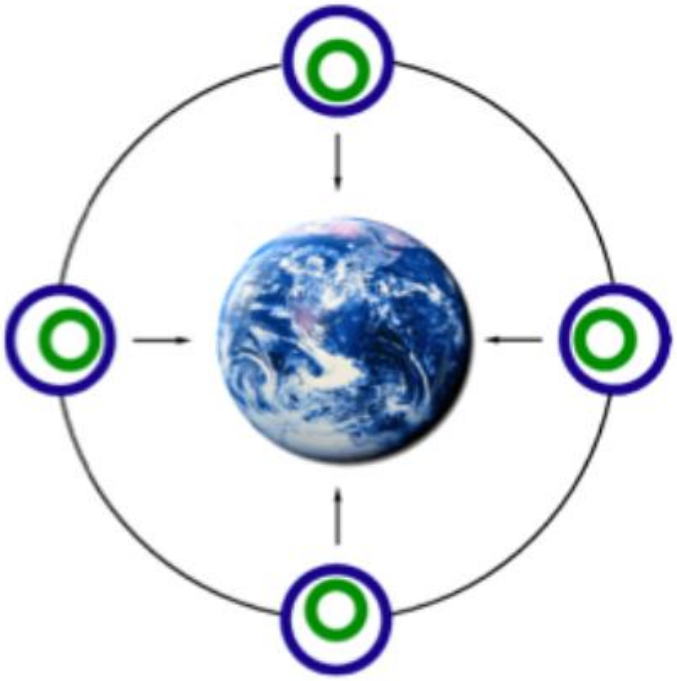
MICROSCOPE orbit



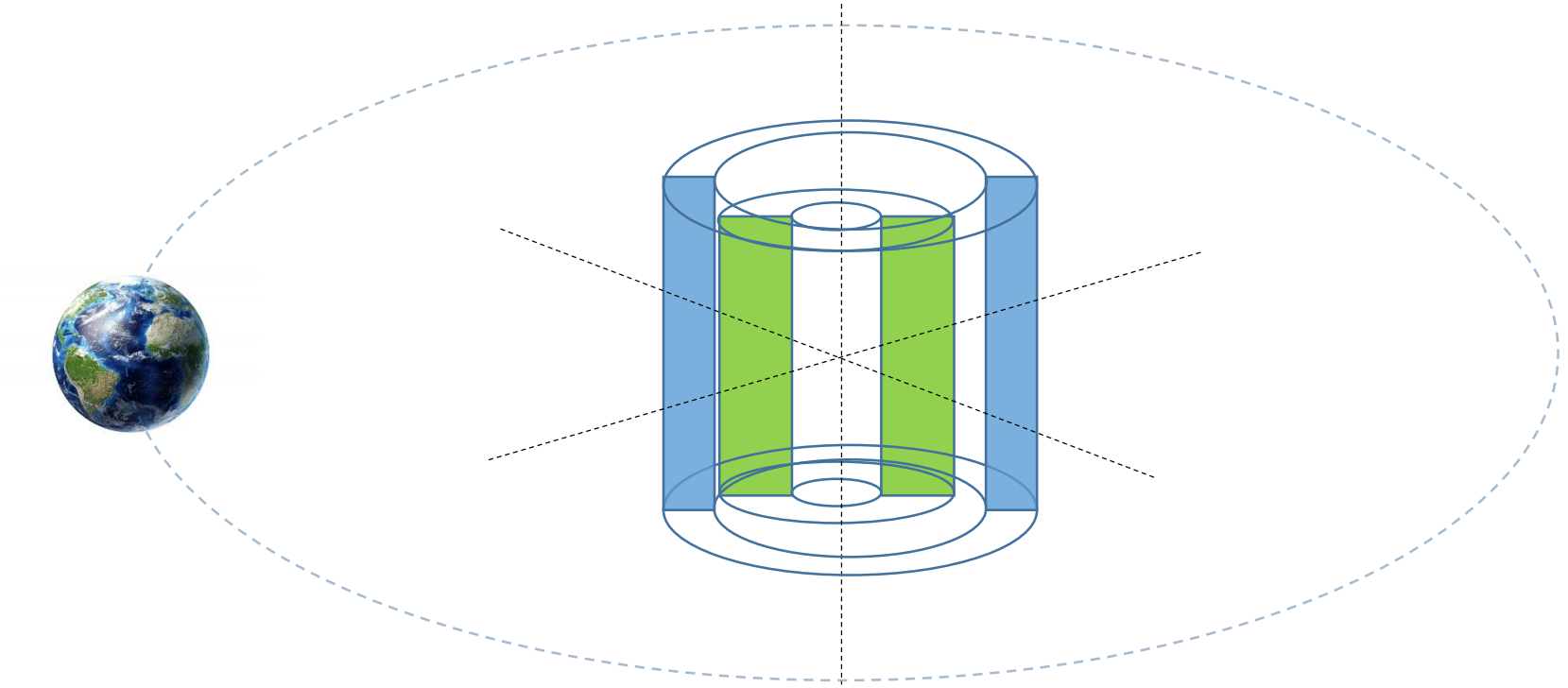
MICROSCOPE violation signal

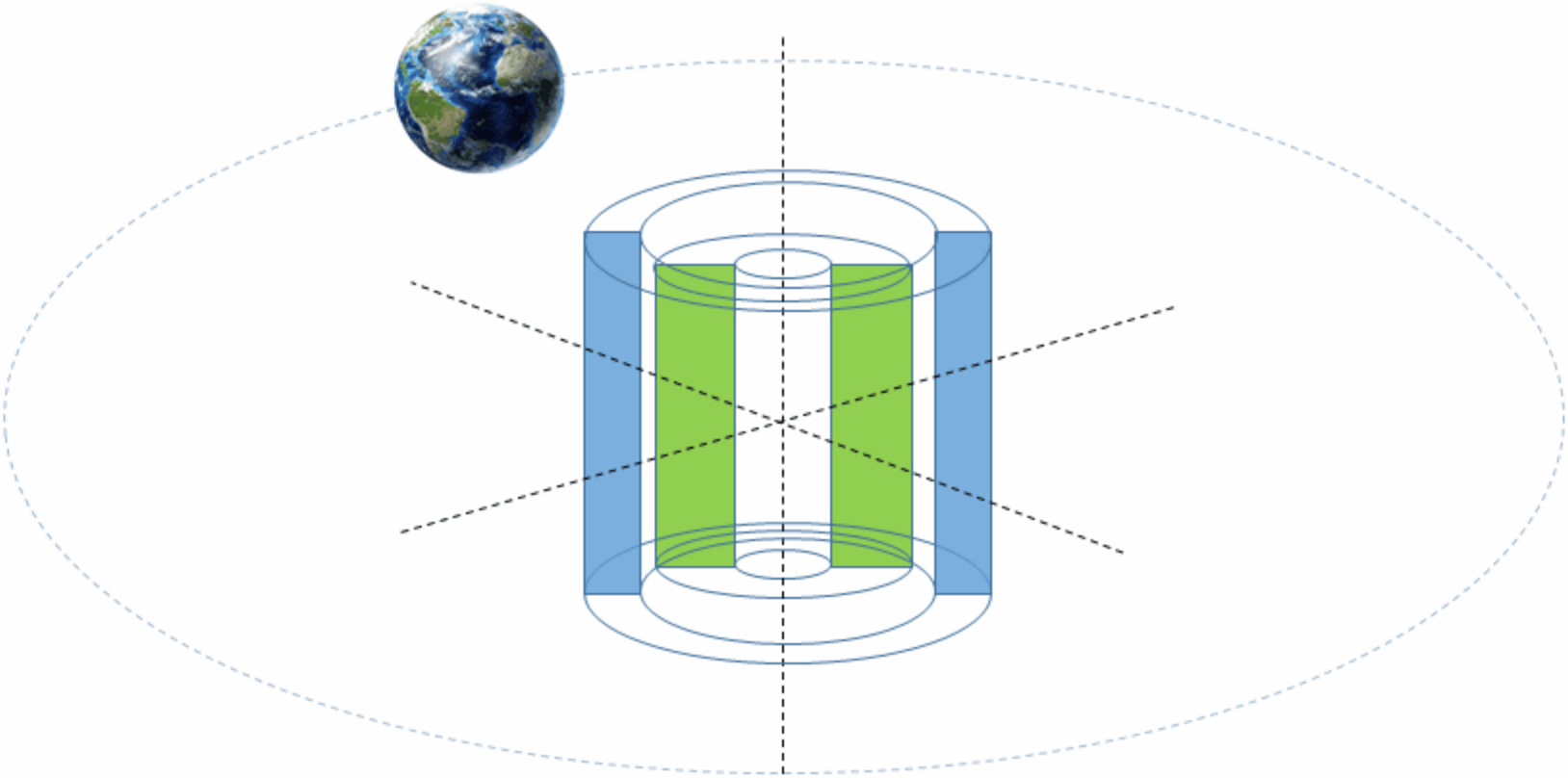


GG orbit



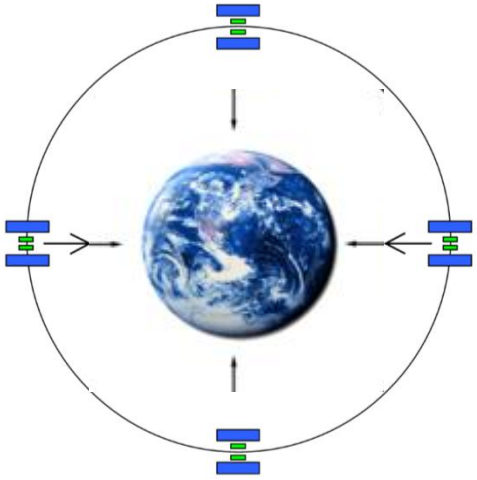
GG violation signal

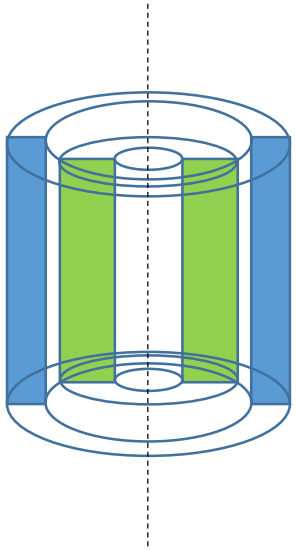


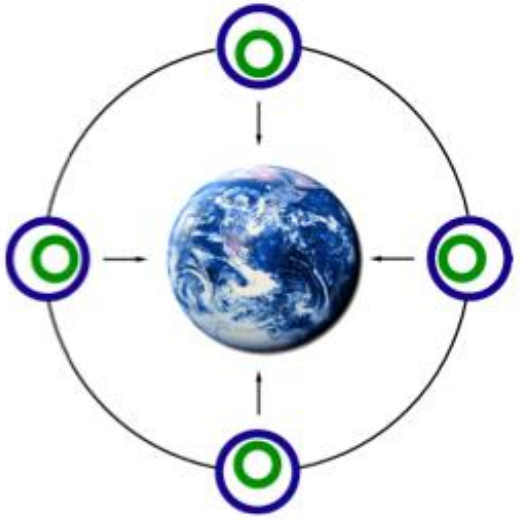


MicroSCOPE vs GG… where is the difference?

- Microscope, h = 700 km
- GG, h = 600 km

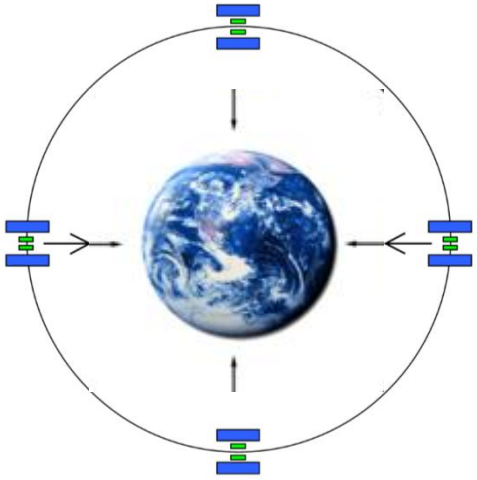


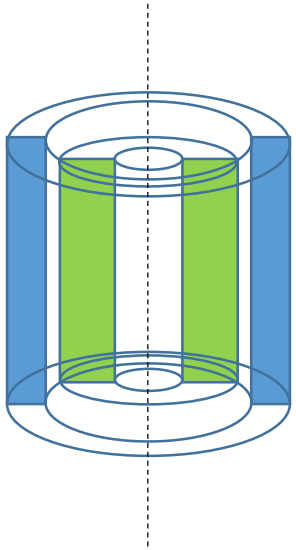


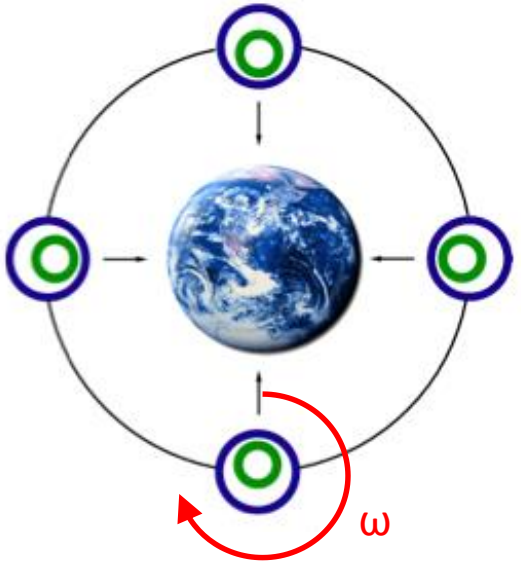


GG is spinning!

- Microscope: violation signature at 0,17 mHz
- GG: violation signature at 1 Hz

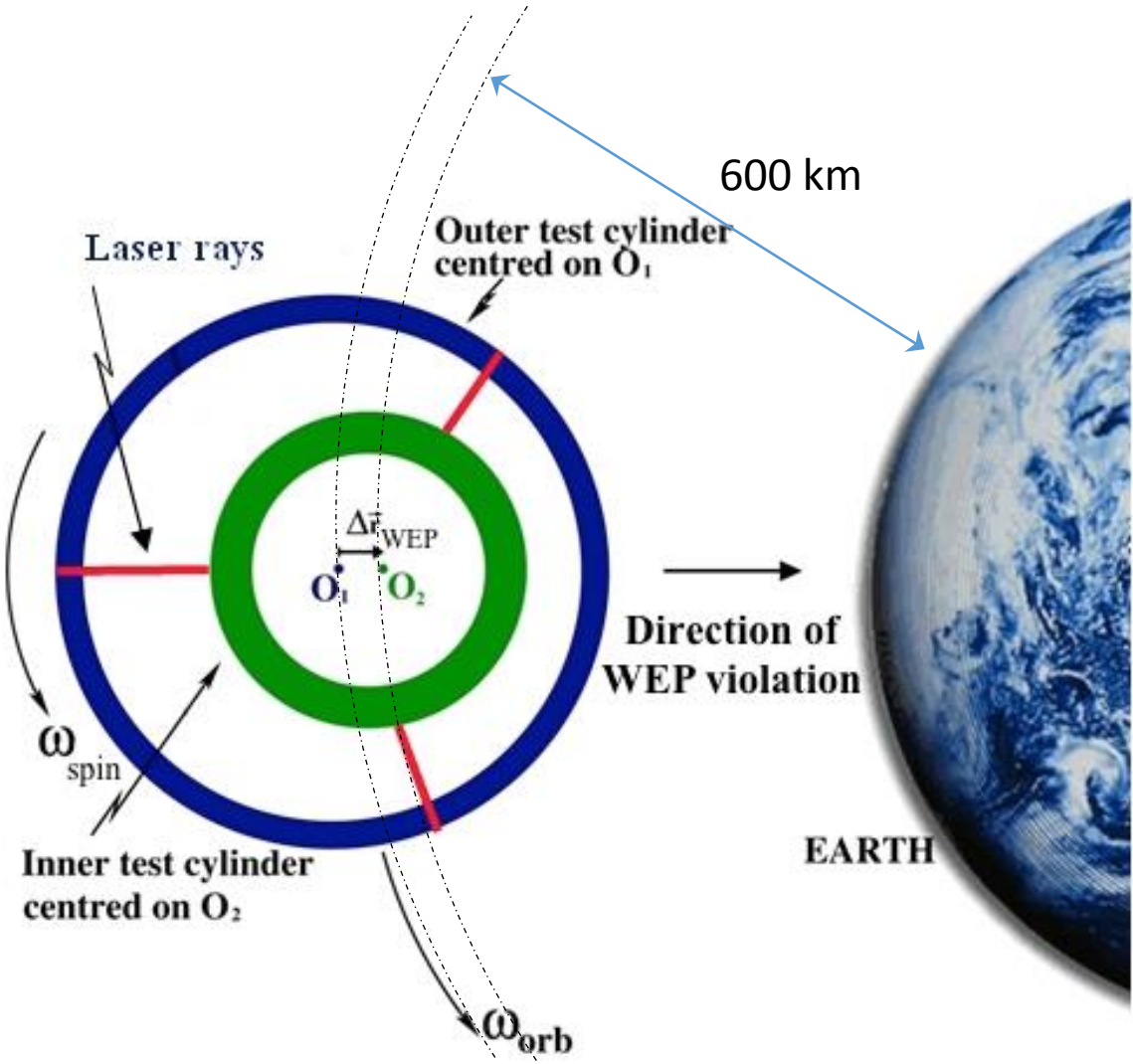






Measurement principle in GG

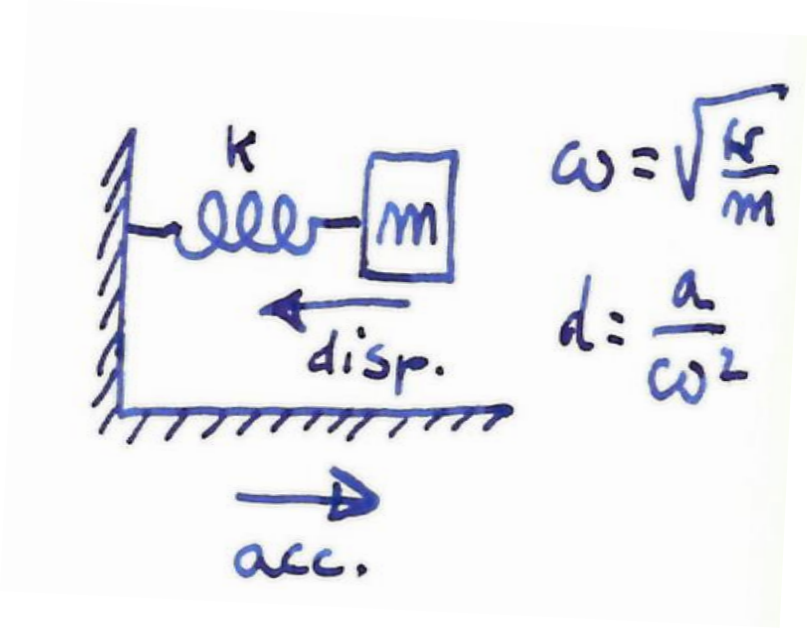
- We measure on 2D the relative displacement of the two masses due to the WEP violation
- In the reference frame of the satellite, the center of mass of the masses oscillates at 1 Hz



Sensitivity of GG

- Test cylinders weakly coupled in 2D. The dynamical system is a 2D harmonic oscillator with a low normal frequency: ν = 1/540 Hz
- The displacement vs acceleration equation is:

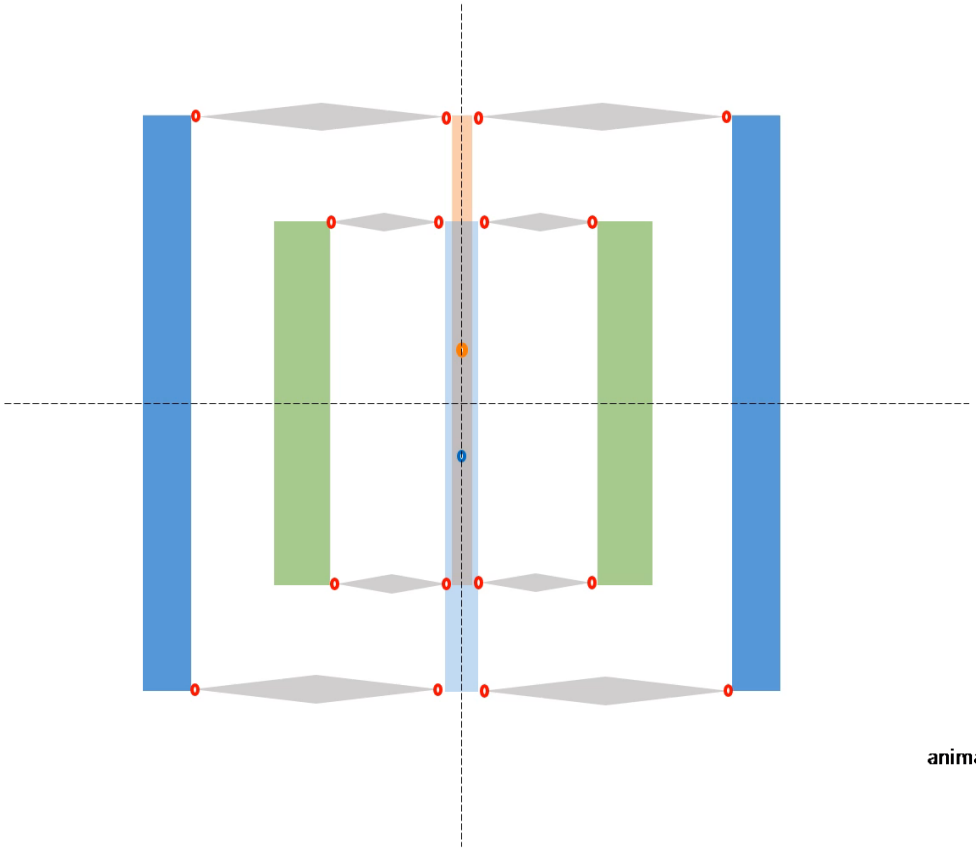
$\Delta d = \Delta a/\omega^2$ → for $\Delta a = 8.1\ 10^{-17}$ m/s^2, $\Delta d =$ 0.6 pm



The heart of GG

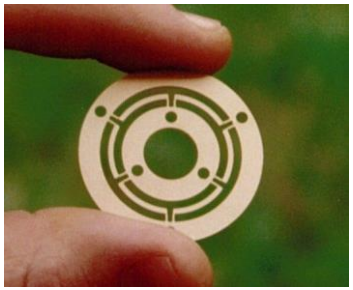
- The heart of GG is a beam balance with the beam (s) along the symmetry axis.
- The center of mass of the two cylinders are coincident
- The connecions between the masses, the beams and the shaft are realized with weak U-shaped Cu-Be springs
- The pivot points can be moved along the axis by means of piezo motors

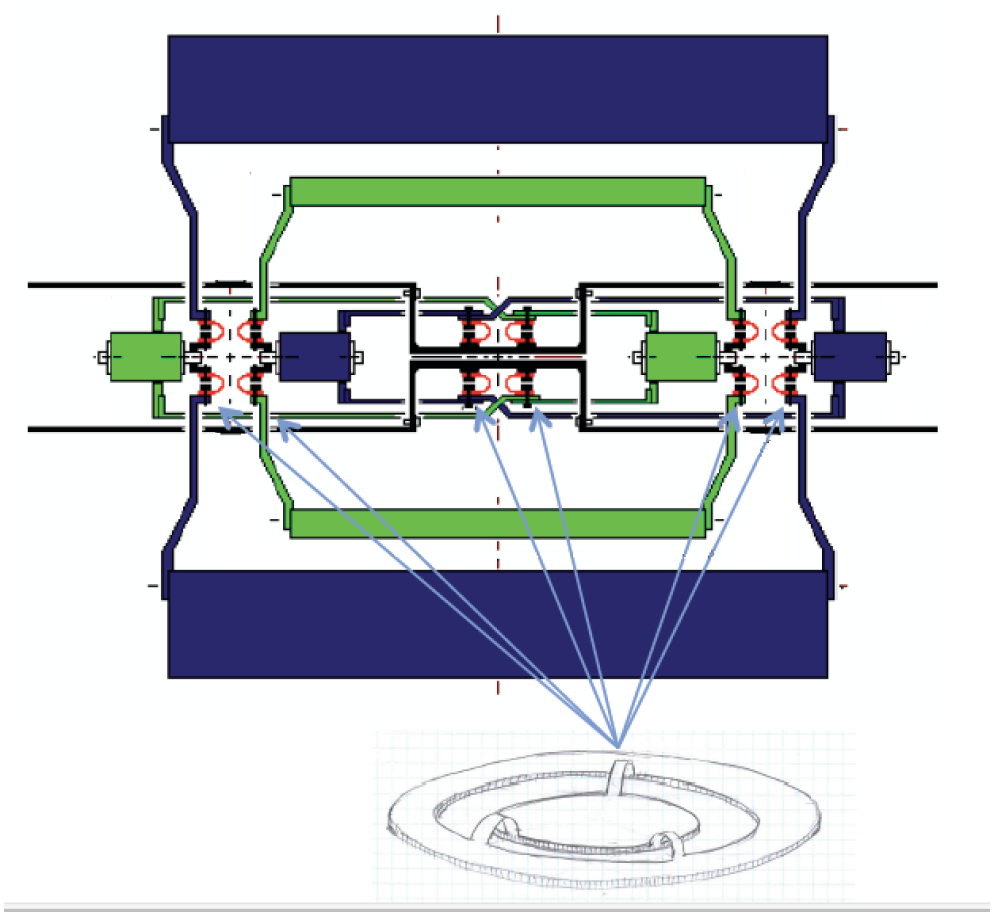
The balance



animazione bilancia GG.mp4

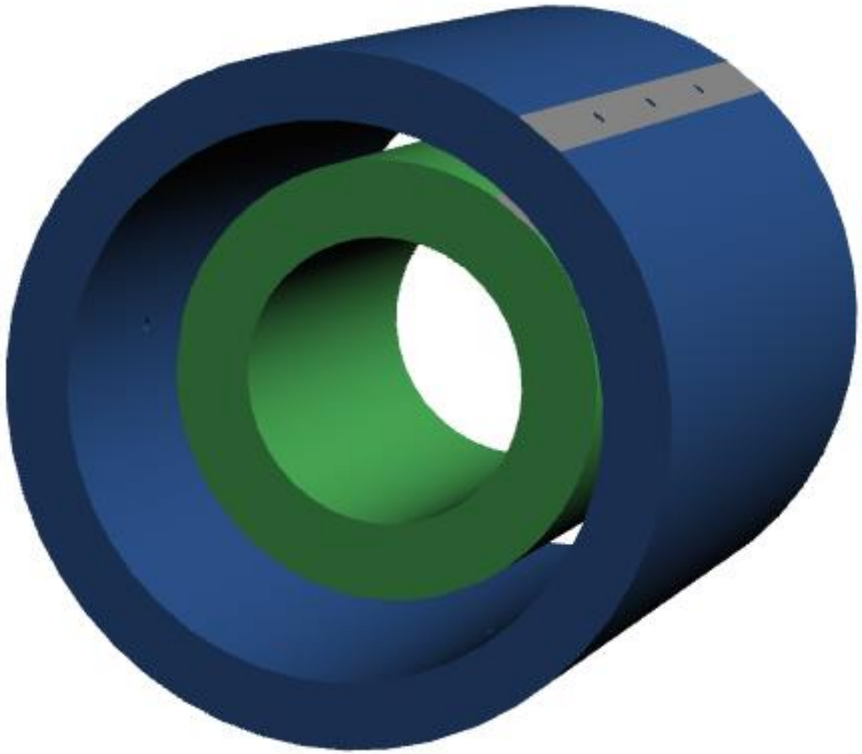
Elastic suspensions

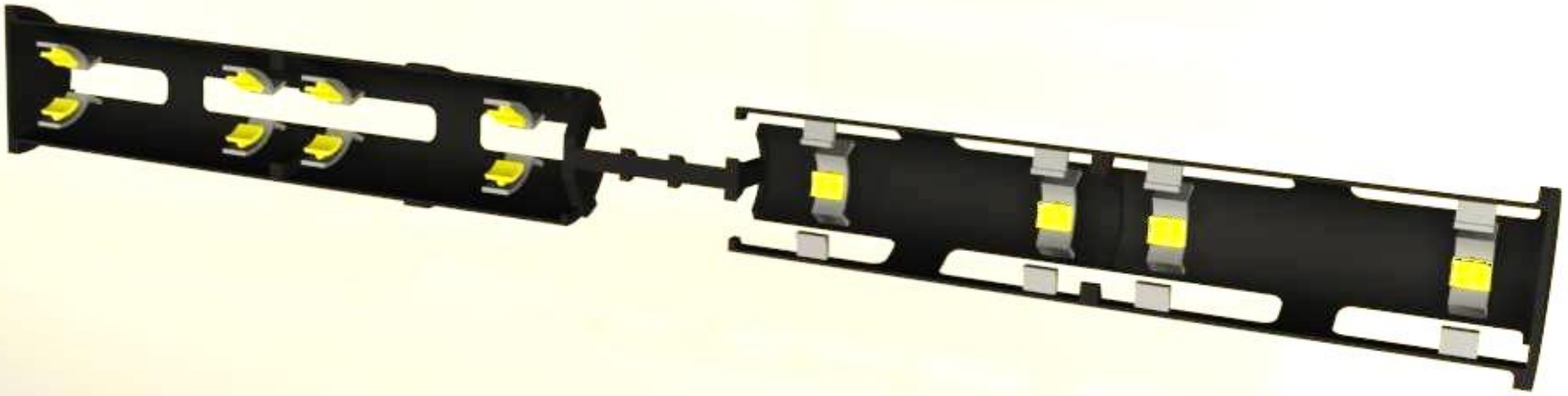


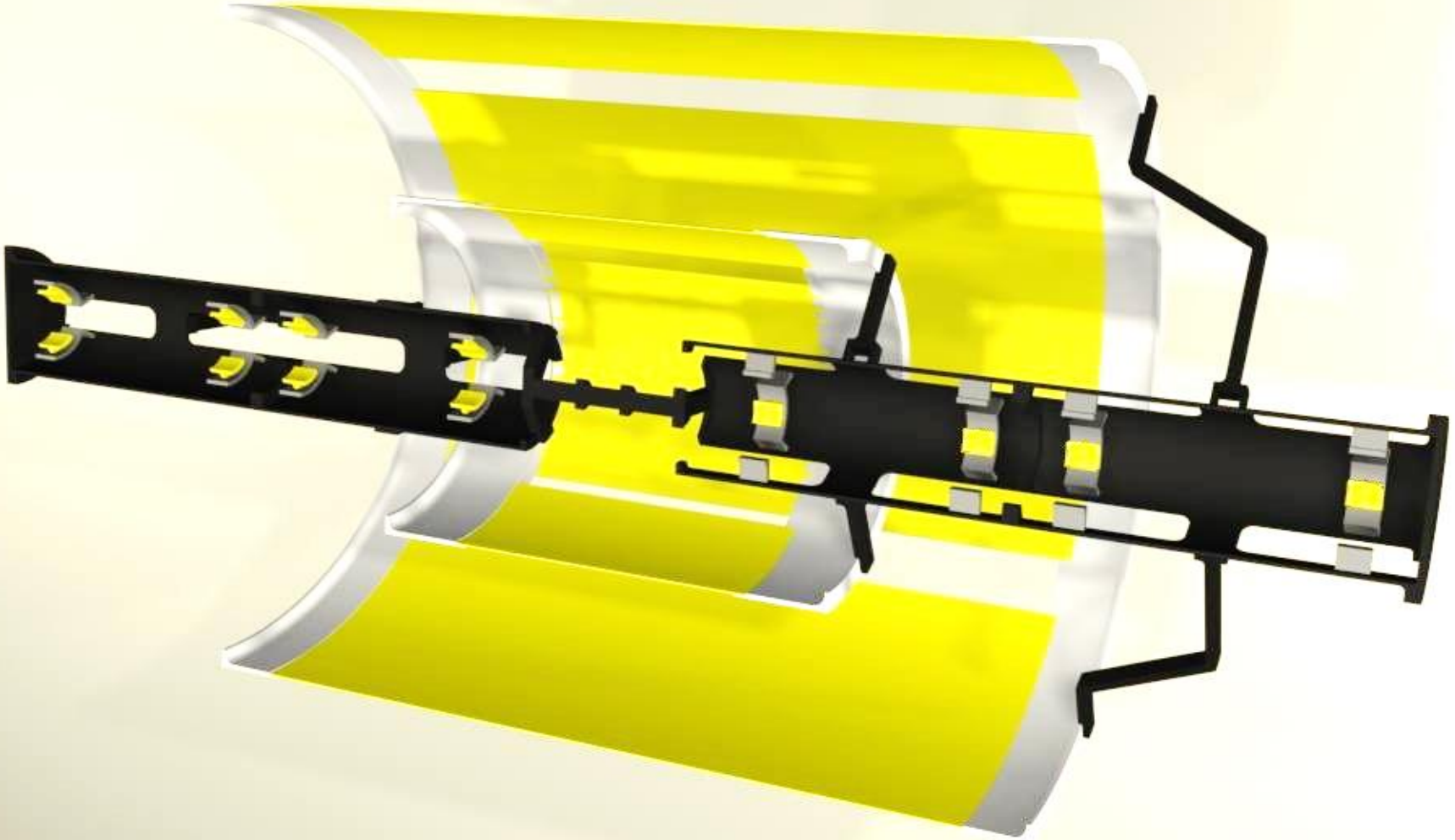


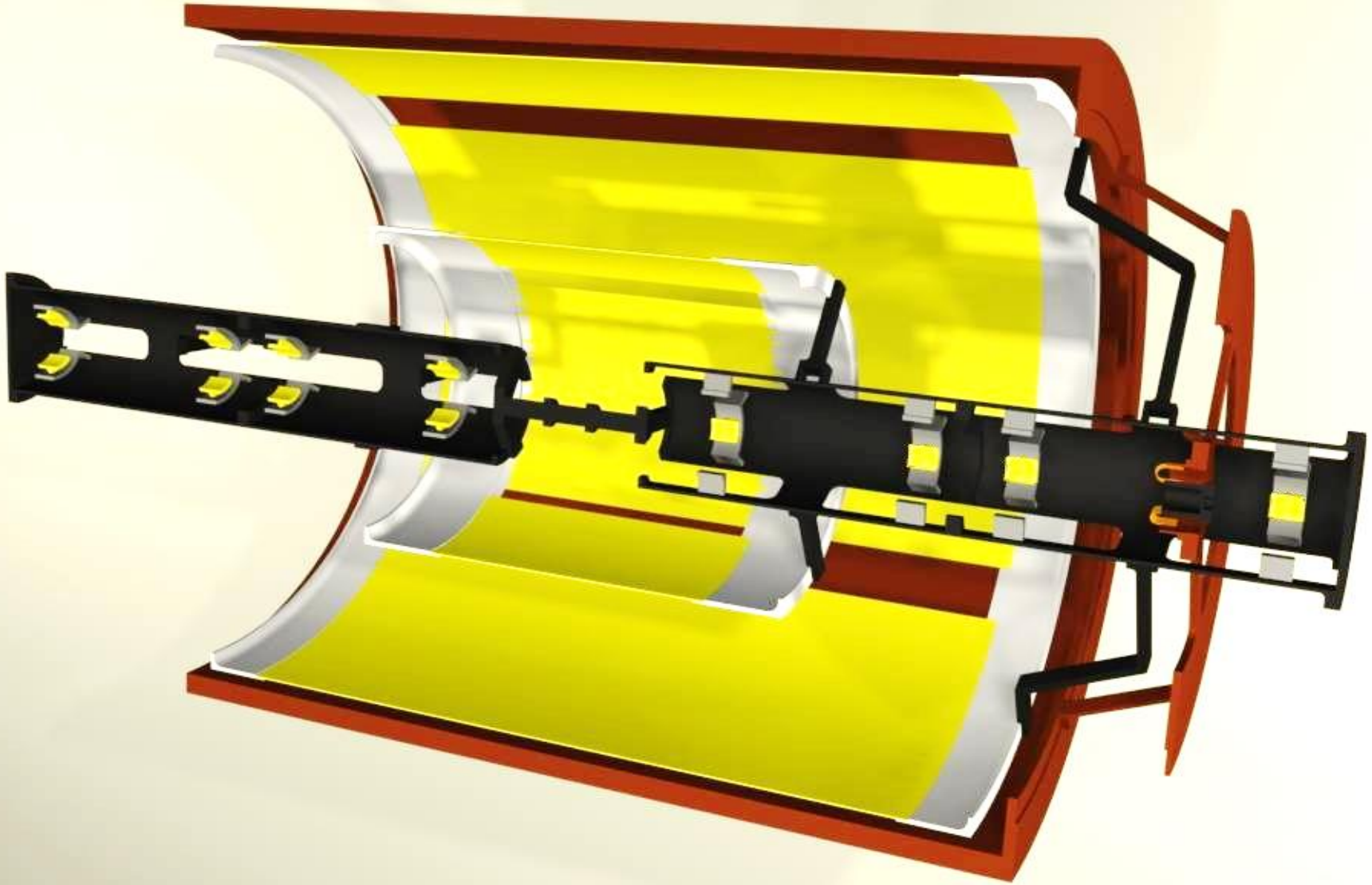
The test masses

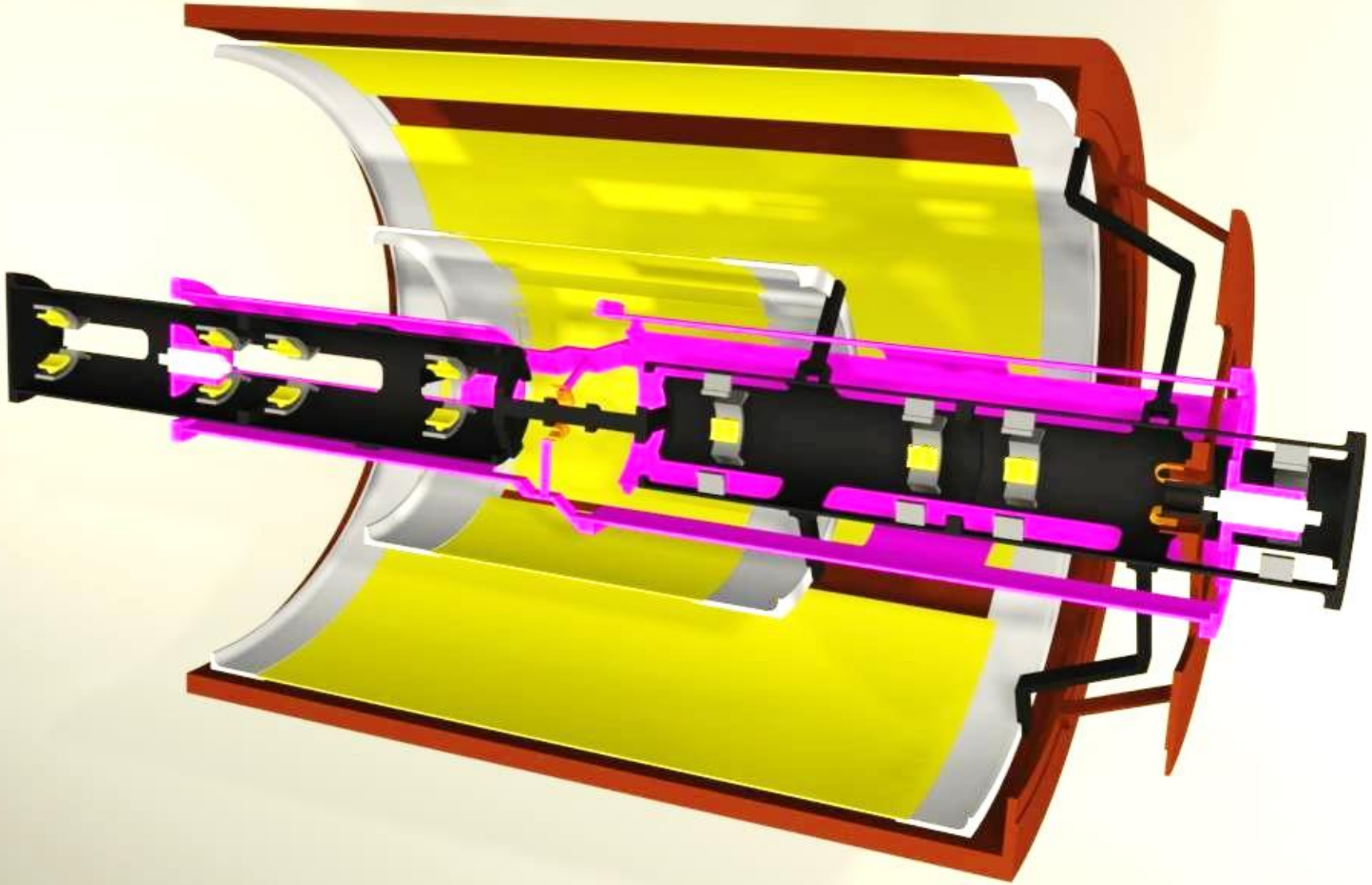
- Titanium and berillium or other combination of materials included plastic materials with high hydrogen content (e.g. PET)

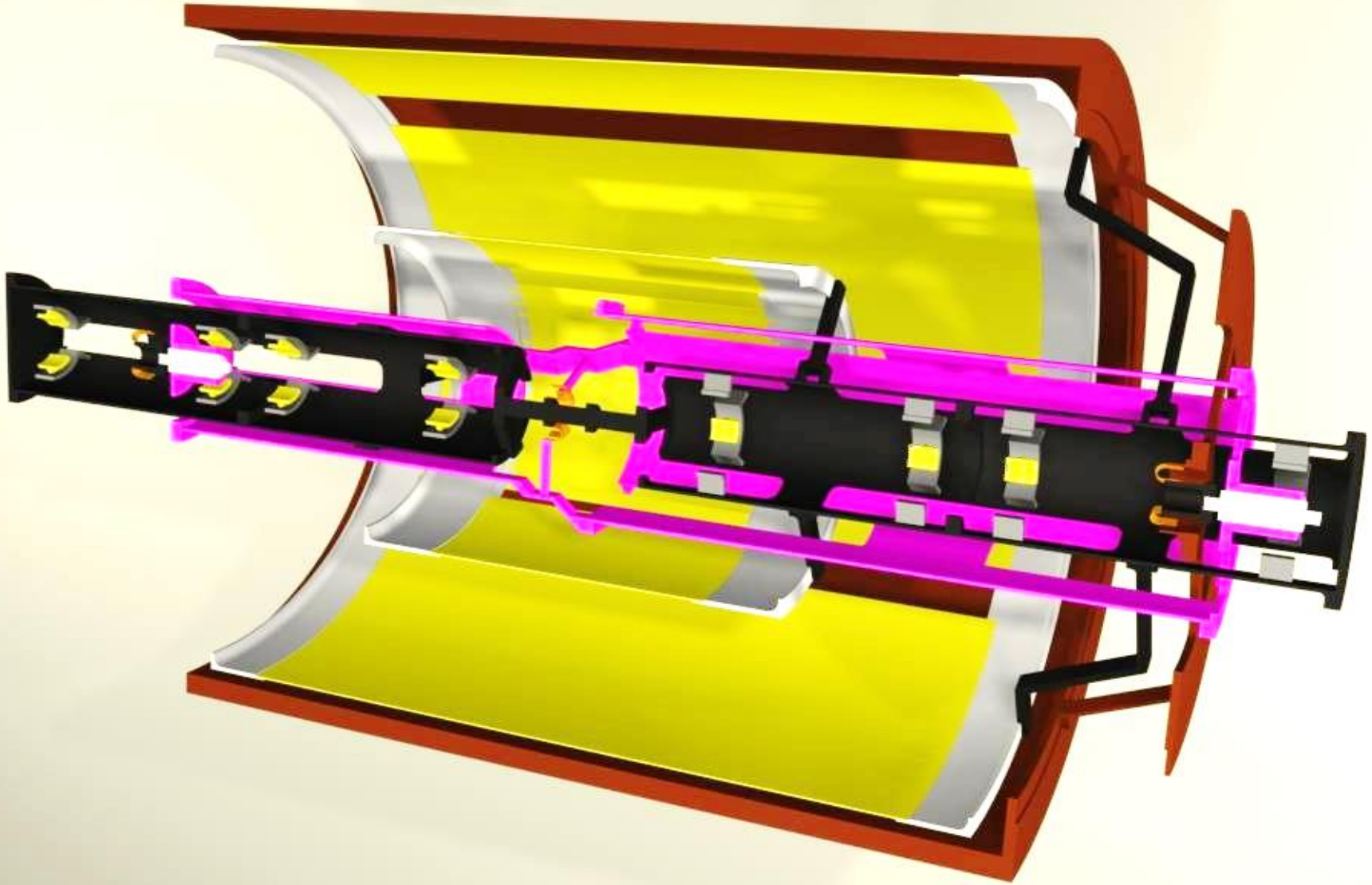


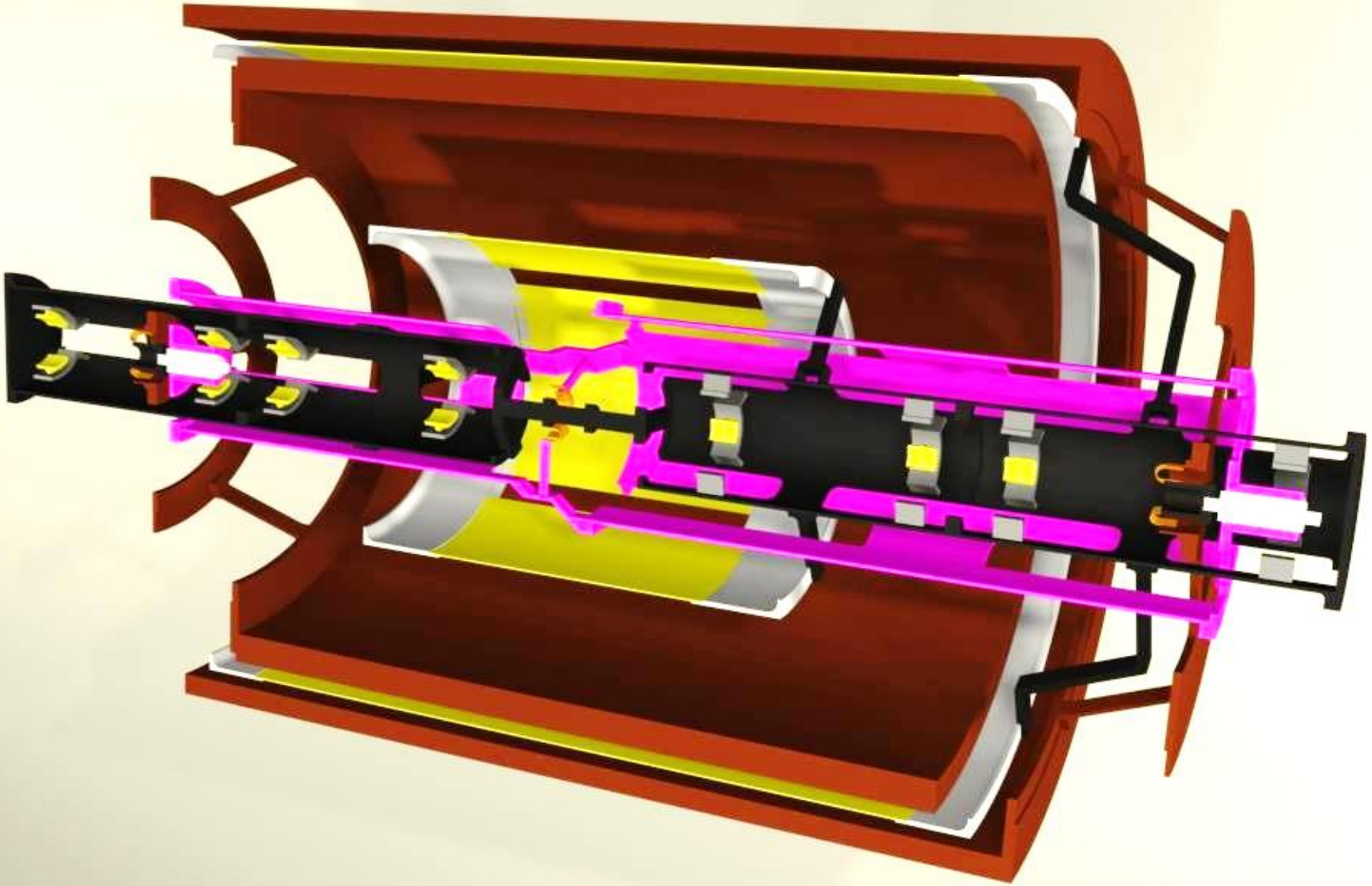


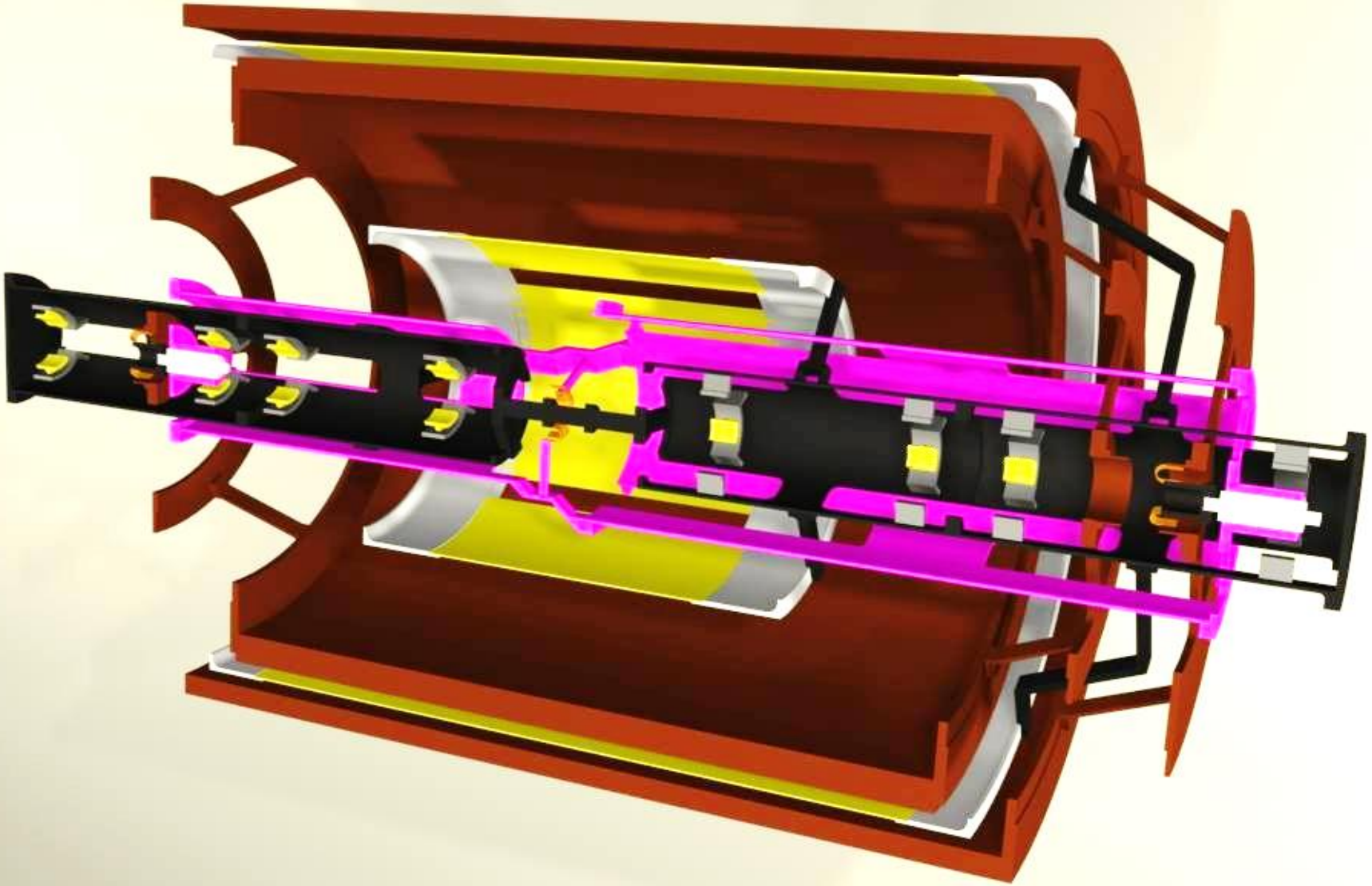


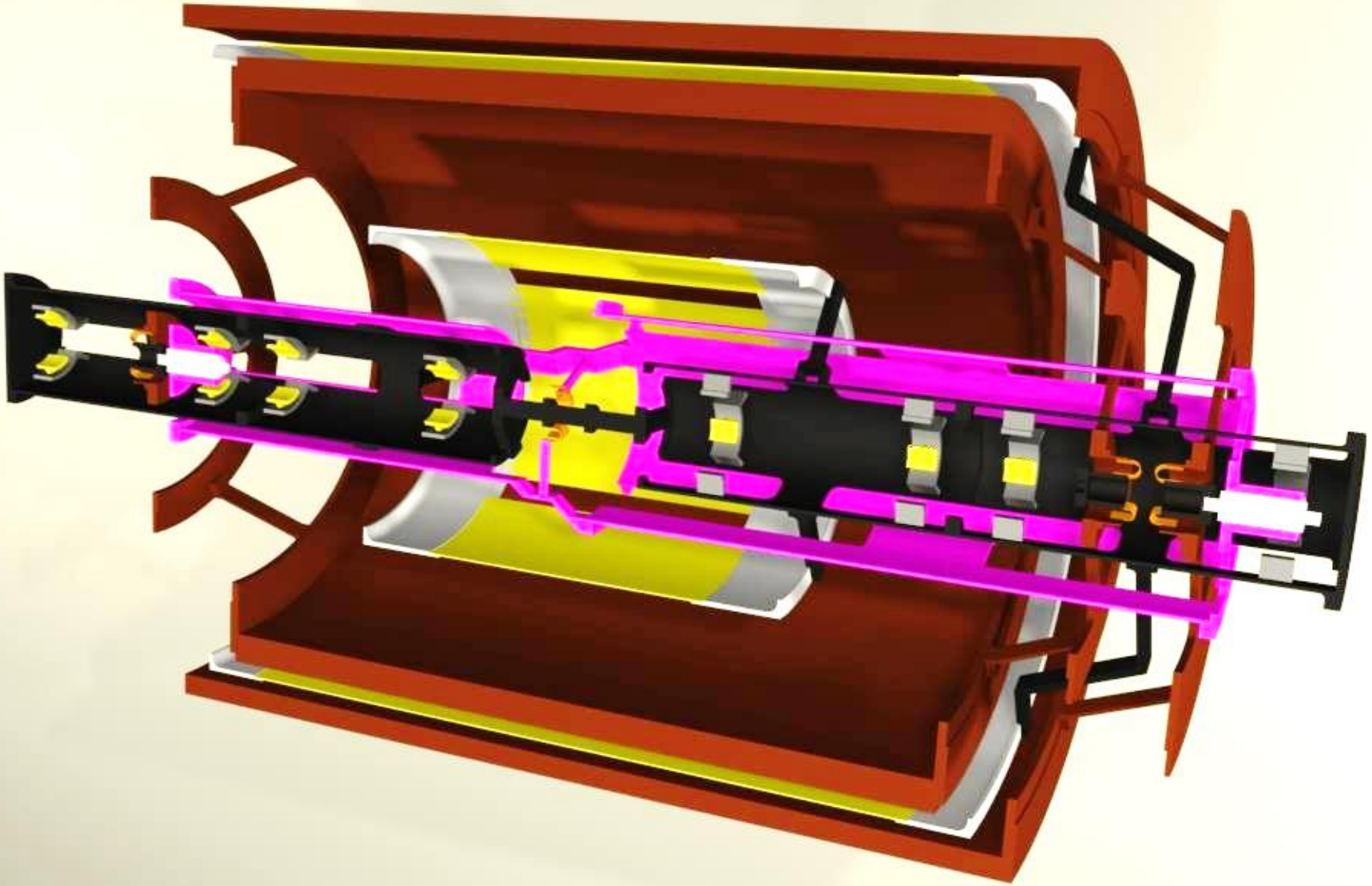


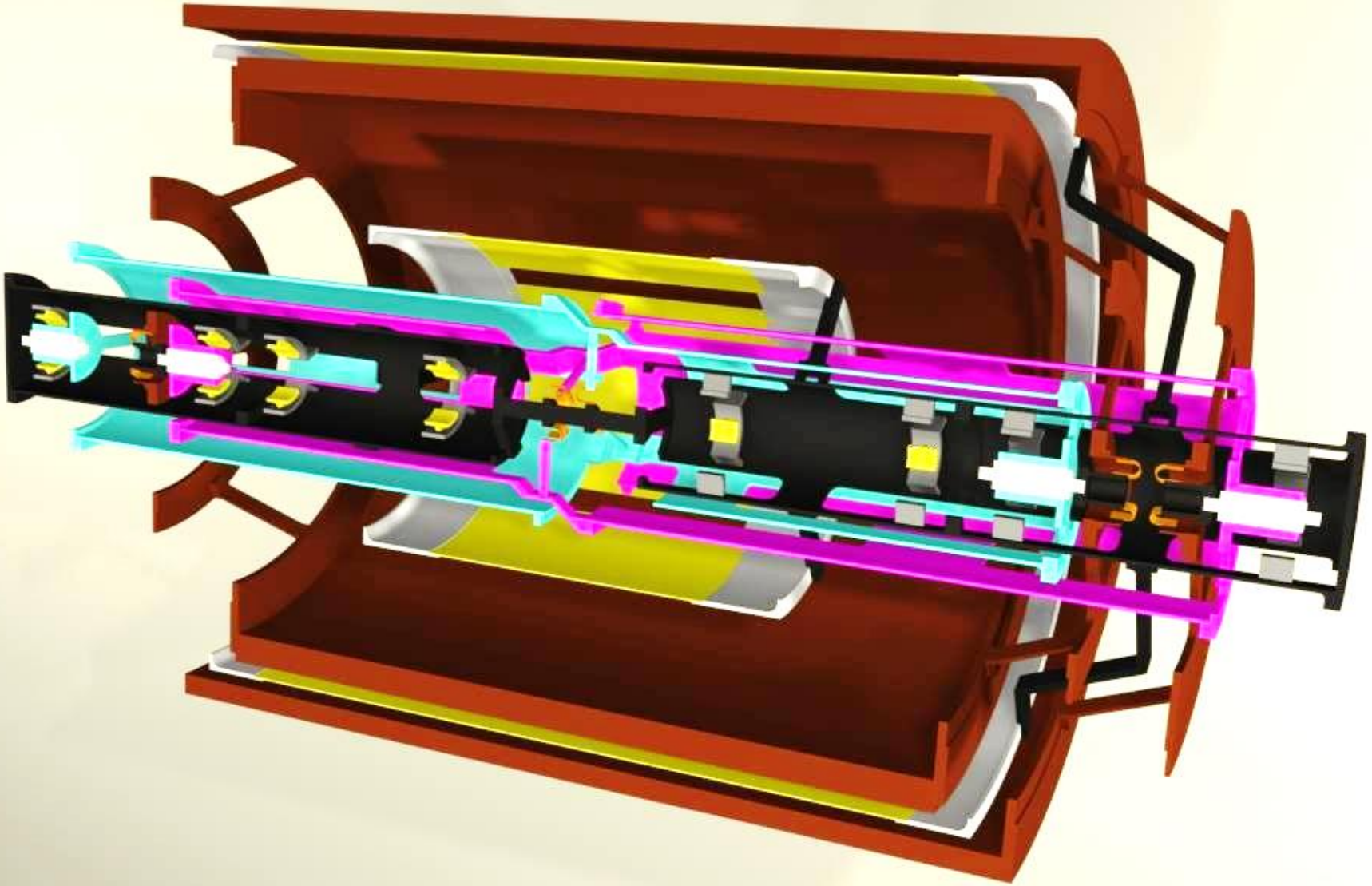


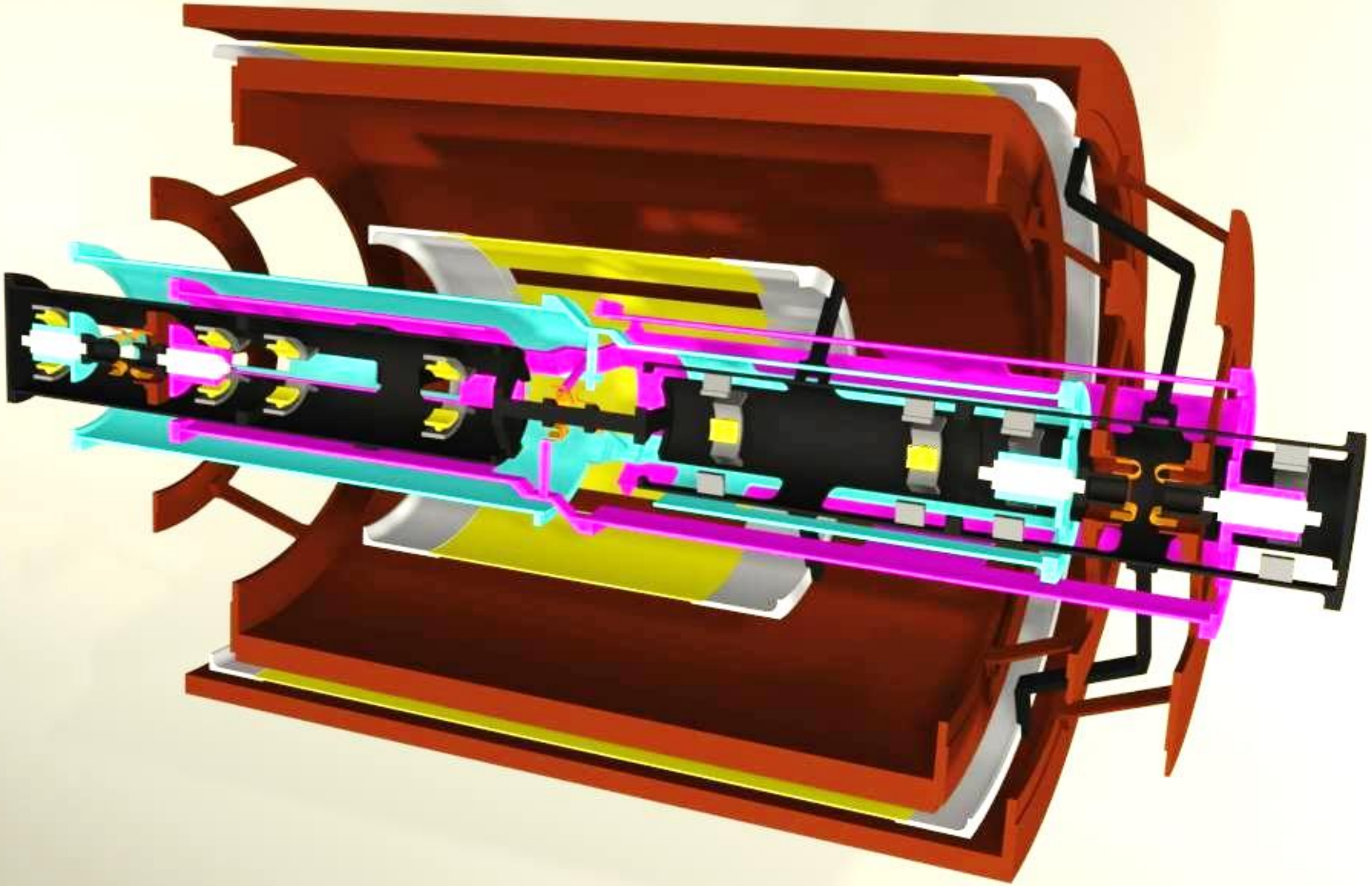


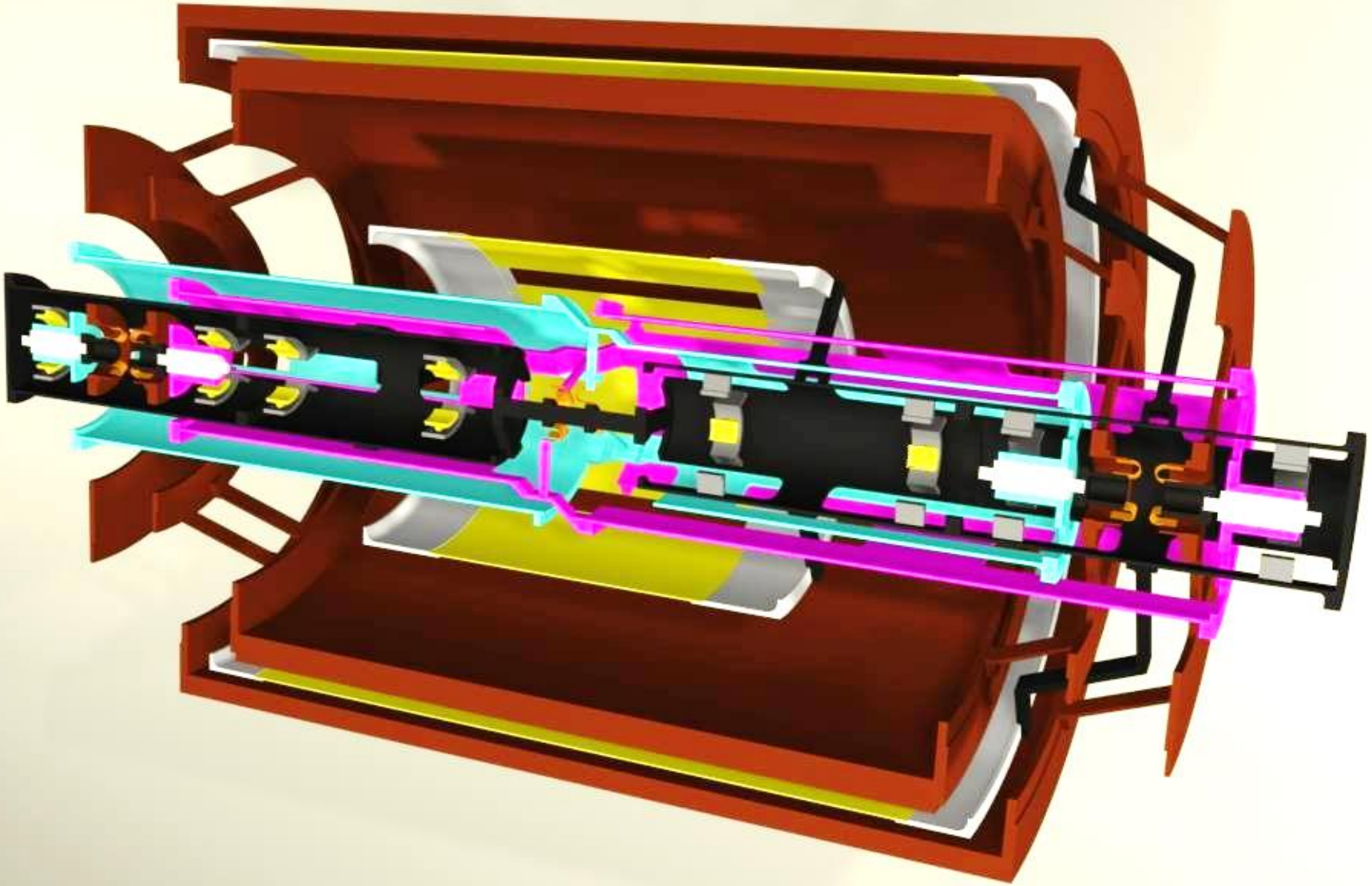


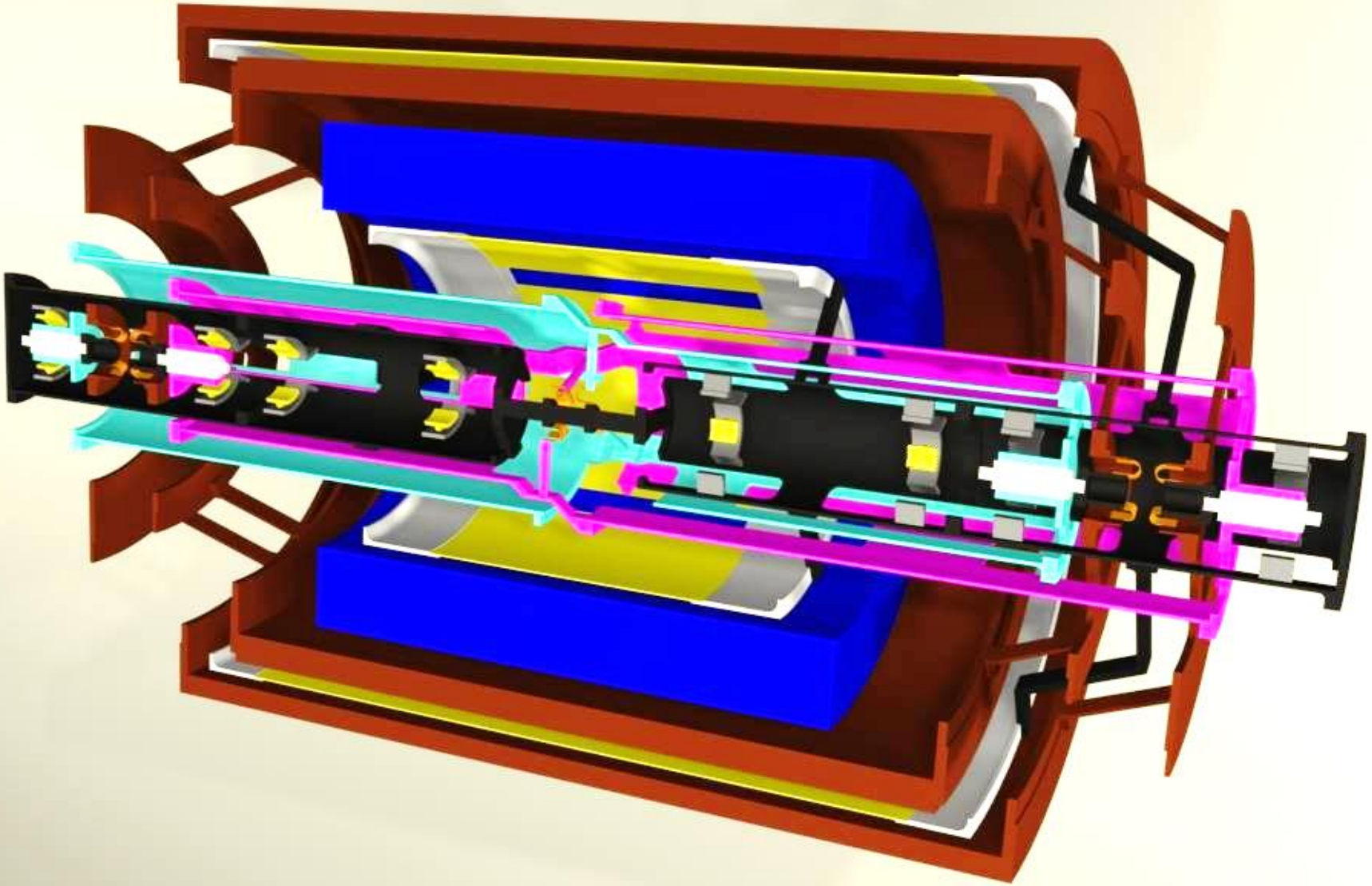


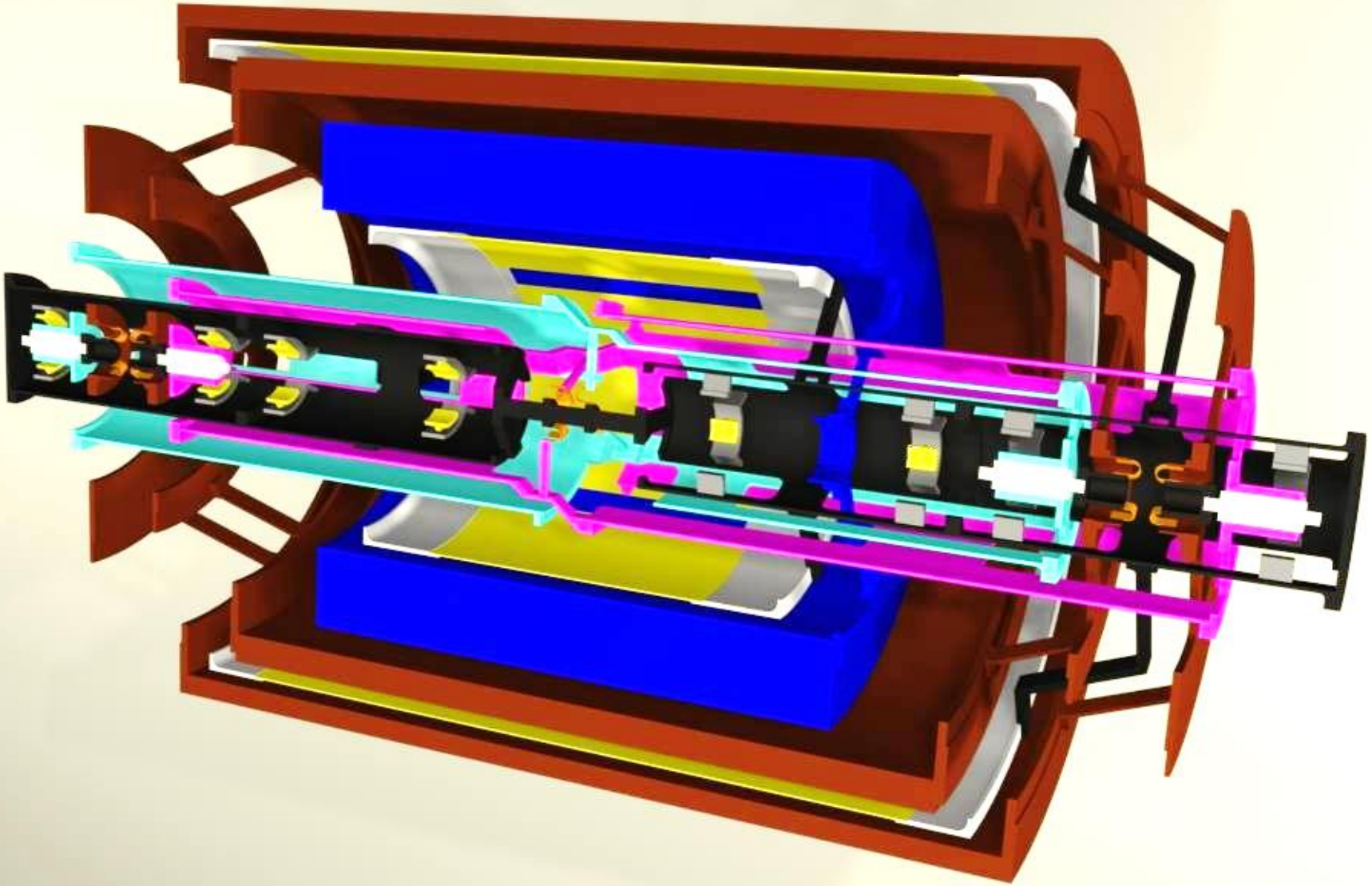


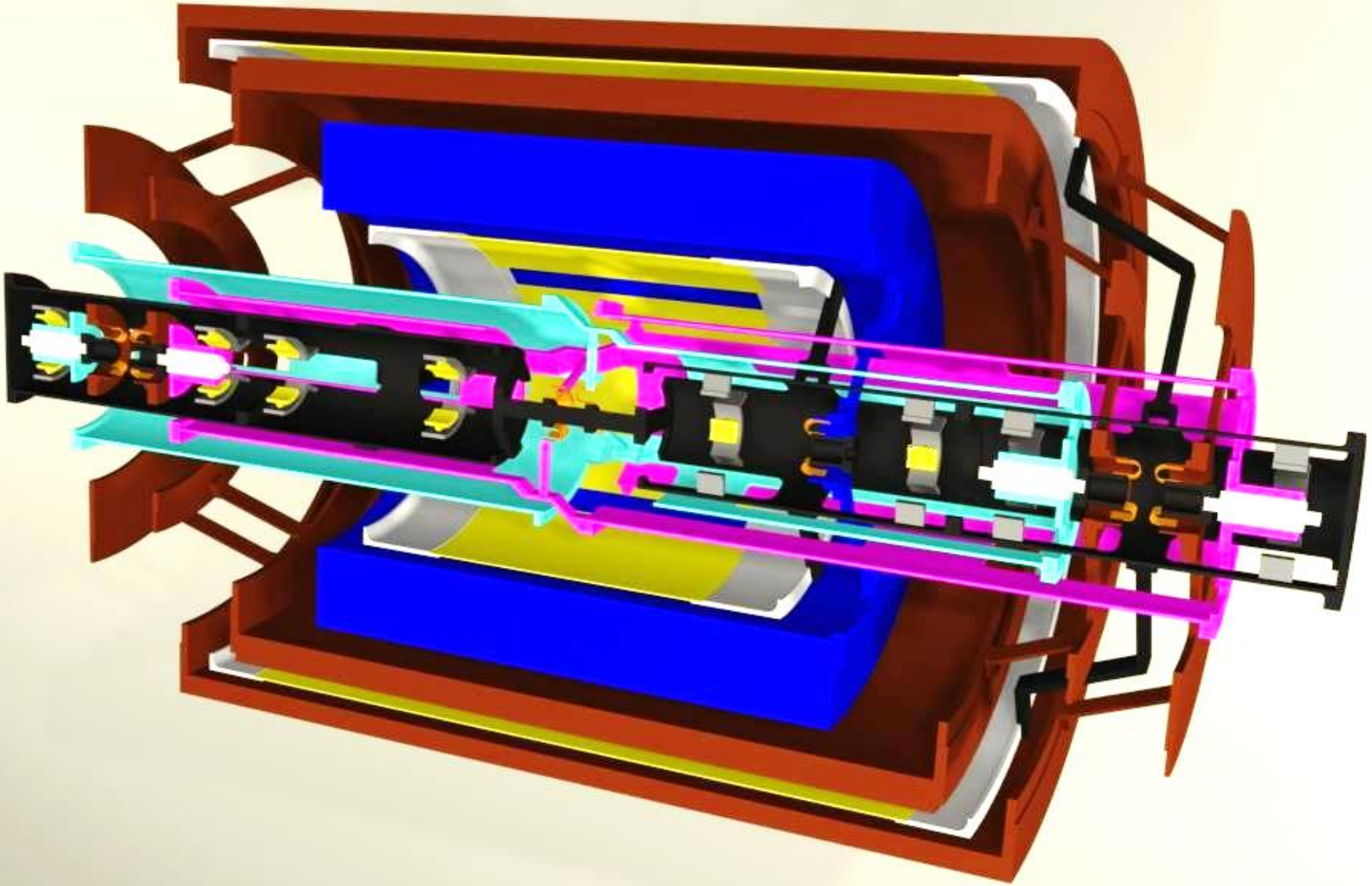


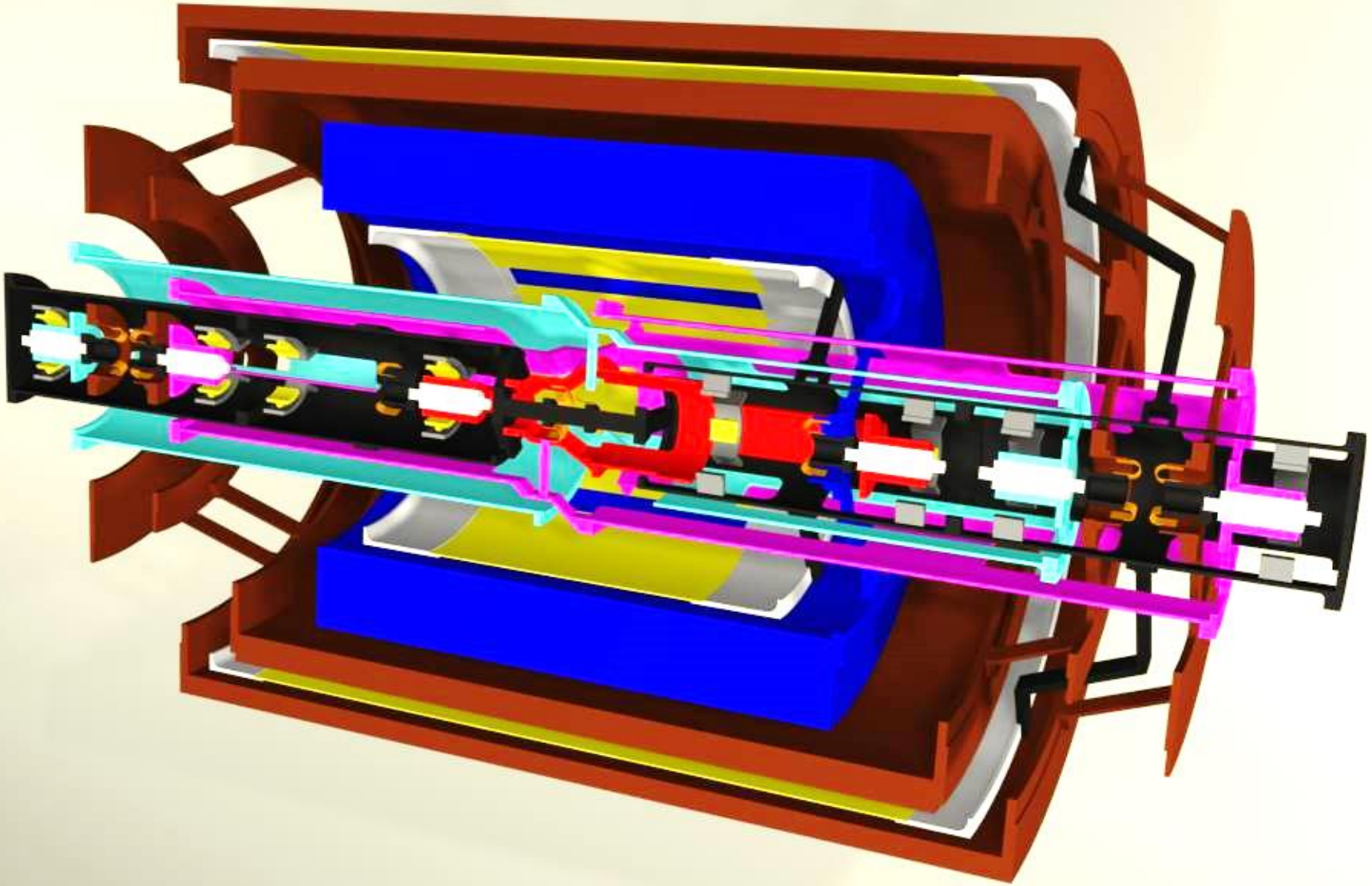


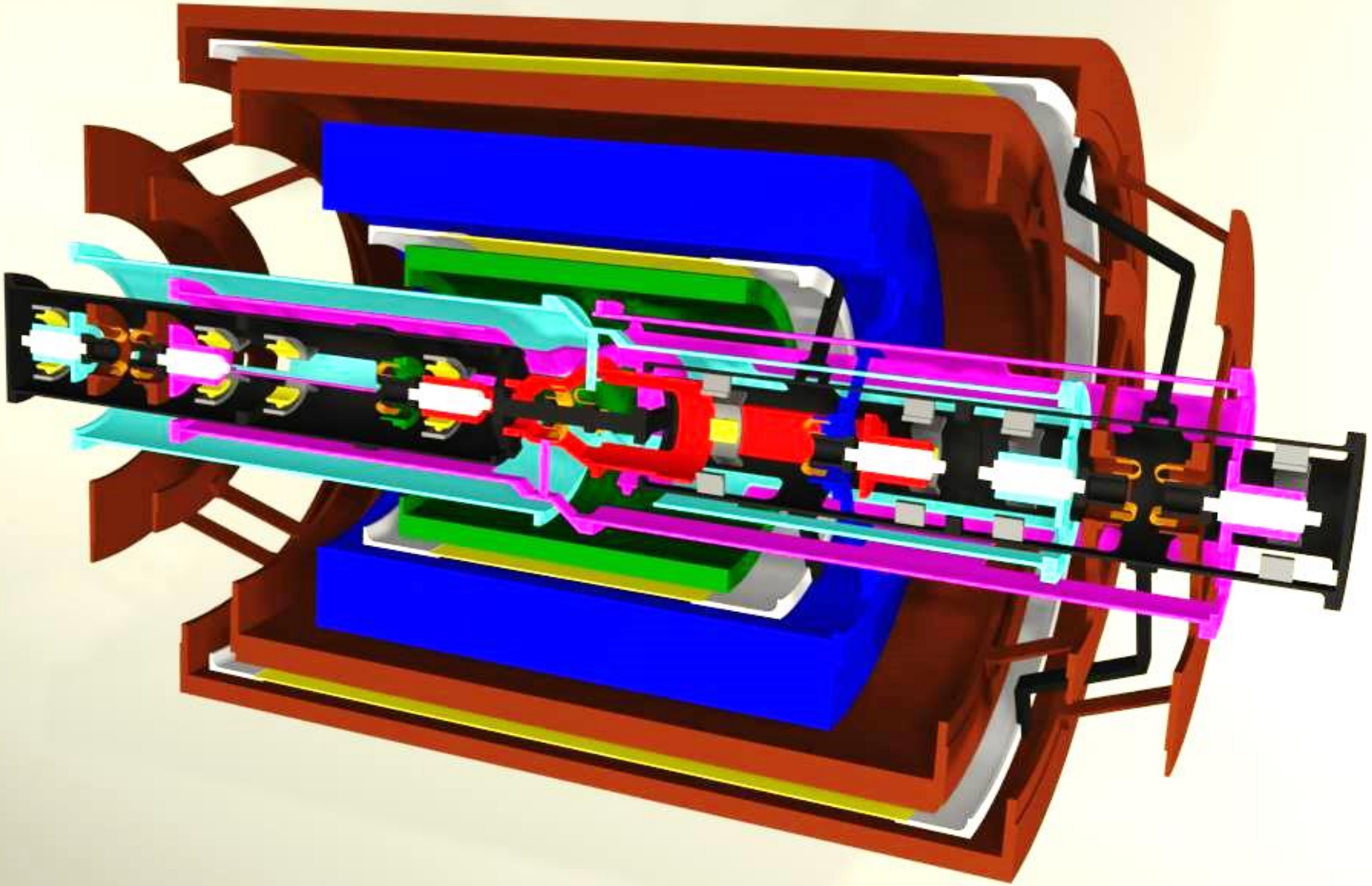


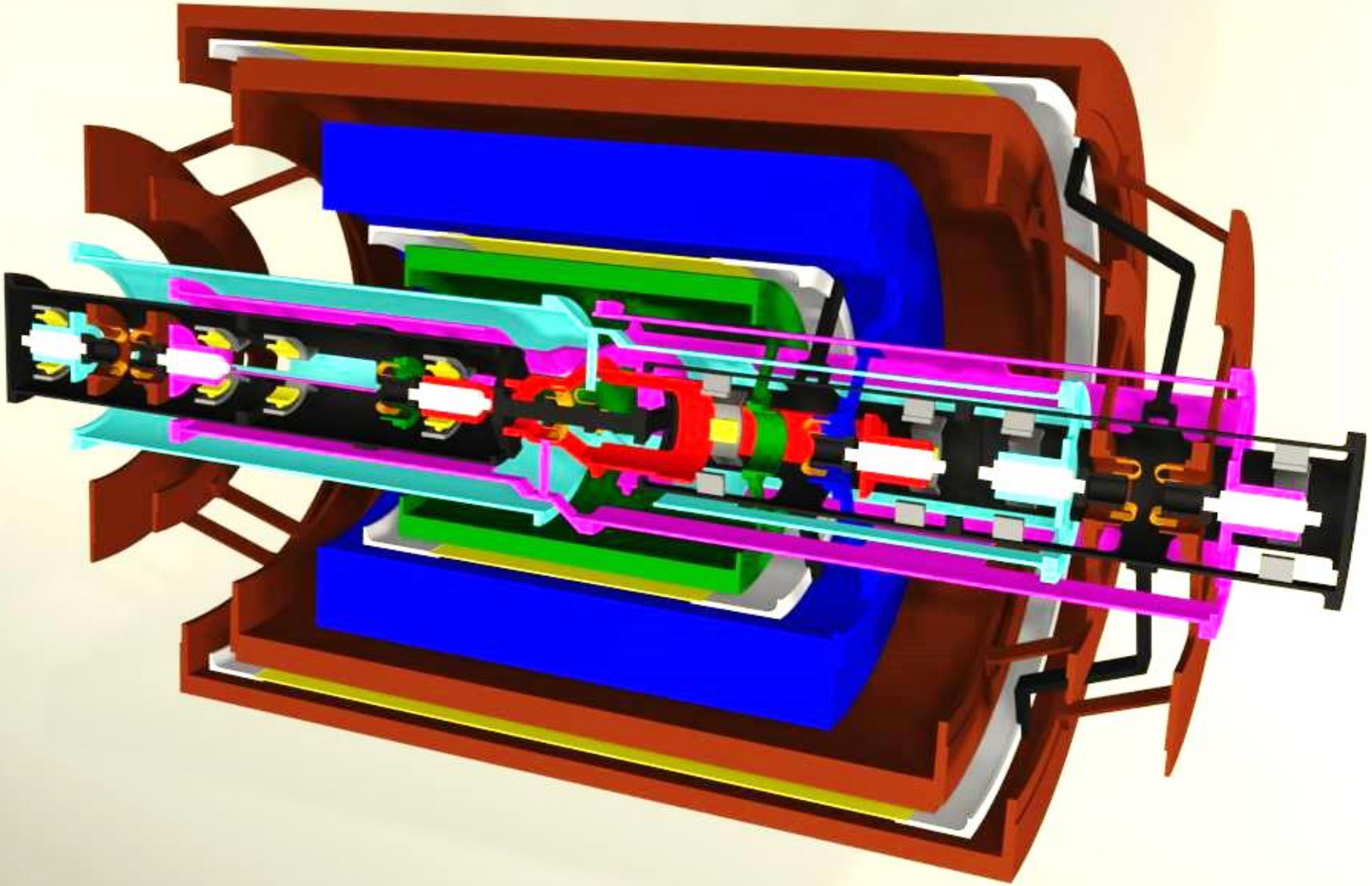


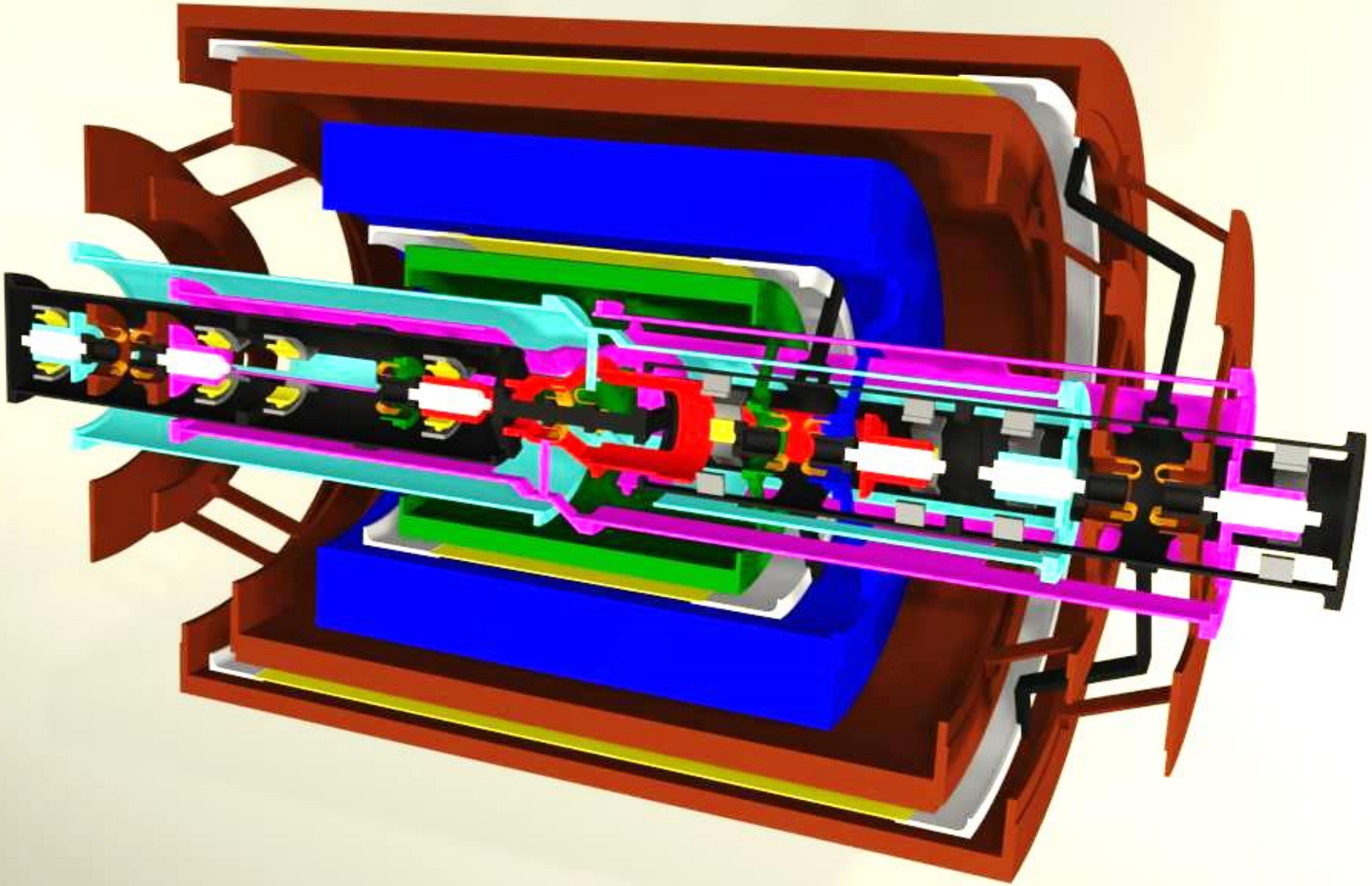


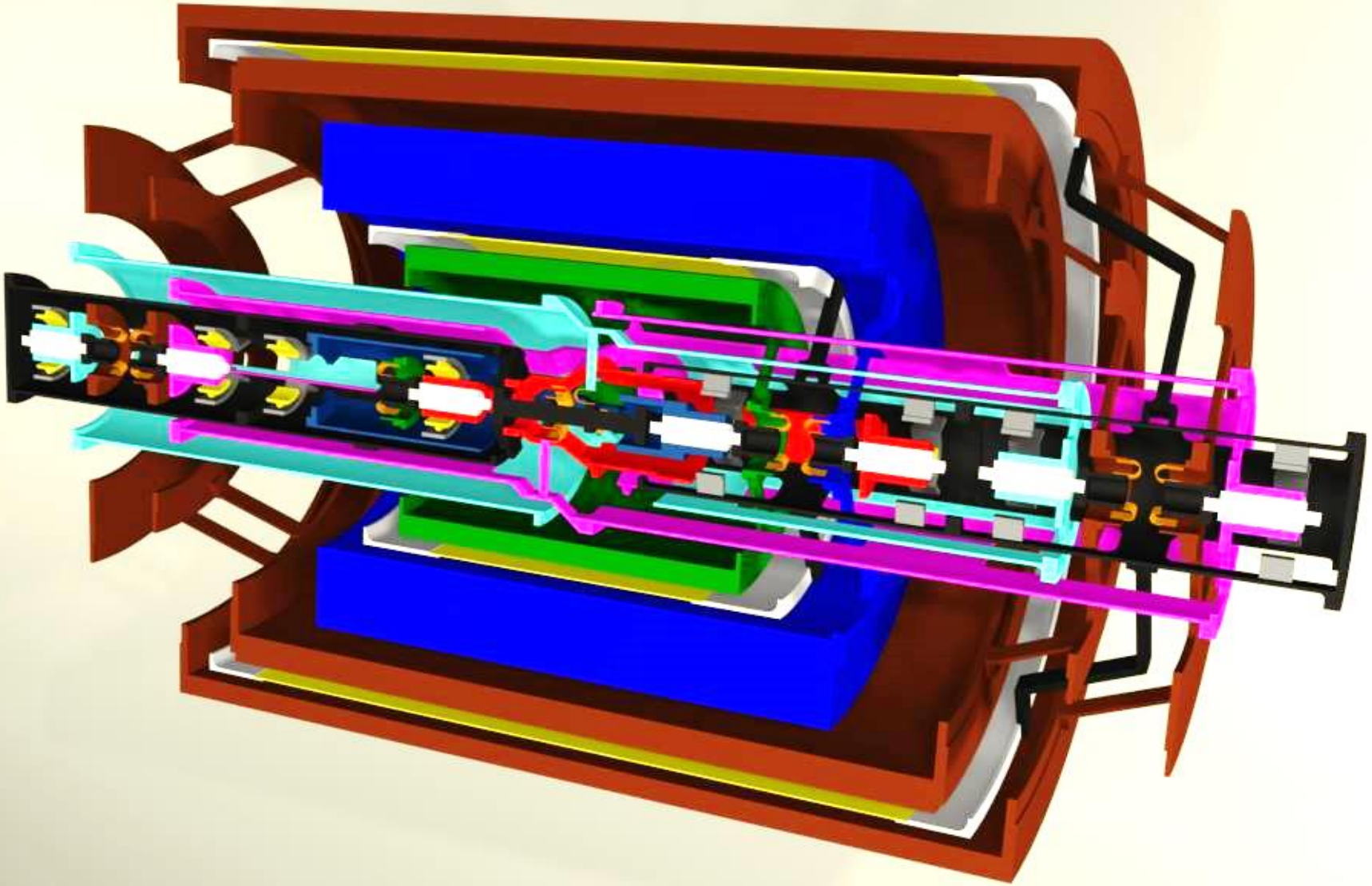


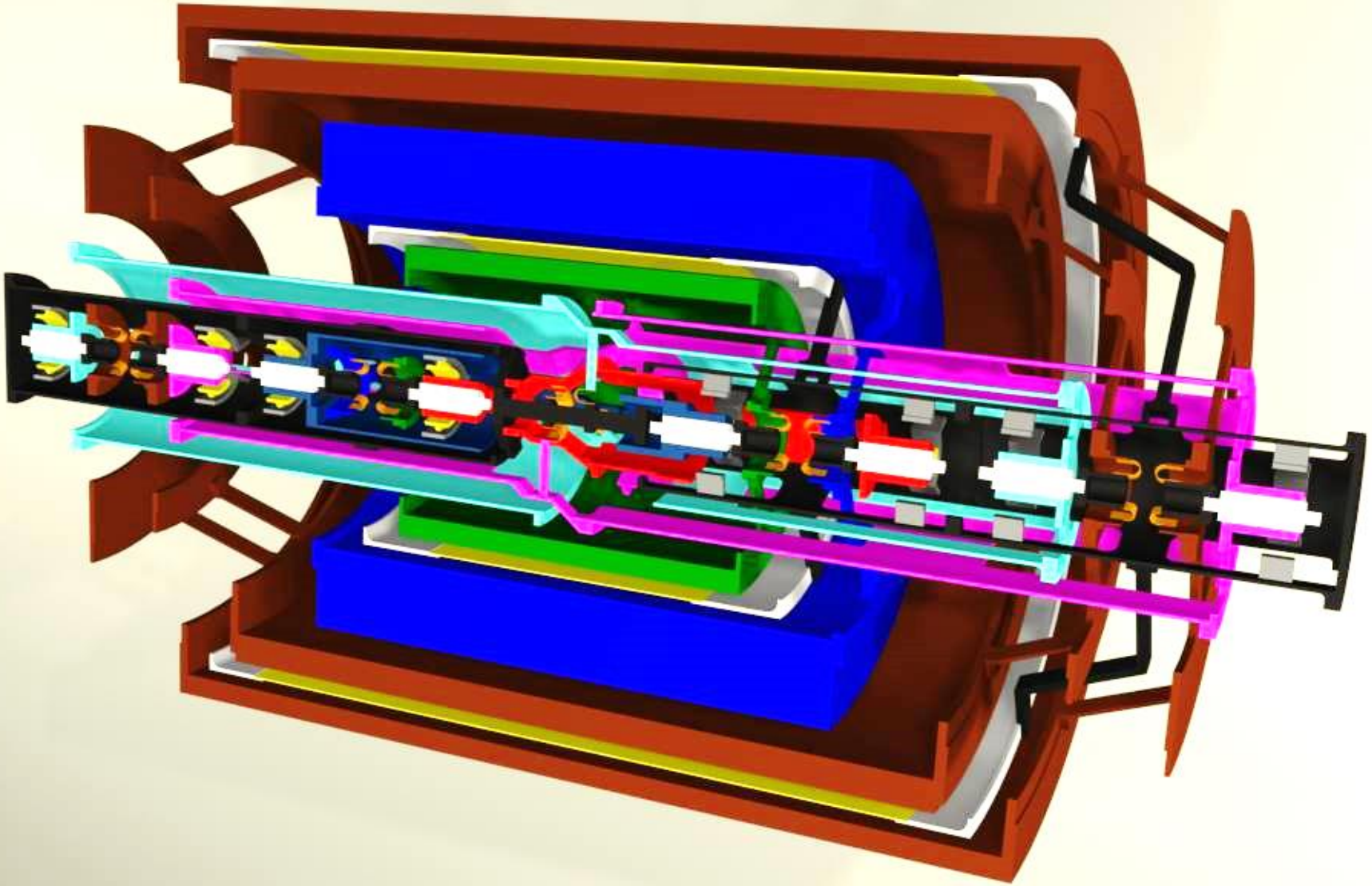










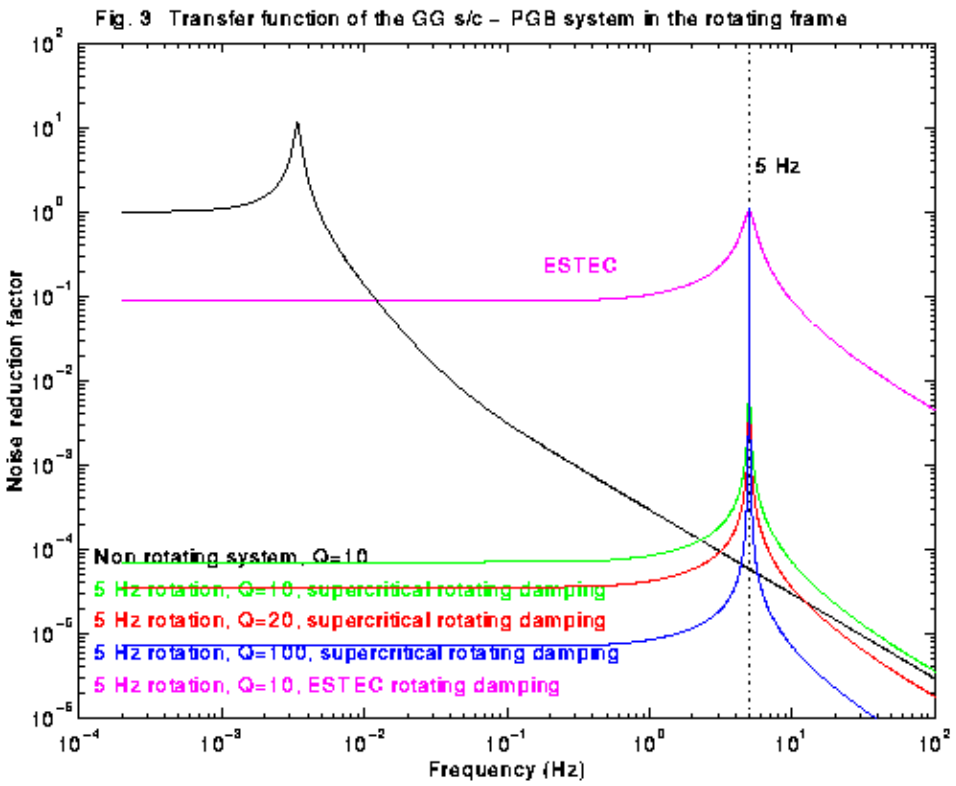


Are GG masses stable?

- Yes: super-critical rotation ensures self-centering
- When the spinning frequency is (much) higher than the normal mode (resonant) frequency the rotor stabilzes

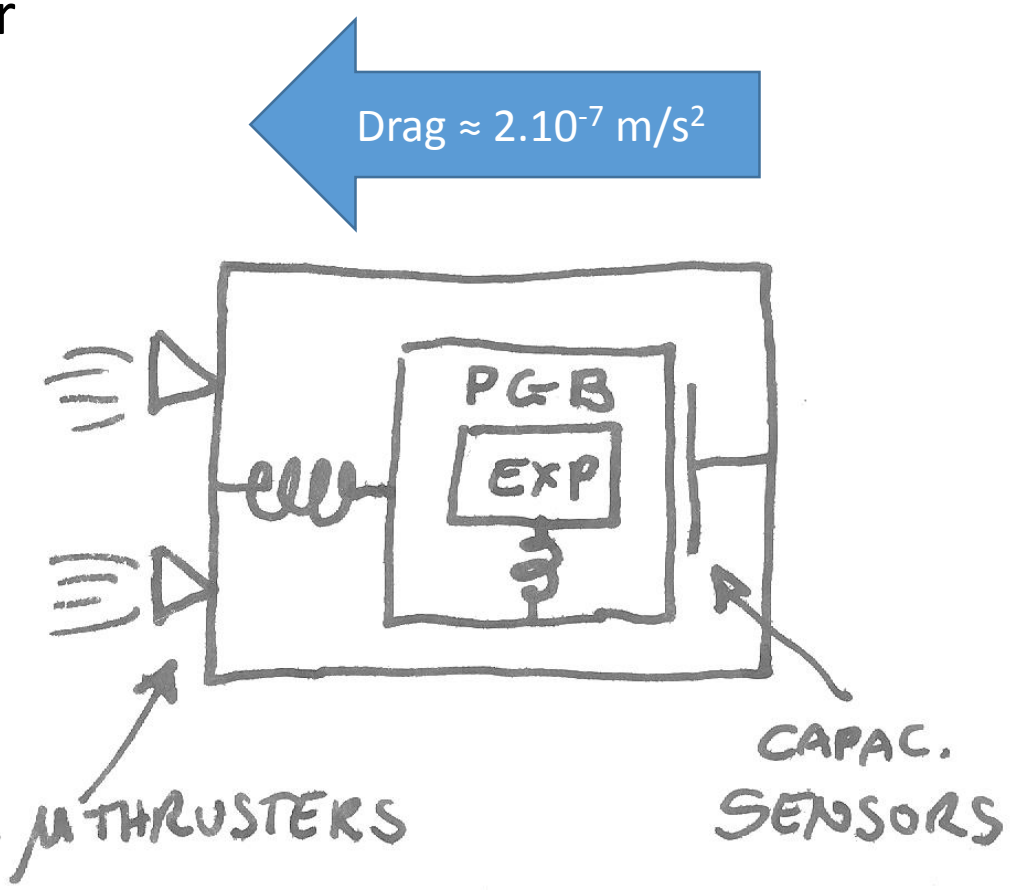
Supercritical rotation in GG

- When the spinning frequency is (much) higher than the fundamental resonant frequency the rotor stabilzes
- In GG the resonant frequency is 1/540 Hz and the spinning frequency is 1 Hz

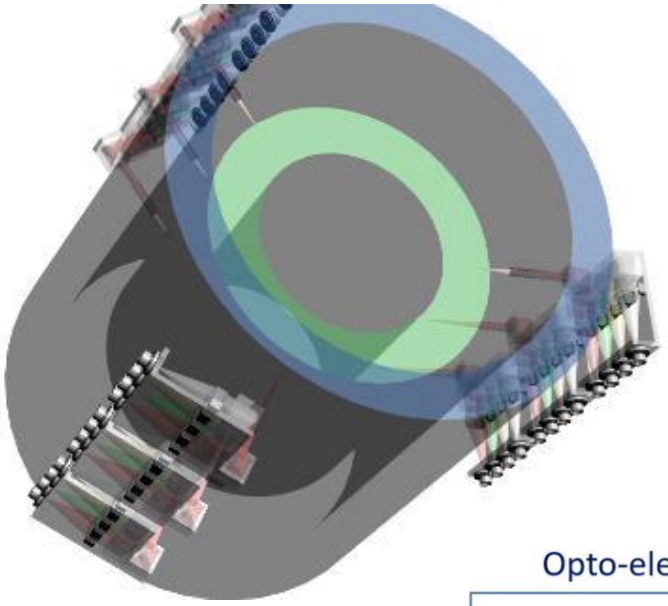


Drag control and the Pico Gravity Box

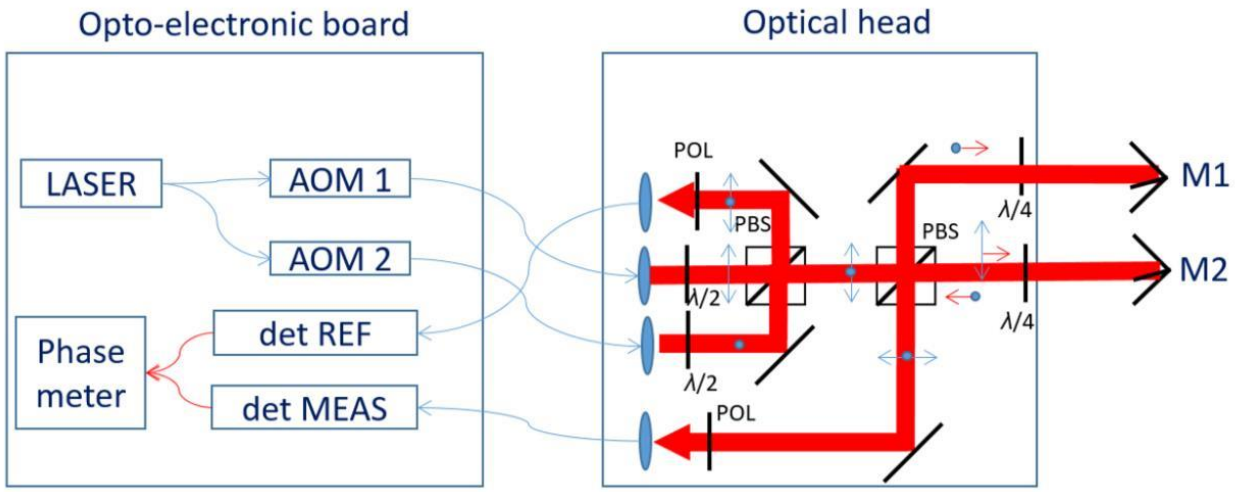
- The drag due to residual atmosphere and to solar wind has an amplitude much larger than the violation signal
- The balance is hosted in a drag free environment called the Pico Gravity Box (PCB)
- The PCB is weakly coupled to the body of the satellite and its 2D position is sensed with capacitive sensors.
- The drag control system used the PCB as an accelerometer and cold gas (nitrogen) thrusters to compensate for the drag



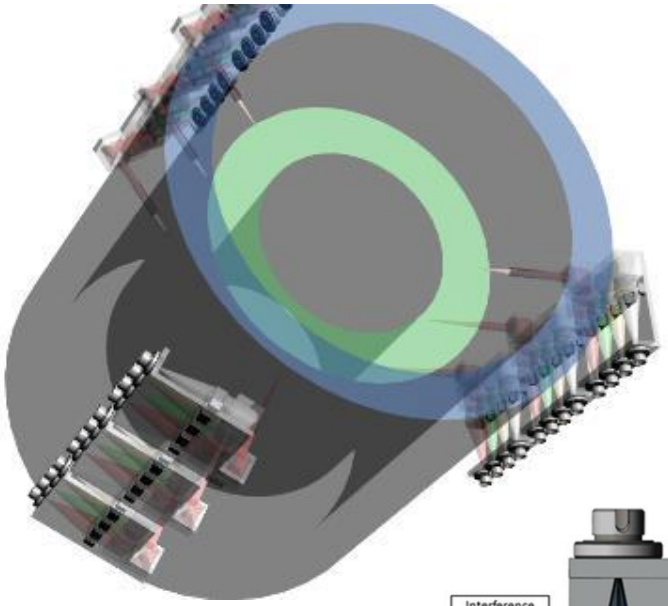
The metrologic system

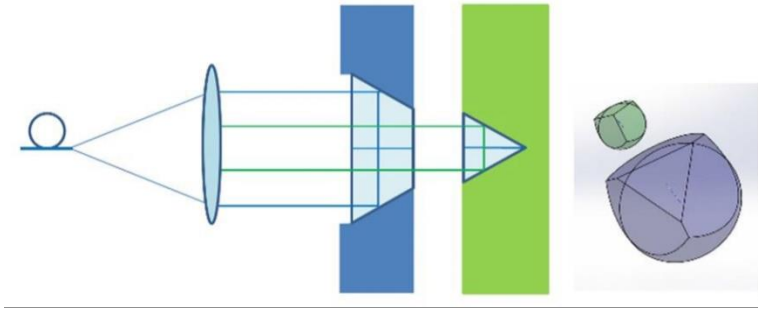


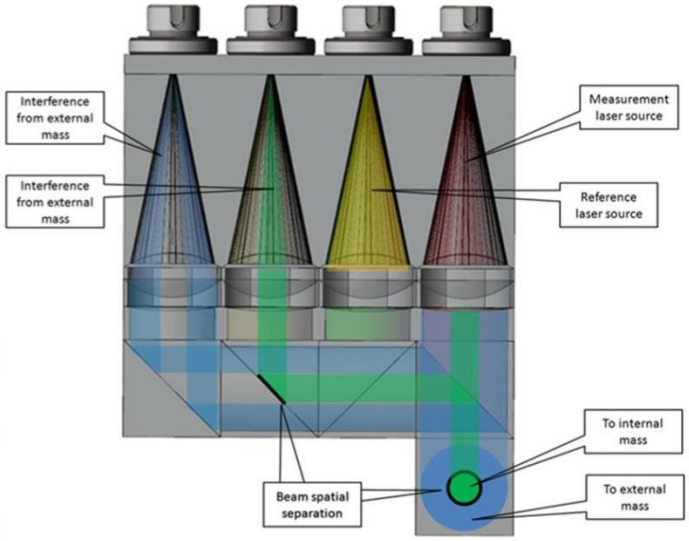
The Δd is measured with a heterodyne interferometer (x 9 optical heads) with picometer resolution



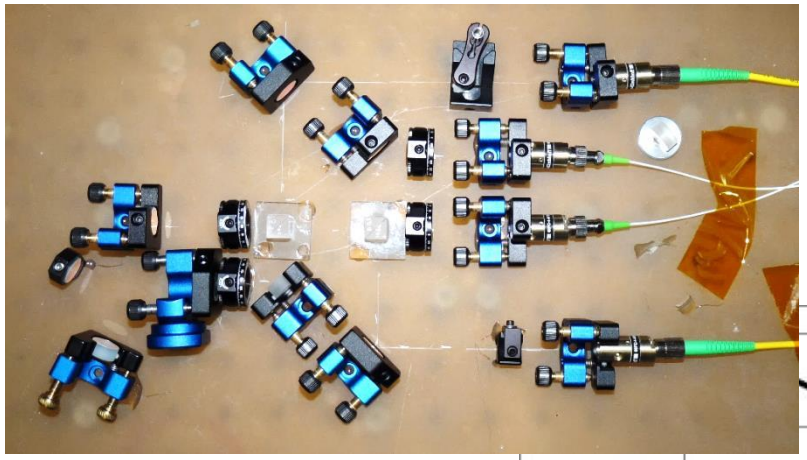
The metrologic system



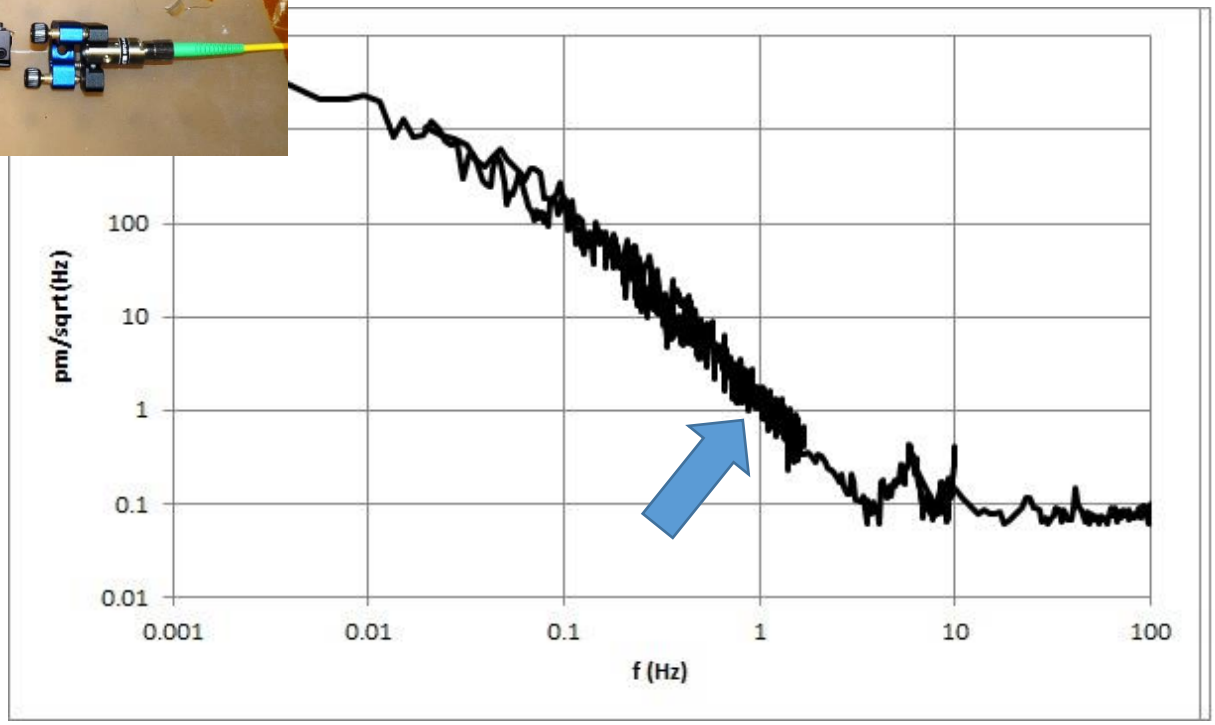




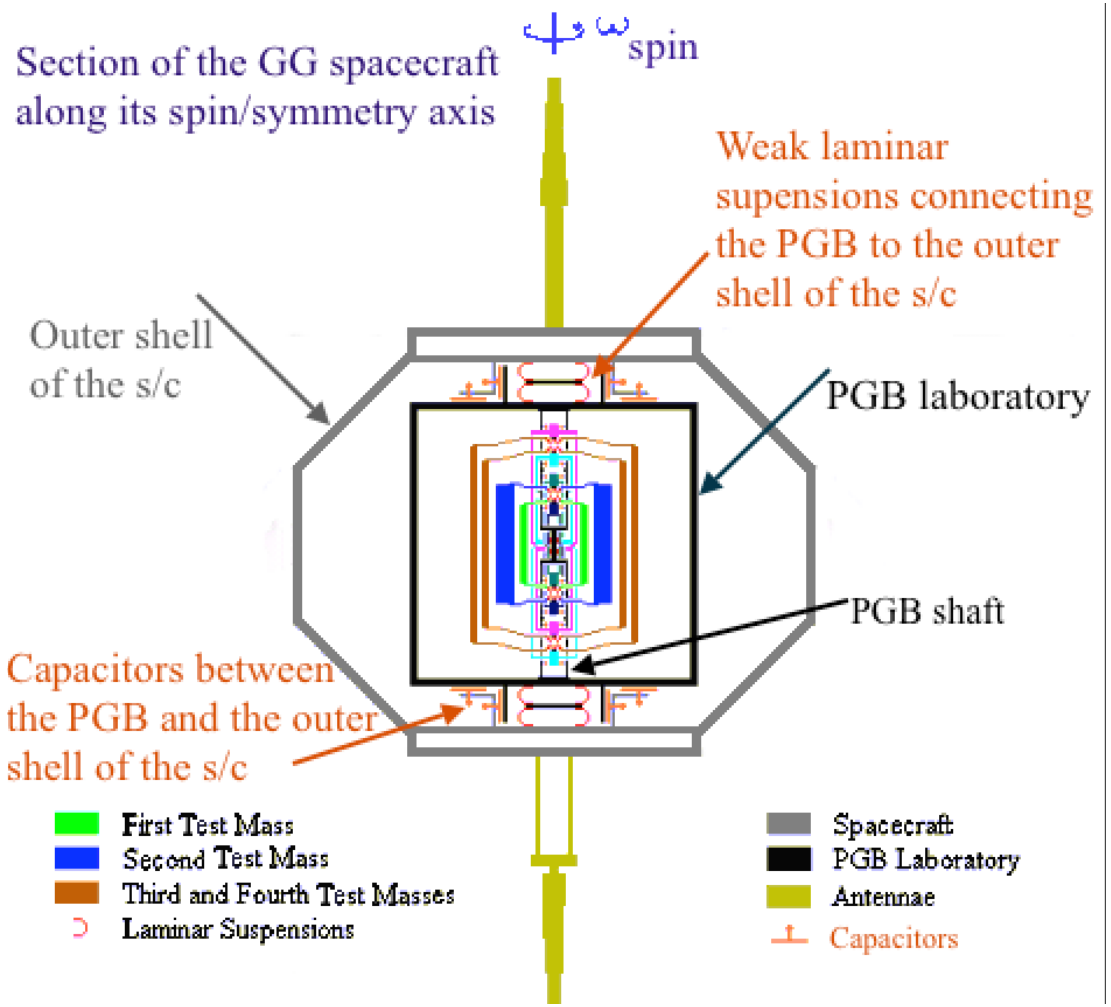
Experimental validation of the interferometer



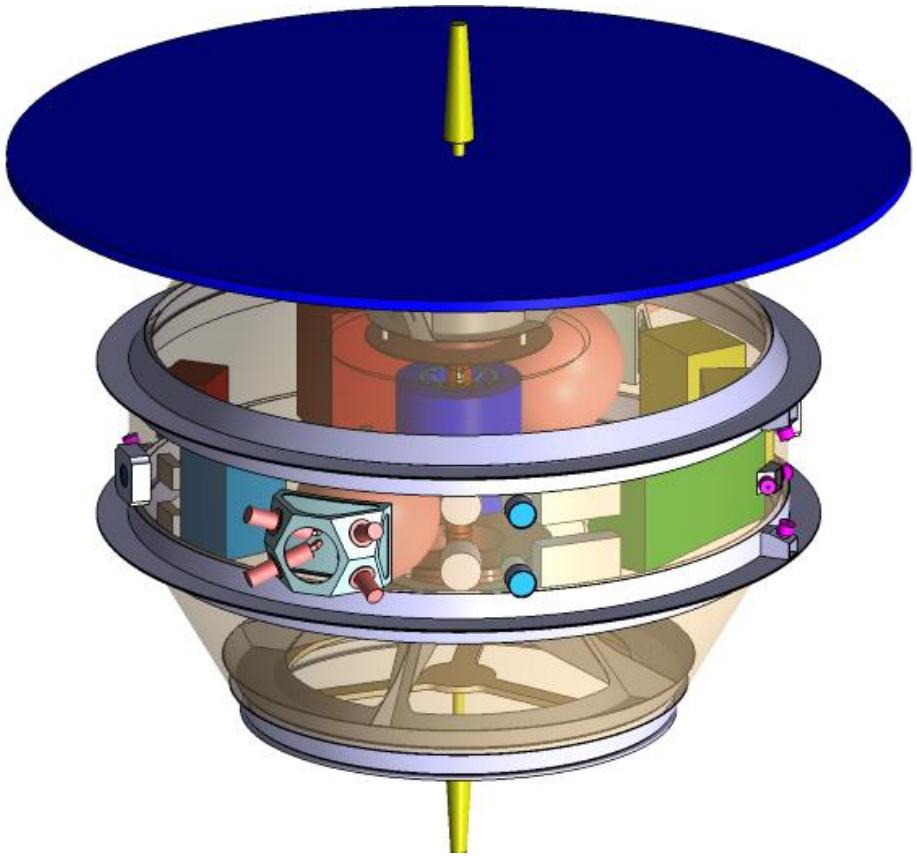
1 pm/√Hz @ 1 Hz has been demonstrated with a breadboard based on a 1 µm free running laser

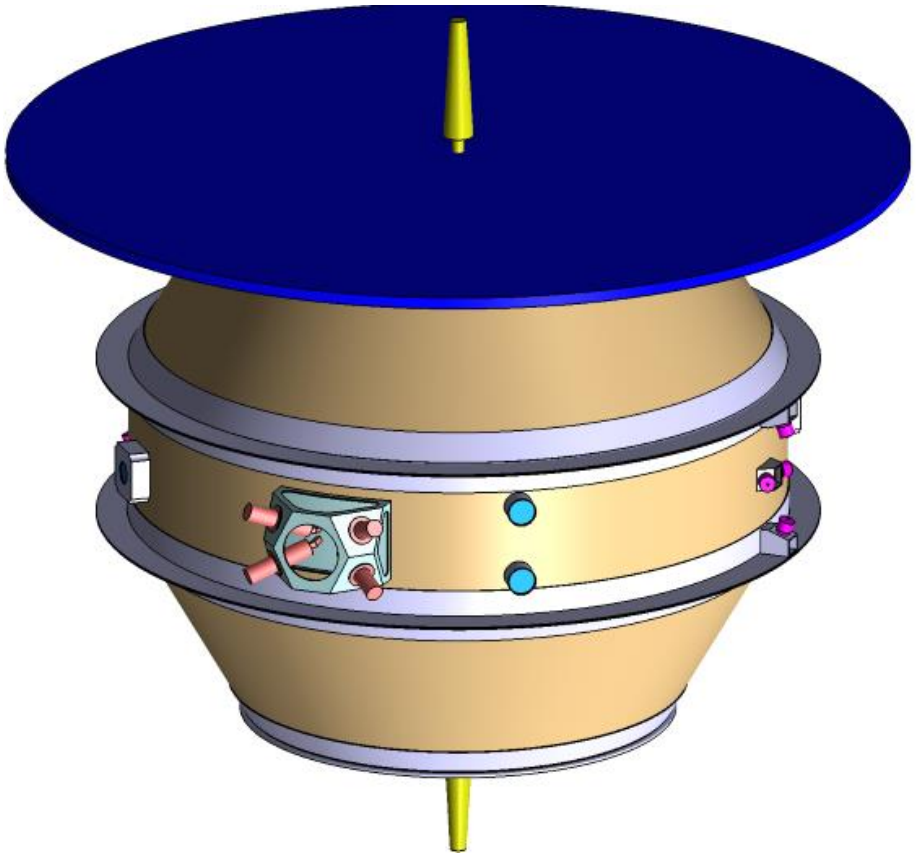


The satellite

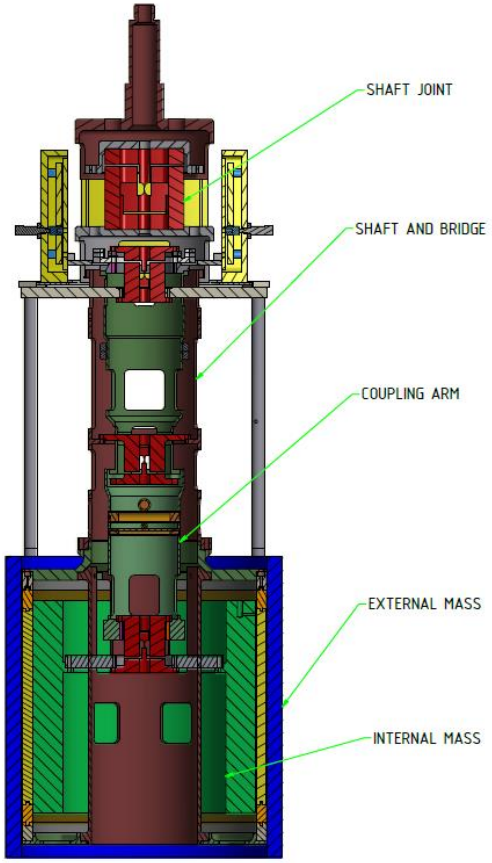


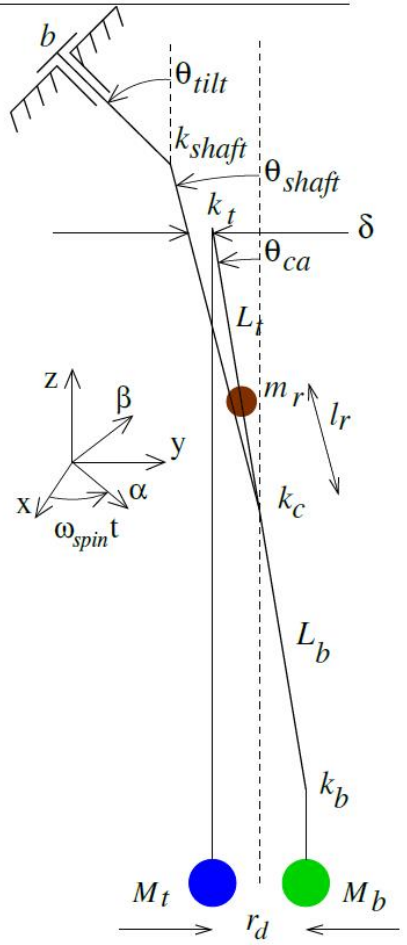
The satellite





GGG (GG on the Ground), 10^{-11}





Conclusions and perspectives

- GG is a simple null experiment to verify the Equivalent Principle with a resolution of 10^{-17}
- The high sensitivity is achieved upconverting the Earth's gravity field to 1 Hz and measuring the test masses with an interferometer with picometer resolution
- Waiting for the results of MICROSCOPE mission, either violation or not, GG is preparing for a confirmation of the results with a 100-fold improved resolution.

Additional information

- GG is a mission invented and designed by the team of Prof. Anna M. Nobili of the University of Pisa
- http://eotvos.dm.unipi.it/ here you can find all you want to know about GG
- THANK YOU!

Truncated CCR set-up