Tracker for Anti-Hydrogen Free-Fall measurement

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Motivation

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- A direct test of the Equivalence Principle with antimatter.
- The acceleration imparted to a body by a gravitational field is independent of the nature of the body :
  Inertial mass = Gravitational mass
- Indirect tests obtained by comparing the properties of particle and antiparticle.[1] [2] [3]
- No stringent constraints on direct tests with antimatter.(ALPHA ruled out ratios between the gravitational mass and the inertial mass of anti-hydrogen less than -65 and greater than +110)[4]

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Experiment

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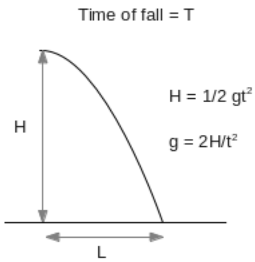

Table: Relative precision on $\overline{g}$

Temperature	Velocity Fluctuation	$\frac{\Delta \overline{g}}{\overline{g}}$	Detected $\overline{H}$
1K	100 m/sec	0.01	1.7×10^8
1mK	4 m/sec	0.01	1.7×10^5
1μK	0.1 m/sec	0.01	170
20μK	0.6 m/sec	0.01	3548
20μK	0.6 m/sec	0.01	9800

GBar values

L=0.3m and v_{hor}=1.5m/s→h=10 cm (T(H)∼20μK∼1 neV)

GBar: *cooled $\overline{H}^+$ → slow H*

N.B: For GBar additional velocity fluctuation due to recoil of atom by laser (mentioned later)

Calculation

Classical Free-Fall: $Z = Z_0 + v_0 t + \frac{1}{2} g t^2$

Main Perturbation: → v_0 *(unknown)*

Velocity fluctuation is Temperature equivalent:

$v_0 = \sqrt{\frac{2KT}{m}}$

K- Boltzmann constant

T- Temperature

Steps

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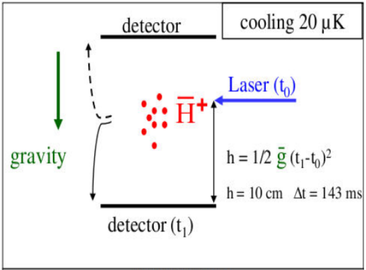
- **Produce ion $\overline{H}^+$.**
  $\overline{p} + oPs \rightarrow \overline{H} + e^-$
  $\overline{H} + oPs \rightarrow \overline{H}^+ + e^-$
- **Capture ion $\overline{H}^+$.**
  Segmented RF Paul Trap for capture.
- **Sympathetic cooling to 20μK.**
  Sympathetic cooling using Be^+ ions.
- **Photodetachment of e^+.**
  Using laser. Laser shot gives the start time.
- **Time of flight.**

  Detection of $\overline{H}$ annihilation gives the stop time and thus the time of flight



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

Improve velocity dispersion

Photodetachment of e^+ $\rightarrow$ Additional recoil velocity $\rightarrow$Additional velocity fluctuation
Threshold energy $= \overline{H}^+$binding energy $= 0.76$ eV
Energy above threshold,ΔE, for laser $\sim 15\mu$eV

Velocity Shaping using Quantum Reflections $\rightarrow$ Reduced velocity dispersion $\rightarrow$ Get required precision for fewer statistics.

Quantum Reflection

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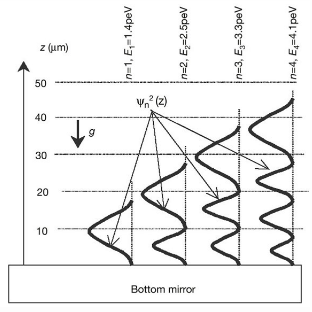
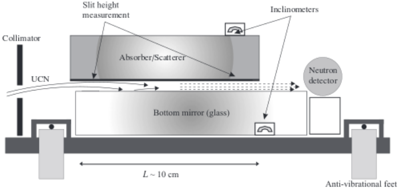
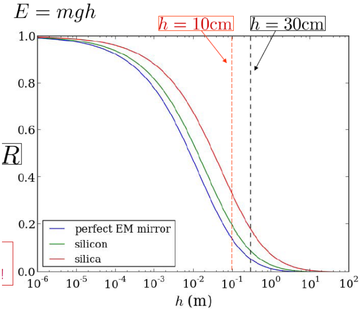




The probability of neutron tunneling through the gravitational barrier at height z corresponding to the n^{th} quantum state is proportional to the square of the wave-function $\Psi_n^2(z)$. E_n is the energy of the n^{th} quantum state [5]



Due to the high efficiency of Quantum Reflections at small energies because of the Casimir interaction, atoms with sufficiently low vertical velocities may bounce off the bottom mirror. This phenomena has already been demonstrated for neutrons in a study of the neutron quantum states in the potential well formed by the earth's gravitational field and a horizontal mirror [6].

Shaper

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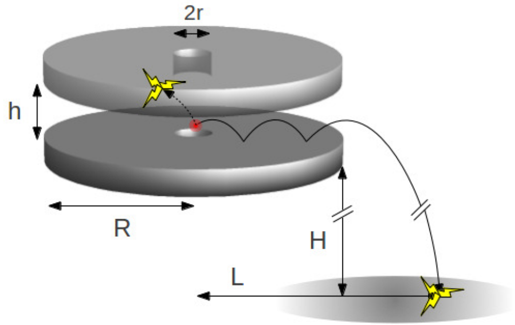

To shape the vertical velocity to reduce the dispersion, a similar shaping scheme with a bottom mirror is envisaged. For this $\Delta v = \sqrt{2\bar{g}h}$
Smaller the height h, lesser will be the velocity dispersion and lesser the required statistics for the aimed precision on $\bar{g}$.

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Final measurement steps

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The calculation of $\overline{g}$ thus comprises calculating the following:

- Total time of flight(T) = Time of detection of annihilation-Time of laser shot.
- Time of free-fall = Total time of flight-Time in shaper.
- Time in shaper $= \frac{R}{v_{horizontal}}$
- $v_{horizontal} = \frac{L}{T}$

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Thus L needs to be measured accurately to improve resolution on $\overline{g}$.

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Aim of thesis

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My work involves building the detector for the experiment to reconstruct the vertex of annihilation. For the first phase of the experiment to reach 1% precision on $\overline{g}$ a vertex resolution ∼4mm is necessary.

- Initially a TPC was thought to be used for the pion track reconstruction. But my simulations showed a XY Microstrip Micromegas achieves much better spatial resolution.
- Advantages of the Microstrip Micromegas includes:
  - No need for drift time calculation for track points since the X-Y strips give directly the position.
  - Much reduced HV(few hundred volts instead of kV)
  - Much lighter detector.
  - Spatial resolution is better.
  - Lesser cost.

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Micromegas Description

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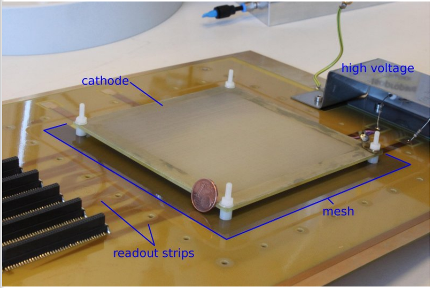
- 150μm diameter epoxy spacers placed every 2mm between anode and mesh to maintain parallelism.



Principle of Operation

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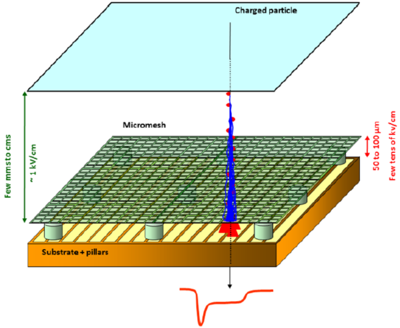
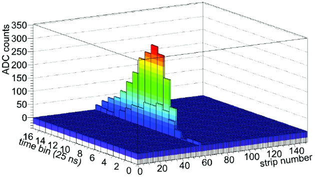
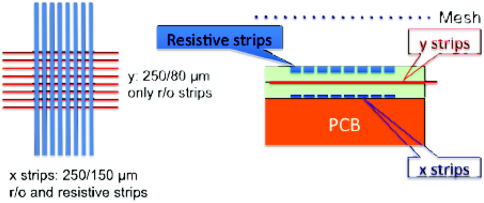
- Incoming particle ionizes gas (eg:Ar-C_4H_{10}, $ArCF_4$ etc. mixture few mbars above atmospheric pressure).
- Electrons drift towards the mesh from the conversion gap under applied electric field.
- Electrons enter the amplification region and produces an avalanche like secondary ionization due to strong electric field.
- Signal induced on the strips is a sum of the electron and ion signal(e^{-}signal rise time $\sim$ 1ns followed by the ion tail $\sim$ 100ns depending on gas mixture and amplification gap) .





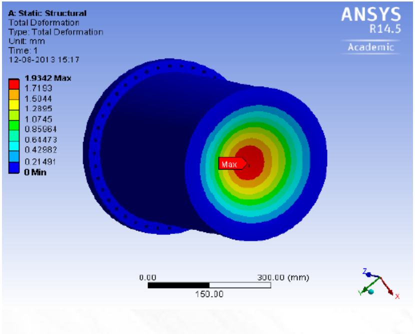
XY Micromegas

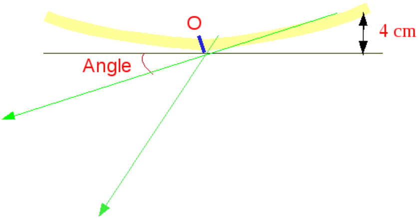
XY Micromegas for two co-ordinate readout from the same gas gap:



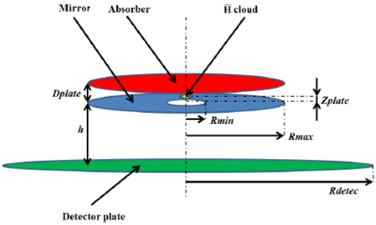
Crossed strips (R16) Each layer separated by 70μm thick layer of insulator. Varying strip width to compensate for the weak capacitive coupling to the X-strips. Achieved charge ratio X:Y=1:2.4. Spatial resolution achieved for each strip layer ∼80 microns.

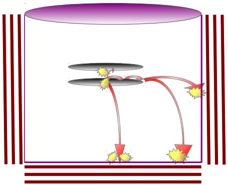
Resolution limitations





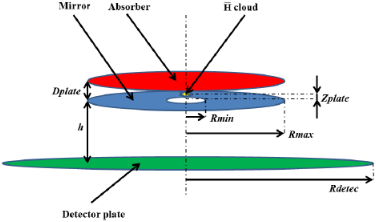
- The resolution is limited by the intrinsic detector resolution and multiple scattering in the annihilation plane and the detector material.
- It would be ideal to make the annihilation plane as thin as possible to limit multiple scattering but due to vacuum deformation we can't make it too thin.
- Vacuum deformation was simulated using ANSYS for different thicknesses and materials to estimate the minimum plane thickness required.
- The plane could have been thinner for a round bottom cylinder but that worsens the resolution due to the longer lever arm for angular tracks as shown in the figure.
- For a flat bottom cylinder simulations showed a plane thickness $\sim$ 4mm of Stainless Steel is the accepted option (staying under the elastic deformation limit) with a 2mm deformation.

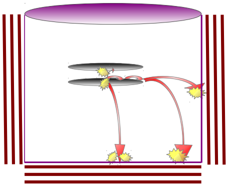




- A Geant4 code was written to simulate anti-hydrogen annihilation.

Simulation





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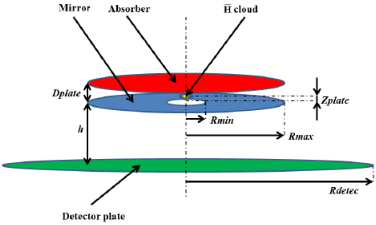

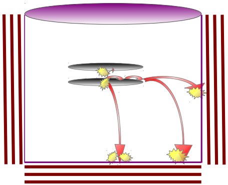

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  - ZPlate = 1.5mm Dplate = 3mm
  - R_{min} = 5mm R_{max} = 30mm

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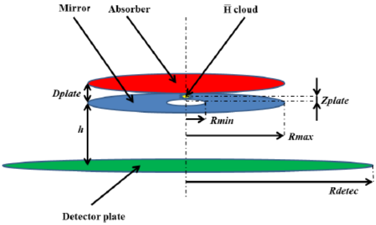

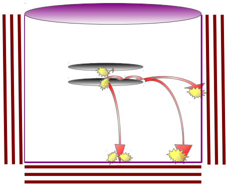

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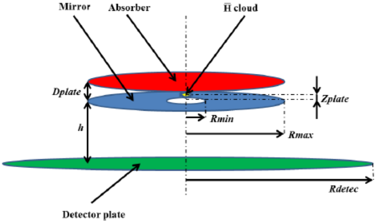

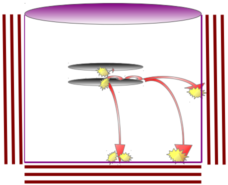

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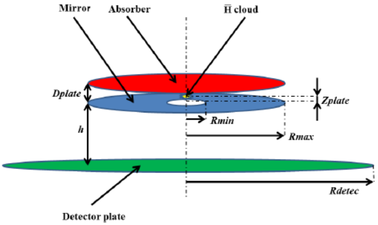

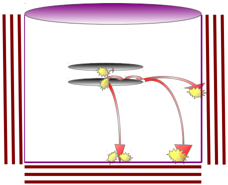

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- The resolution for vertex reconstruction is estimated and compared tracking all tracks and only the ones through the bottom detector modules with a time-cut.

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Results

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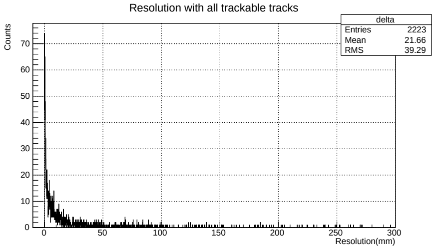
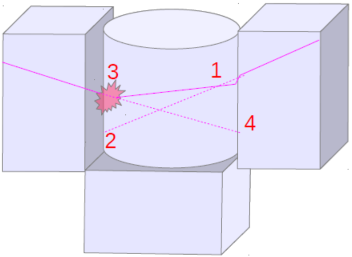
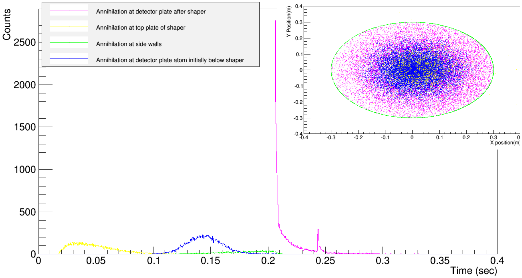
The plot shows a long tail which is because of the annihilation on the side walls. With the side annihilation there is always an ambiguity in the position of annihilation with there being two possibilities on two wall faces.

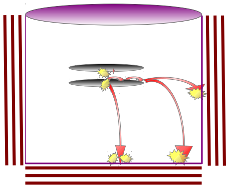




Time Distribution

The time distribution shows a time cut at $\sim$ 205ms will include only the events with annihilation near or at the bottom plate.





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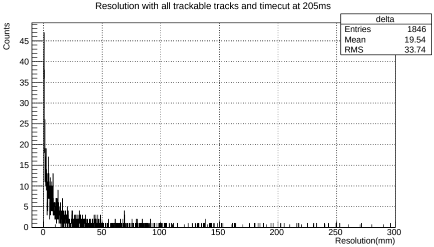

With the time cut we have 83% of the events through the shaper with $\sigma_g = 0.43$. We still have the tail as we include the side tracks for reconstruction. Using only the down tracks for vertex reconstruction we eliminate the tail with an improved $\sigma_g = 0.13$. Thus to achieve 1% resolution on g we will need around 170 detected events with this scheme.

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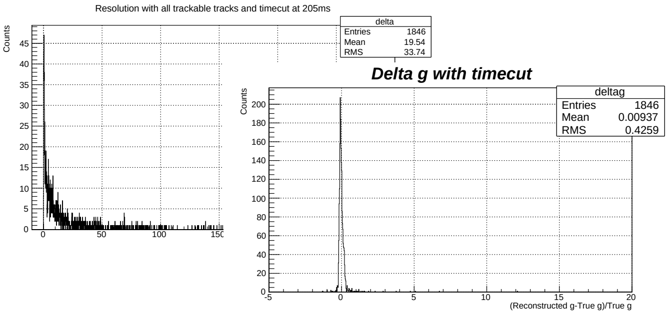

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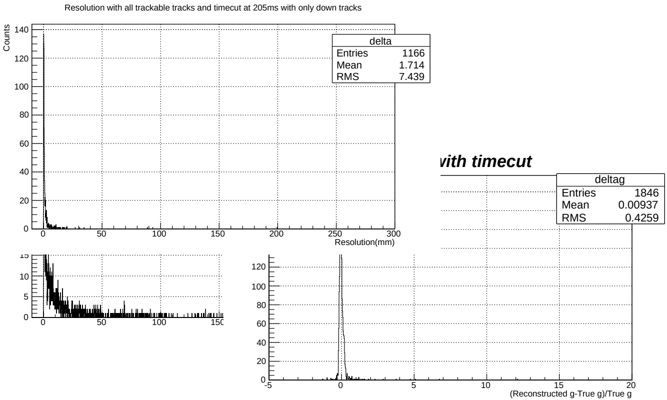

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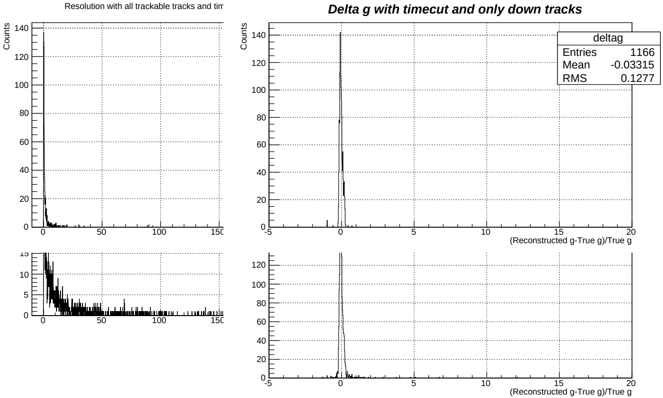

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Efficiency

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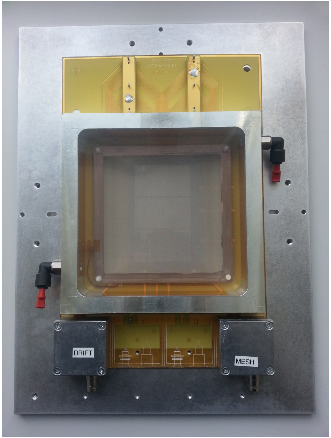
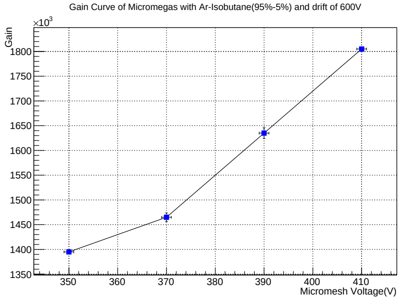
Table: Efficiency of tracking

	Full Coverage at the sides	Corners not covered
Total number of events simulated	10000	10000
Number of events through shaper	2223	2223
Events with time cut at 205ms	1846	1846
Events with the time cut and at least 1 trackable track through the bottom modules	1166	1166
Events with the time cut and at least 2 trackable tracks with 1 going through the bottom modules	956	934
Events with the time cut and at least 3 trackable tracks with 1 going through the bottom modules	425	403

Test Bench

A test bench is set up at ETH, Zurich with a 1-D 10cm$\times$6cm Micromegas prototype received from Saclay. Preliminary tests to characterize the detector have already been performed reading signals off the mesh. Electronics to read the strips will be available soon.





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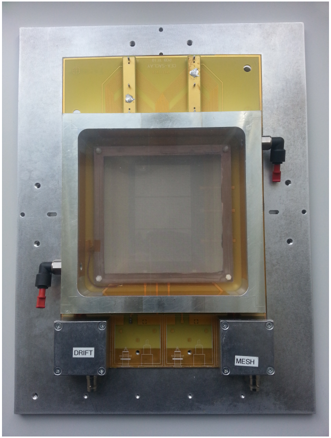

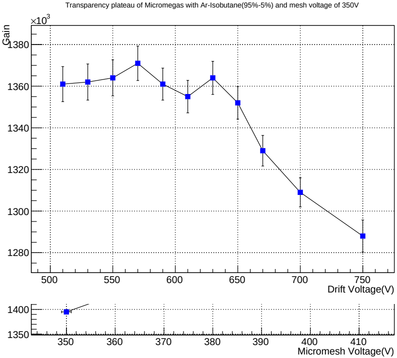

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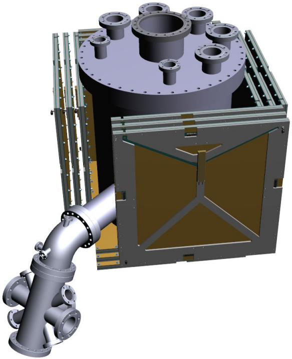
Detector Geometry

Detector Geometry. Production of a prototype with three detector modules together with the mechanics and electronics is foreseen for testing with cosmics by beginning next year.



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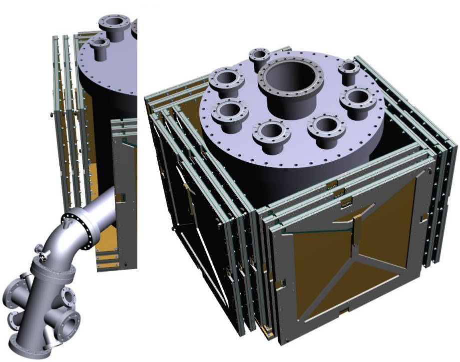

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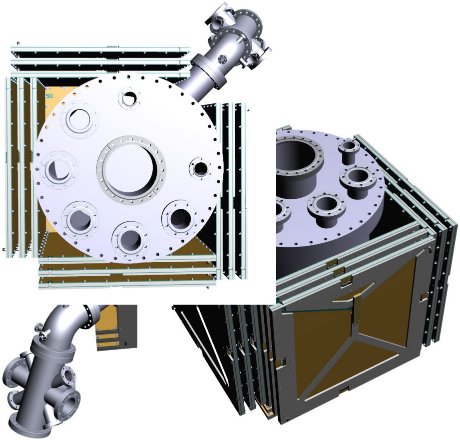

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- This improves σ_g by ∼70% compared with only the timecut.

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- The production of a prototype (a triplet) with mechanics and electronics is foreseen following which it will be tested with cosmics.

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Thank You!!!