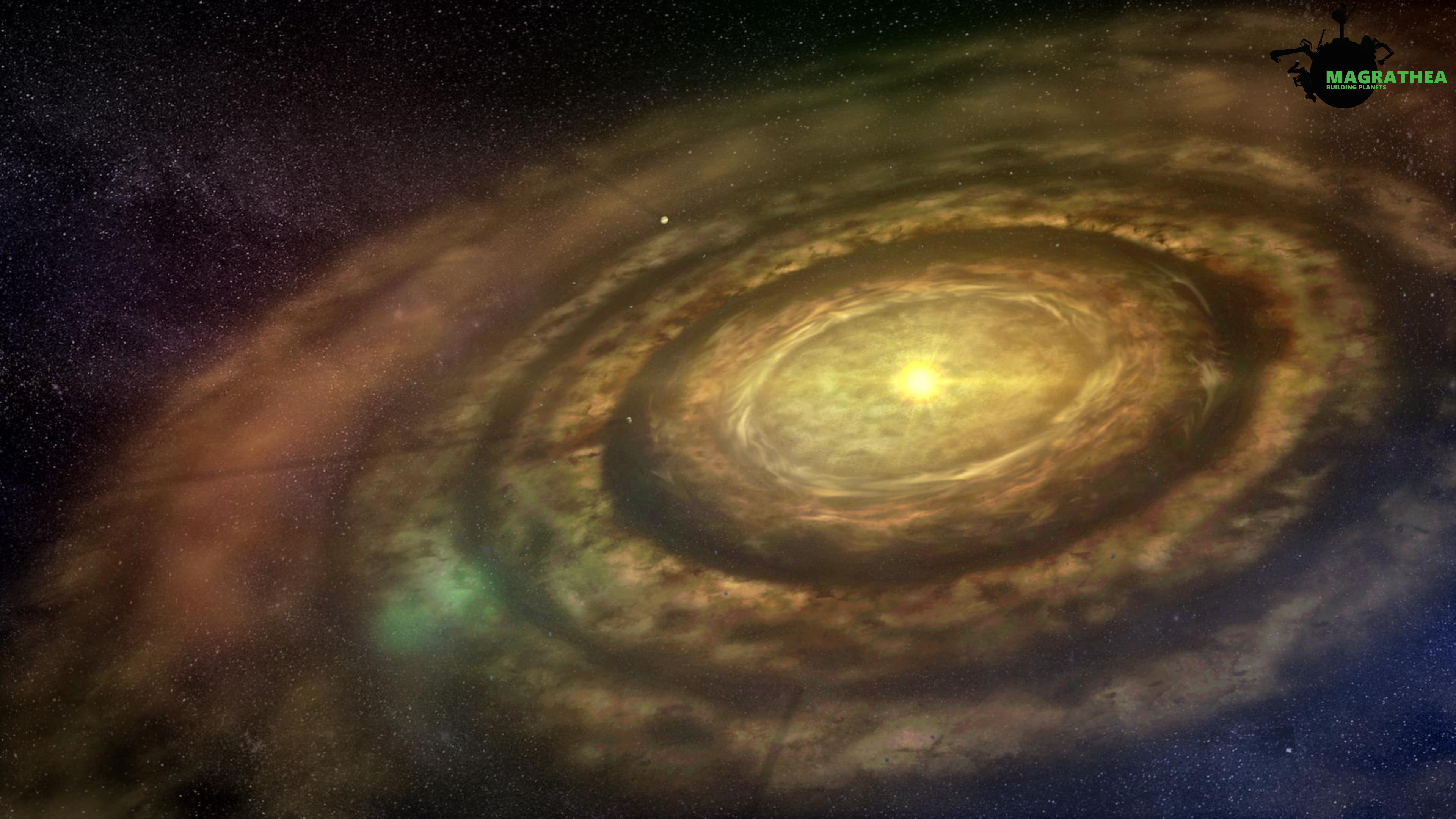
MAGRATHEA
BUILDING PLANETS

MAGRATHEA

BUILDING PLANETS

Teams

Team	Personnel
1. Team leader and system engineer	**Marine**
2. Science	**Jonas**, Esmee, Julia, Victoria
2. Payload	**John**, Adrian, Gwenael
3. Platform	**Marine**, Adrian, Fabio, Lisa, Marta
4. Mission analysis	**Mattia**, Andre, Jophiel

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BUILDING PLANETS

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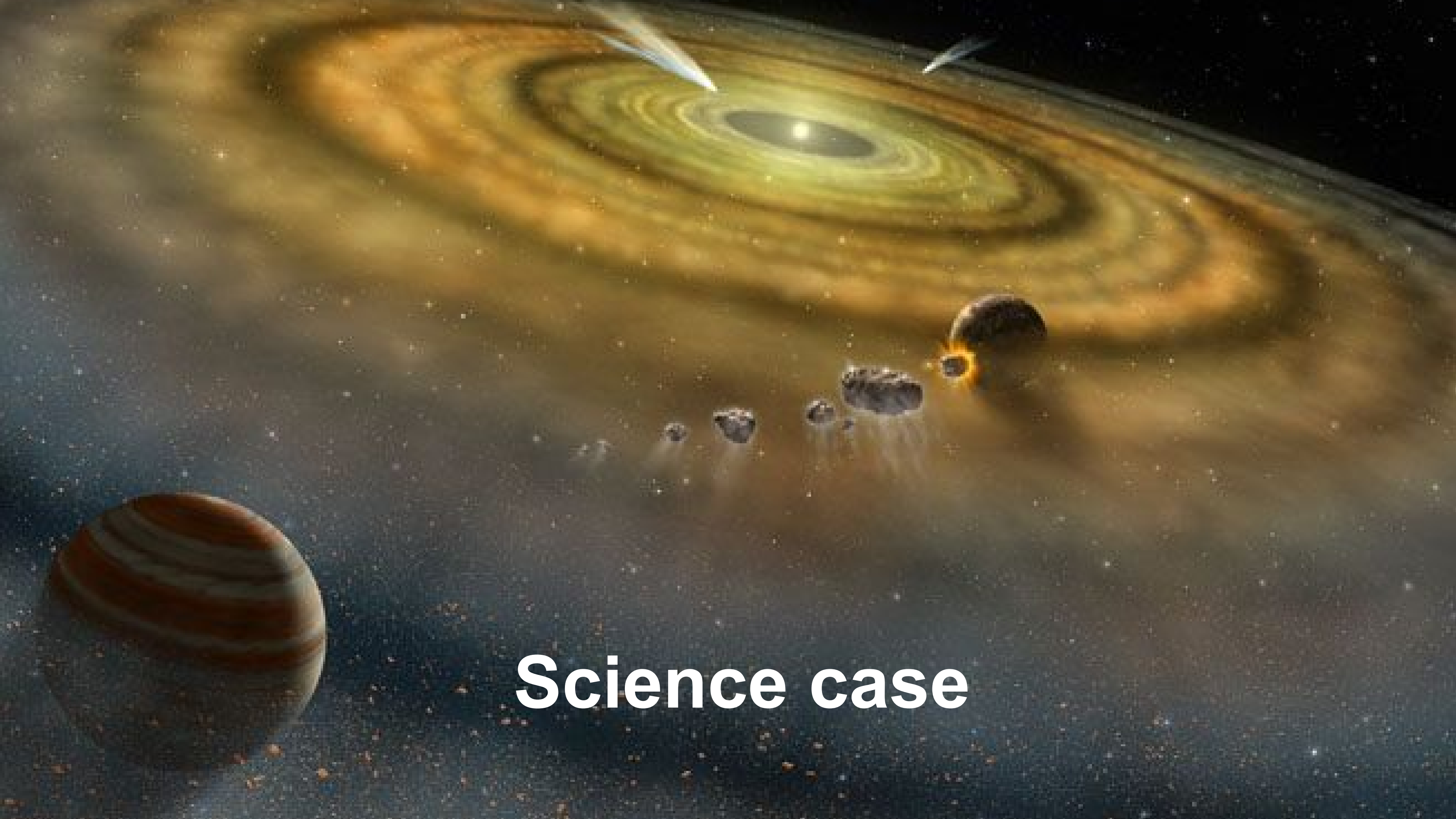


Science case

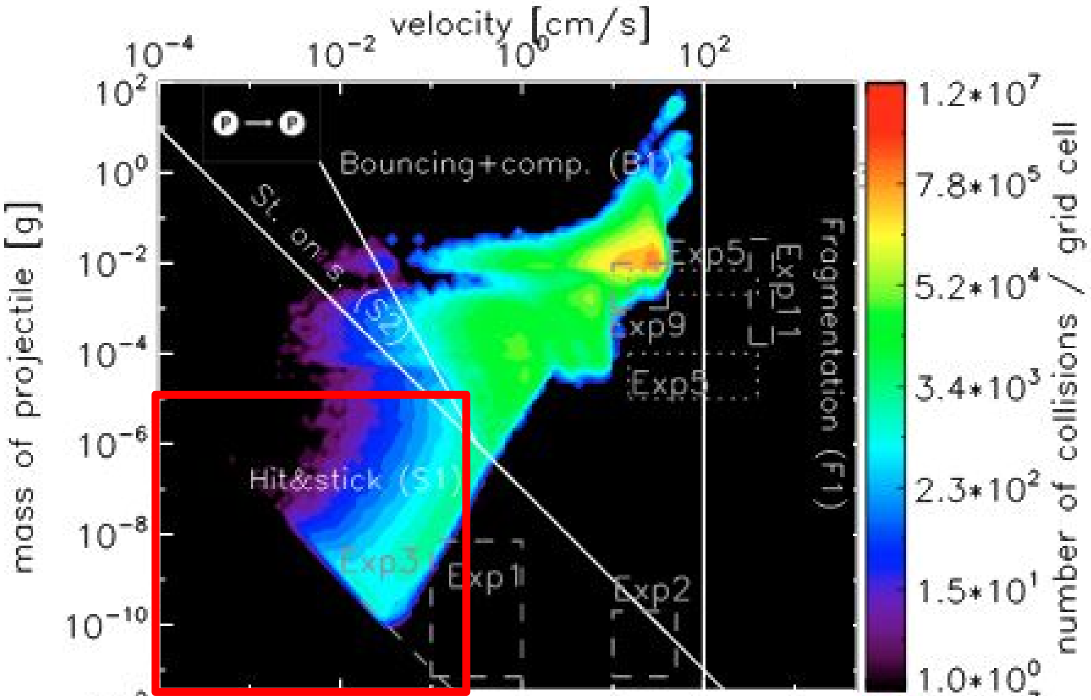
Investigating the physics of grain growth

Why study dust growth?

- Planets
- Gaps in knowledge
  - Models
  - 30 µm - 100 µm
  - Low velocity interaction

Why a laboratory in space?

- Remote observations cannot resolve interactions
- Need:
  - Low relative velocities
  - Long time in micro-gravity
  - No big disturbances



Zsom et al. 2010

Science objective

Understand the physics of dust growth at **low velocities** (<5 mm/s) in protoplanetary disks by observing the **evolution** of dust size and shape in **micro-gravity** over **long time scales**.

The physics of grain growth - Measurements

Size
Same/different initial sizes

Shape
Sample particles

Composition
- Quartz/Fayalites separately
- Porosity

Rotation frequency

Ice layers
With and without

Temperature changes
- Water sublimation
- T increase

Relative velocity
Before collision

Type of collision
Güttler et al. 2010

The physics of grain growth - Environment

- Gas : dust mass ratio = 100 : 1 for µm-sized particles

- Magnetic field: expected to be in the order of ~$2.9*10^{-5}$ T inside the volume
- Temperature: < 230 K inside the volume
- Pressure: between 0.1 - 6 mbar inside the volume

Initial experimental conditions

Monodisperse

Varying composition:

→ 4 different initial grain sizes
→ 4 different compositions each

Varying porosity:

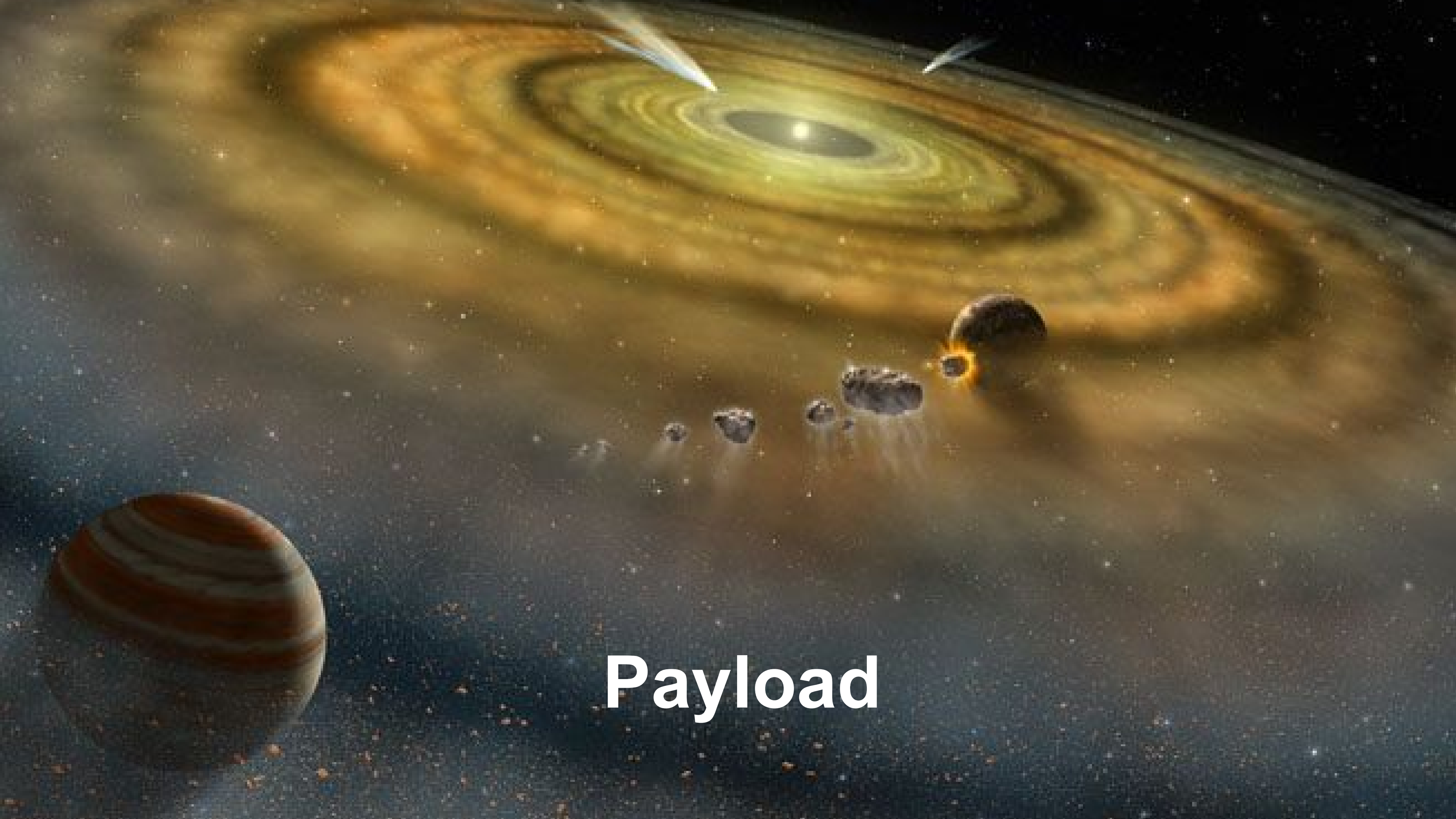
→ 1 initial grain size
→ 4 different porosity distributions

Polydisperse

Varying size distribution:

→ 2 different initial size distributions
→ 4 different compositions each

→ 28 experiments in total



Payload

Measurement requirements

Scientific requirement	Measurement requirement	Rationale
Measure of size	The size shall be measured in the range between 1 μm and 1cm with a precision of 10%.	Analyze how the size of the incoming particles affect the grain growth.
Measure of relative velocity	The relative velocity of incoming and outgoing particles shall be measured in the range between 1μm/s and 5 mm/s with a precision of 1%.	Analyze the influence of relative velocity in the grain growth.
Measure of rotational velocity	The rotational velocity of incoming particles shall be measured at 120 fps (frames per second).	Analyze possible influence of rotation in the particle interaction and grain growth.

Measurement requirements: timescale

Measurement requirements	Driving science requirements
At least 10^6 collisions shall be recorded during each experiment.	S1, S2, S3, S4, S5, S7
The mean free path of grains shall not exceed 0.01 of the smallest dimension of the containing volume.	S1, S2, S3, S4, S5, S7
The experimental volume shall be sampled at least once every 2 hours.	S1, S3, S7

Measurement requirements: cleanliness

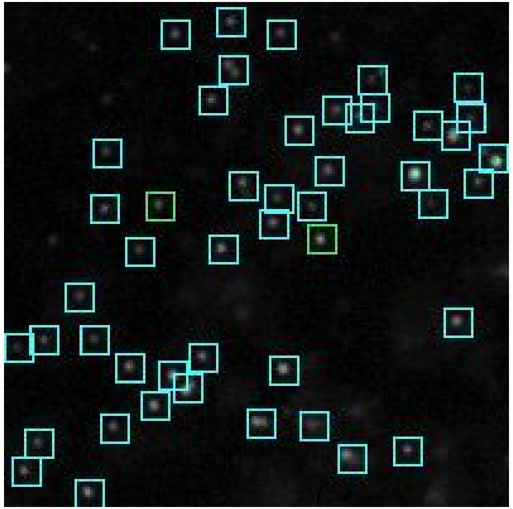
Measurement requirements	Driving science requirements
No more than 20% of particles may be stuck to the walls of the containing volume during any experiment	S1, S2, S3, S4, S5, S7
The speed of particles released from walls after any agitation shall not exceed 2 mm s^{-1}	S1, S2, S3, S4, S5, S7
No more than 1% of particles may remain in the chamber after each experiment	S1, S2, S3, S4, S5, S7

Main instruments

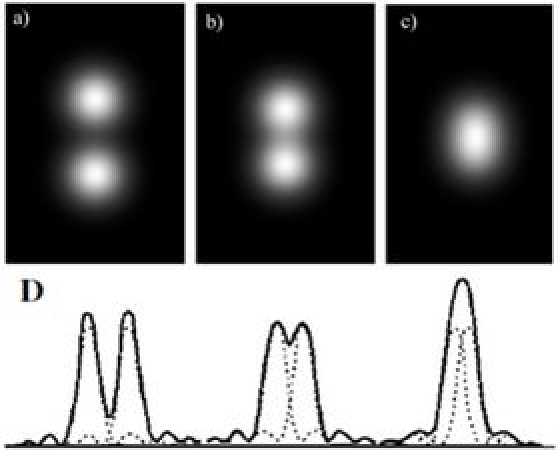
Instrument	Qty	Measurement requirements					
		Size Range	Collision type	Shape	Velocity	Rate of rotation	Porosity
Particle tracking camera (P-CAM)	3	1 cm - 3 μm	Yes	Yes	Yes	Yes	Yes
Optical Microscope (OM)	1	50 - 1 μm		Yes			Yes
Atomic Force Microscope (AFM)	1	1 - 0.1 μm		Yes			Yes

Measurement principles

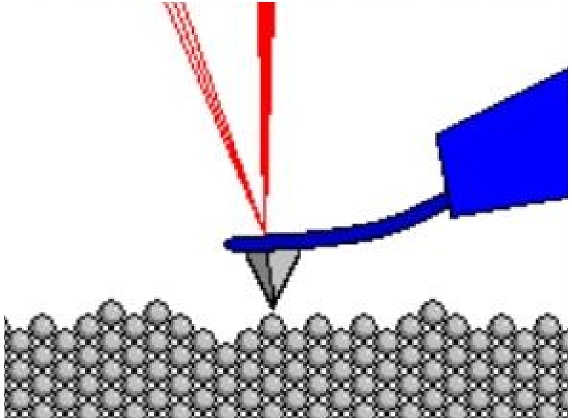
Particle tracking



Optical microscopy

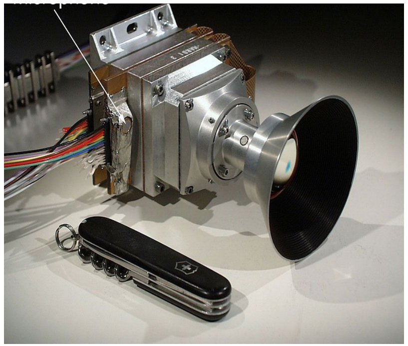


Atomic force microscopy



Instrument description

Particle Tracking Camera (P-CAM)

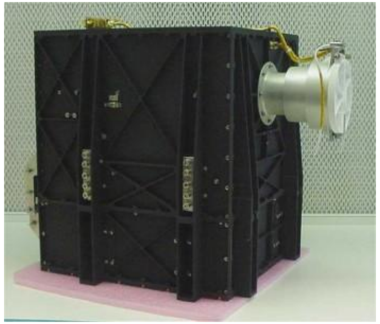


Heritage: Phoenix (MARDI)
Mass: 1.5 kg
Power: 4 W
Data rate: 5.4 Mb s^{-1}
Volume: 70x70x70 mm

Optical Microscope (OM)

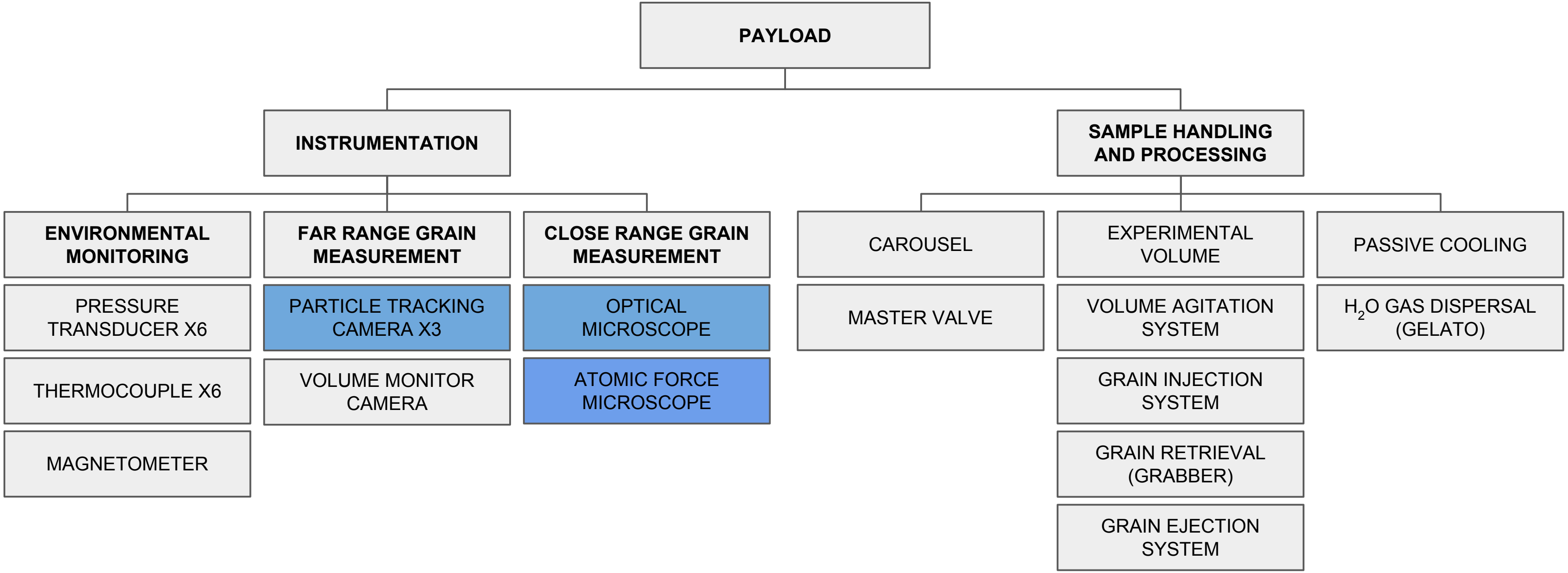
Heritage: Rosetta (CIVA-M/V)
Mass: 1.1 kg
Power: 1 W
Data rate: 0.075 Mb s^{-1}
Volume: 70x50x91 mm

Atomic Force Microscope (AFM)

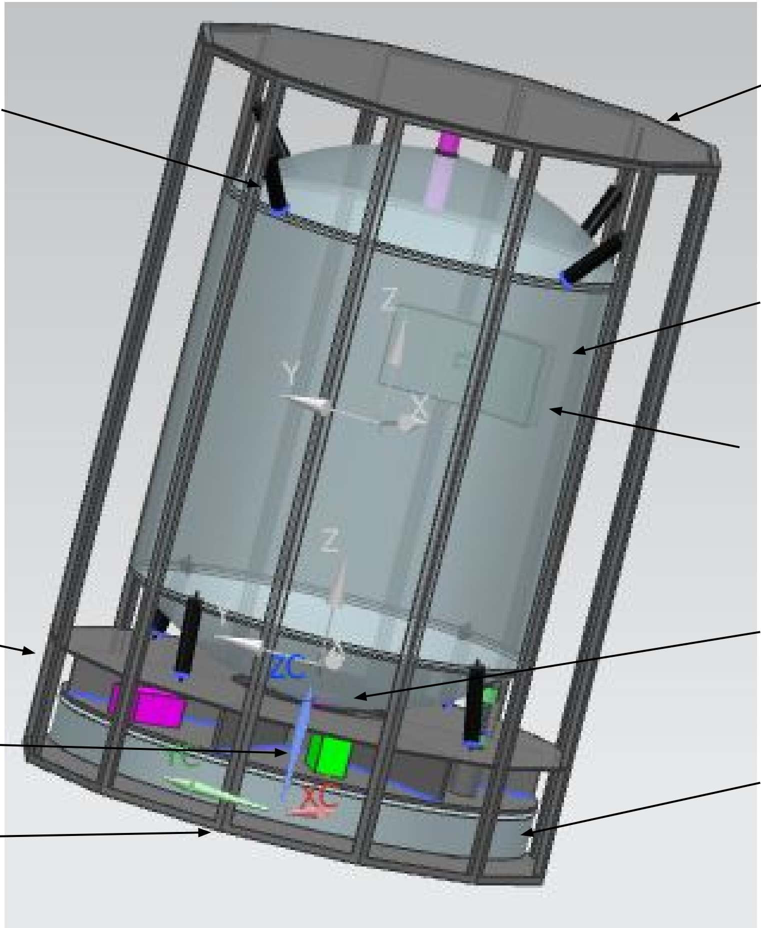


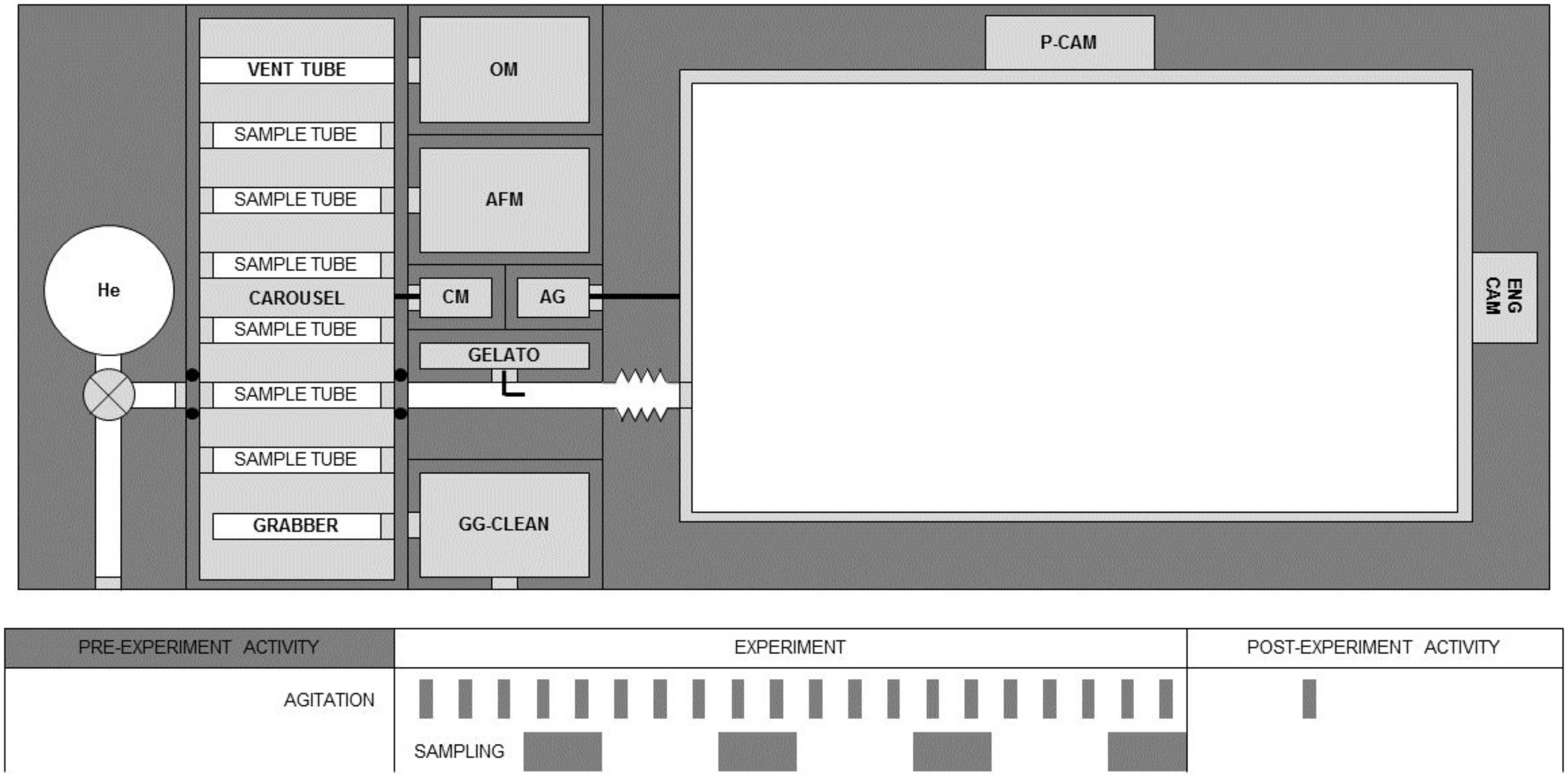
Heritage: Rosetta (MIDAS)
Mass: 8.3 kg
Power: 17 W
Data rate: 0.001 Mb s^{-1}
Volume: 300x250x100 mm

Payload breakdown structure



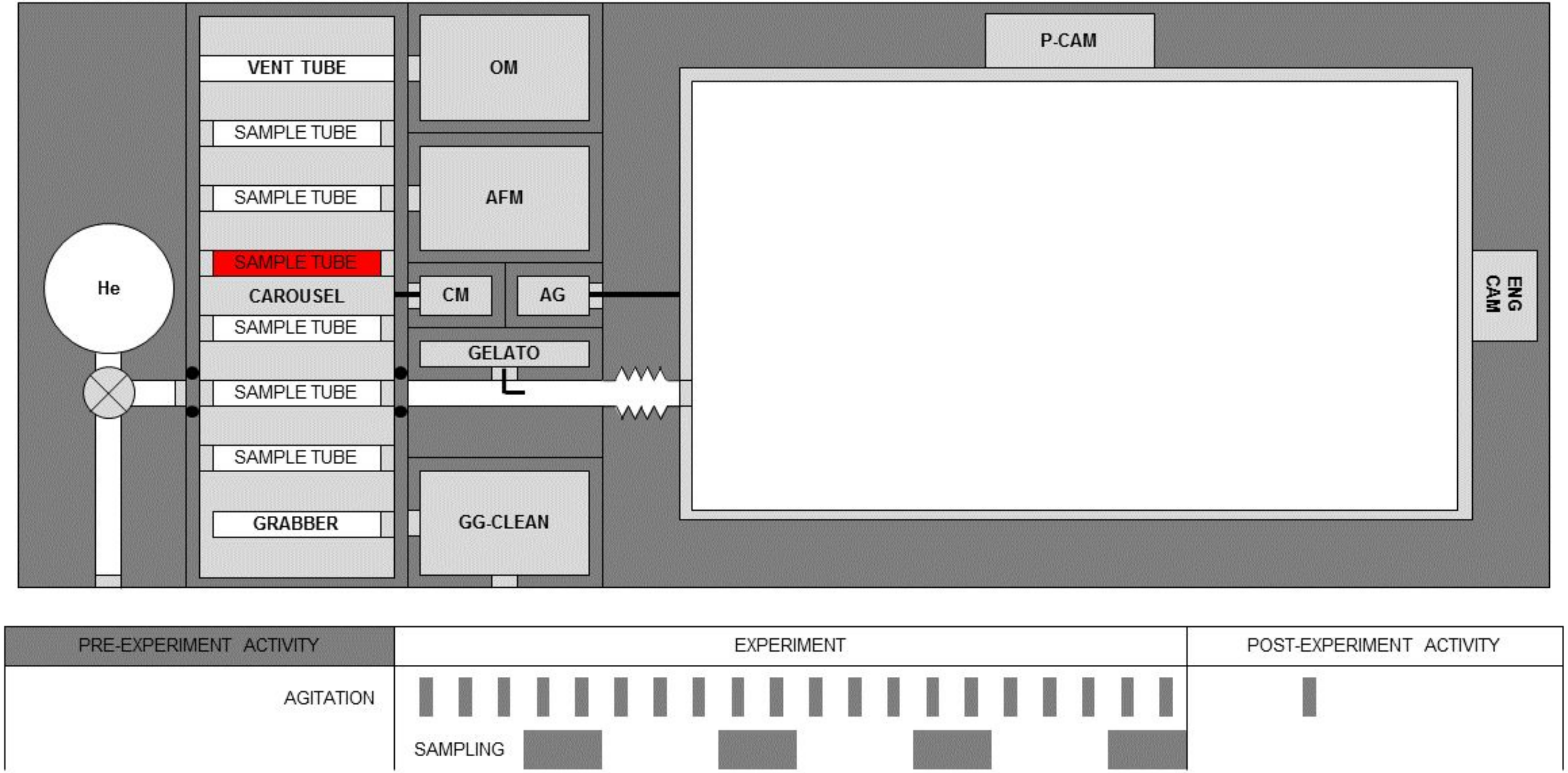
Payload design



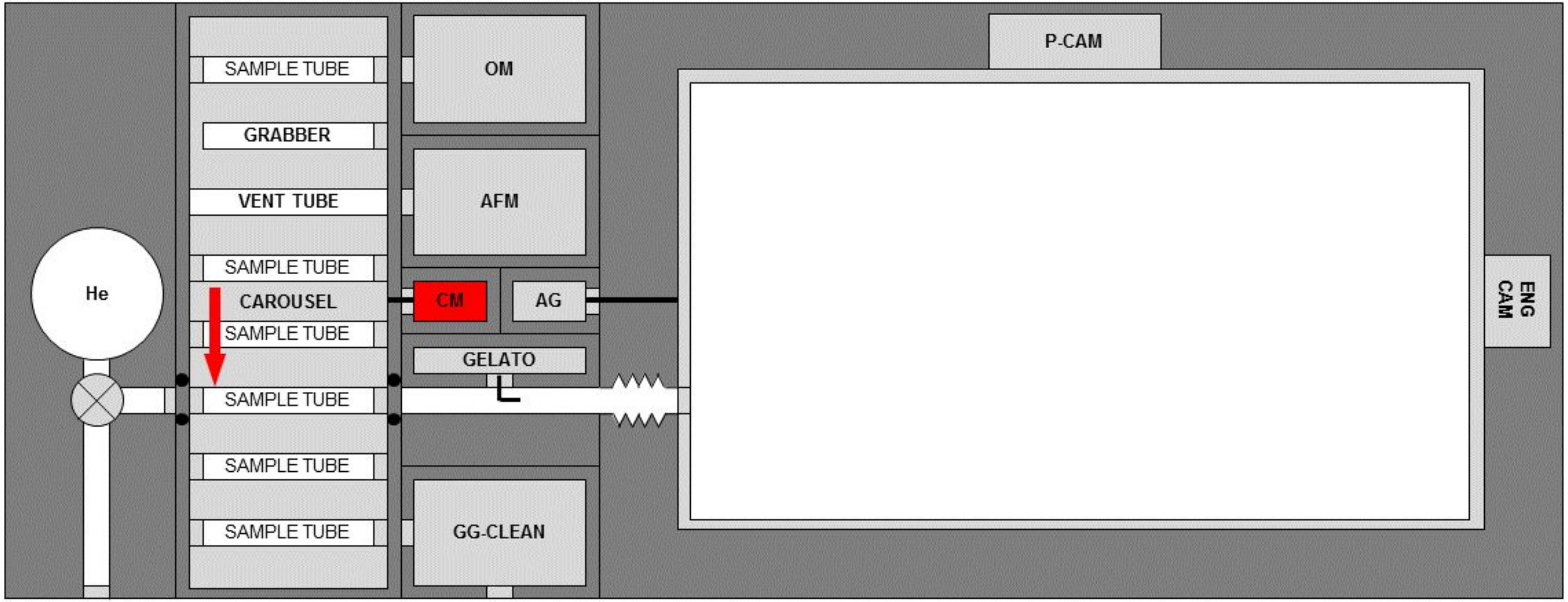


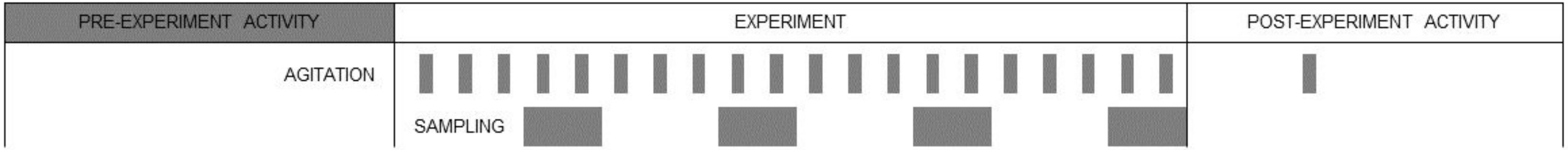
P-CAM
VENT TUBE
OM
SAMPLE TUBE
SAMPLE TUBE
AFM
SAMPLE TUBE
He
CAROUSEL
CM
AG
ENG CAM
SAMPLE TUBE
GELATO
SAMPLE TUBE
SAMPLE TUBE
GRABBER
GG-CLEAN
PRE-EXPERIMENT ACTIVITY
EXPERIMENT
POST-EXPERIMENT ACTIVITY
AGITATION
SAMPLING

Identify sample tube containing desired dust

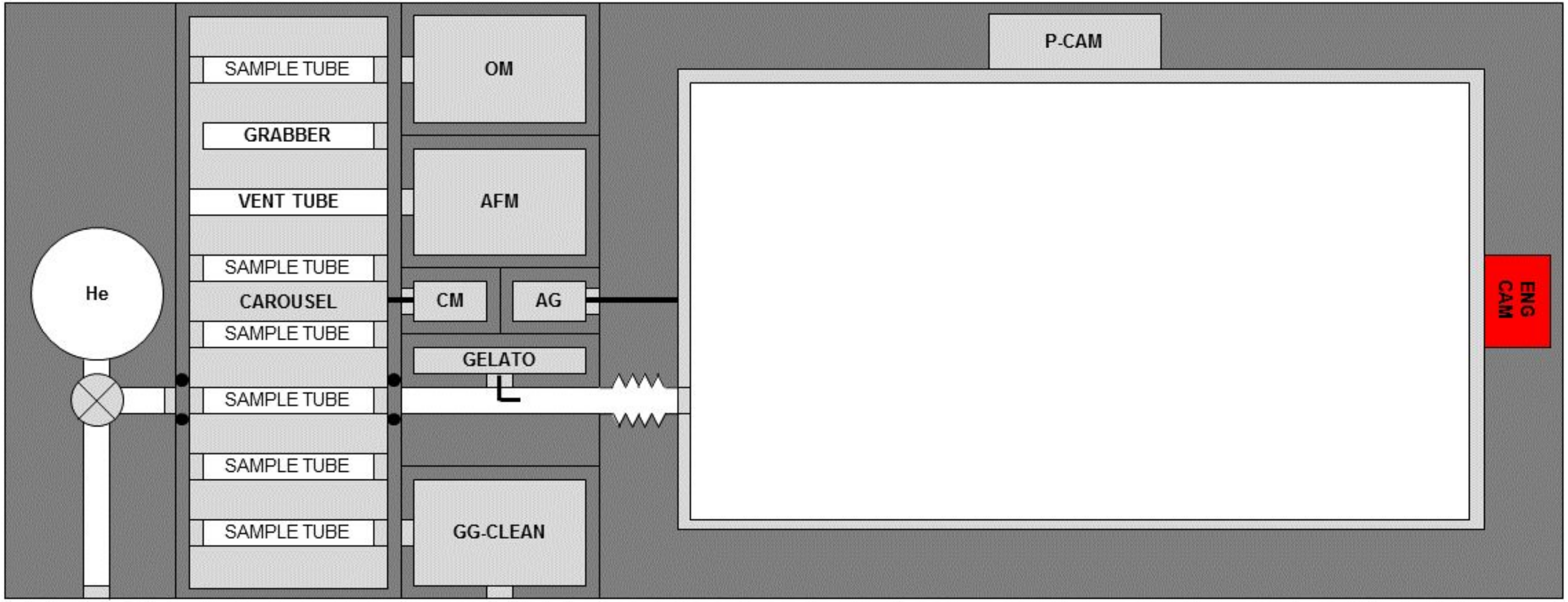


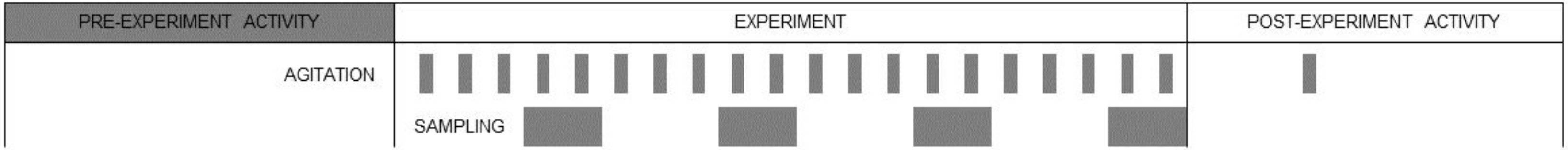
Rotate carousel to align sample tube with injection port



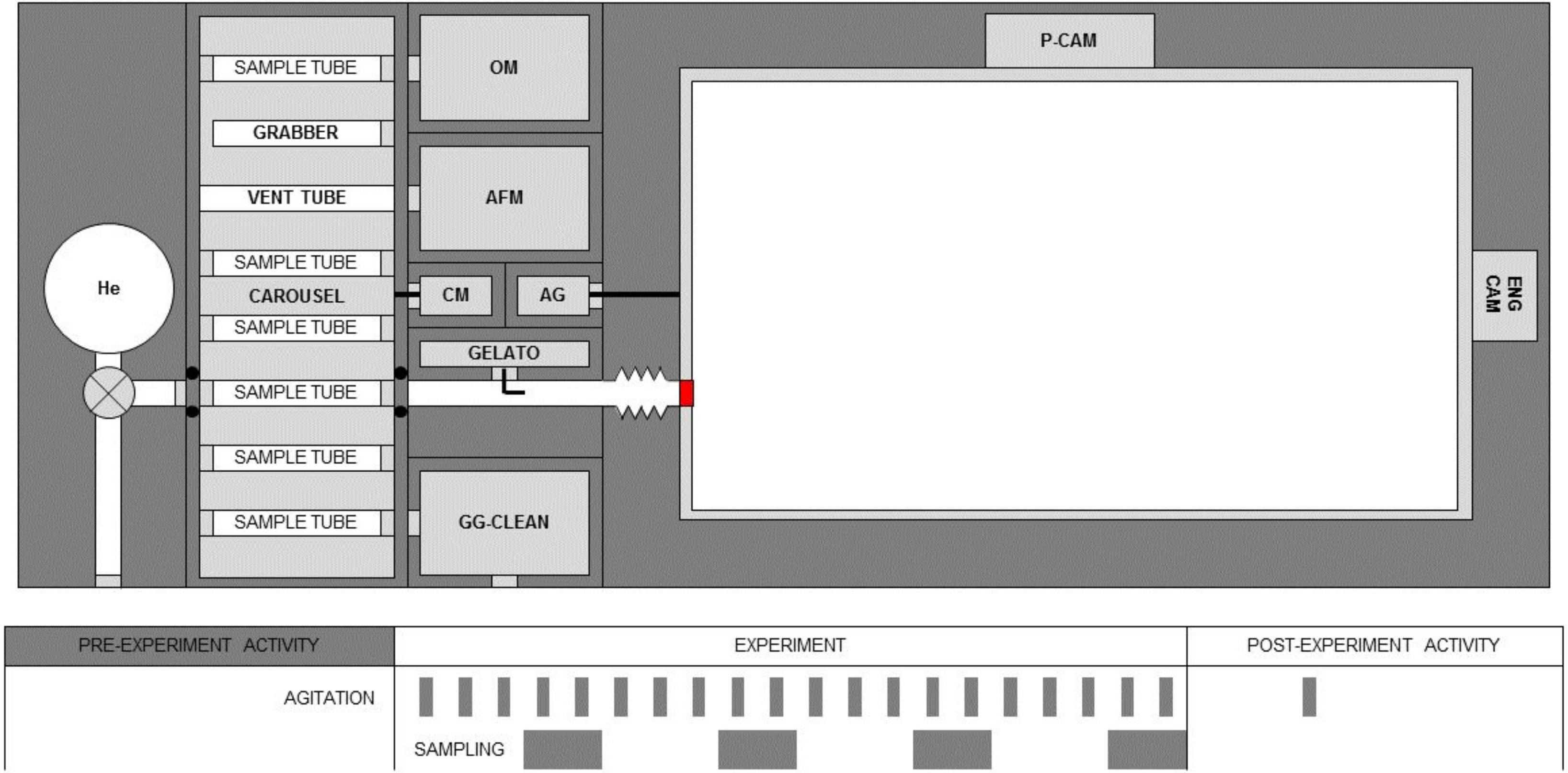


Start engineering camera to observe dust injection

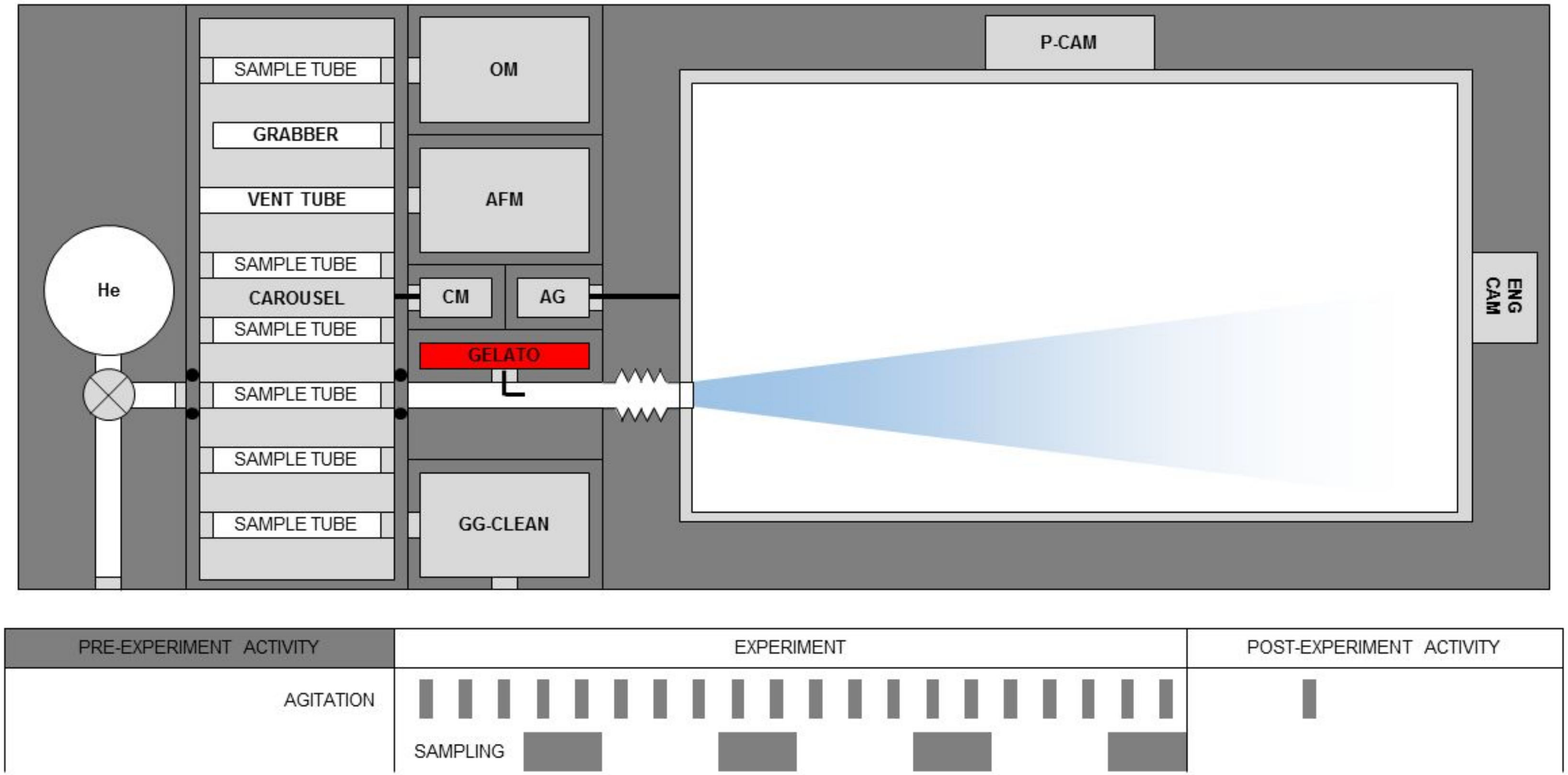




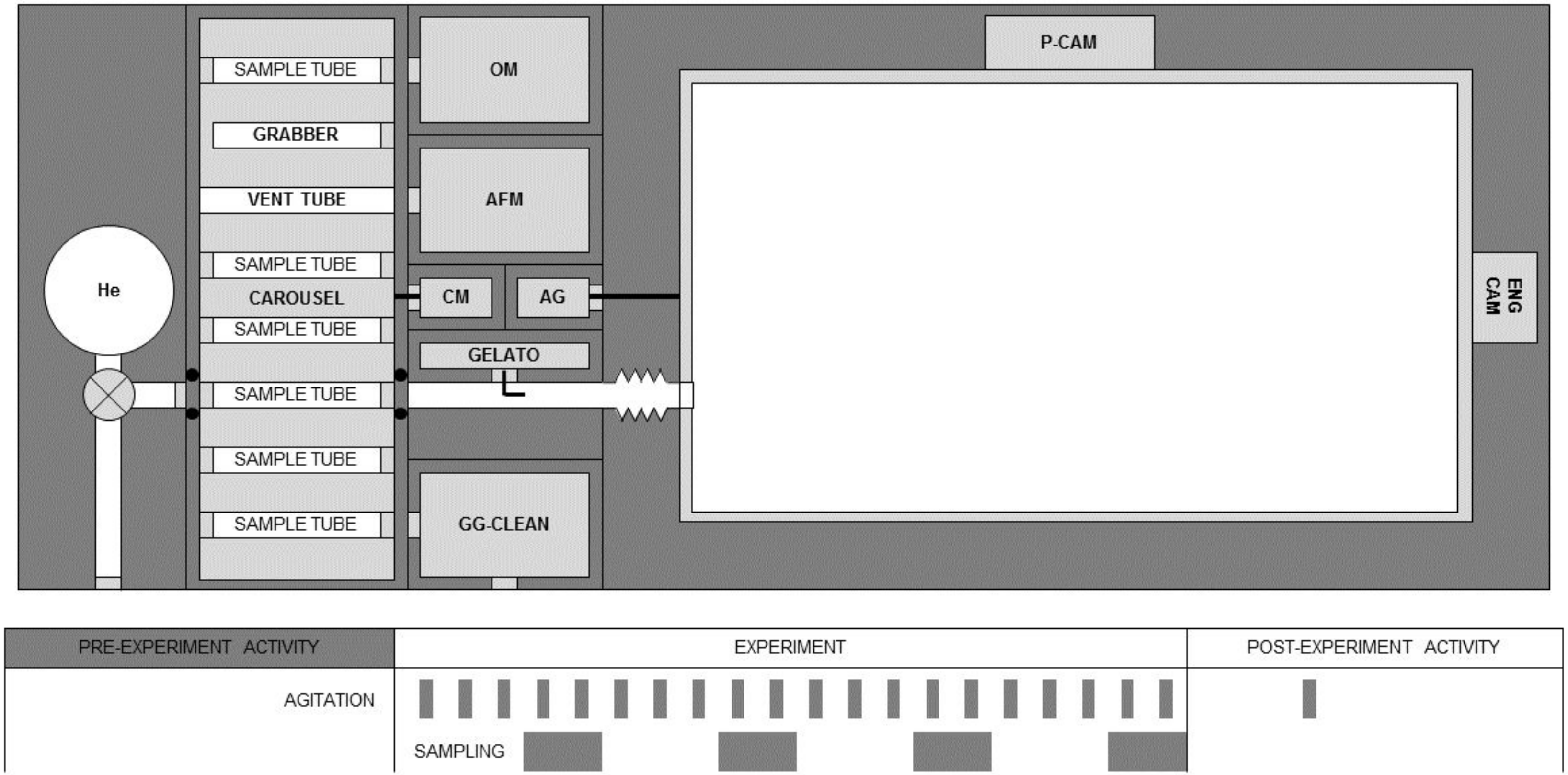
If ice layer required on dust, open valve at chamber



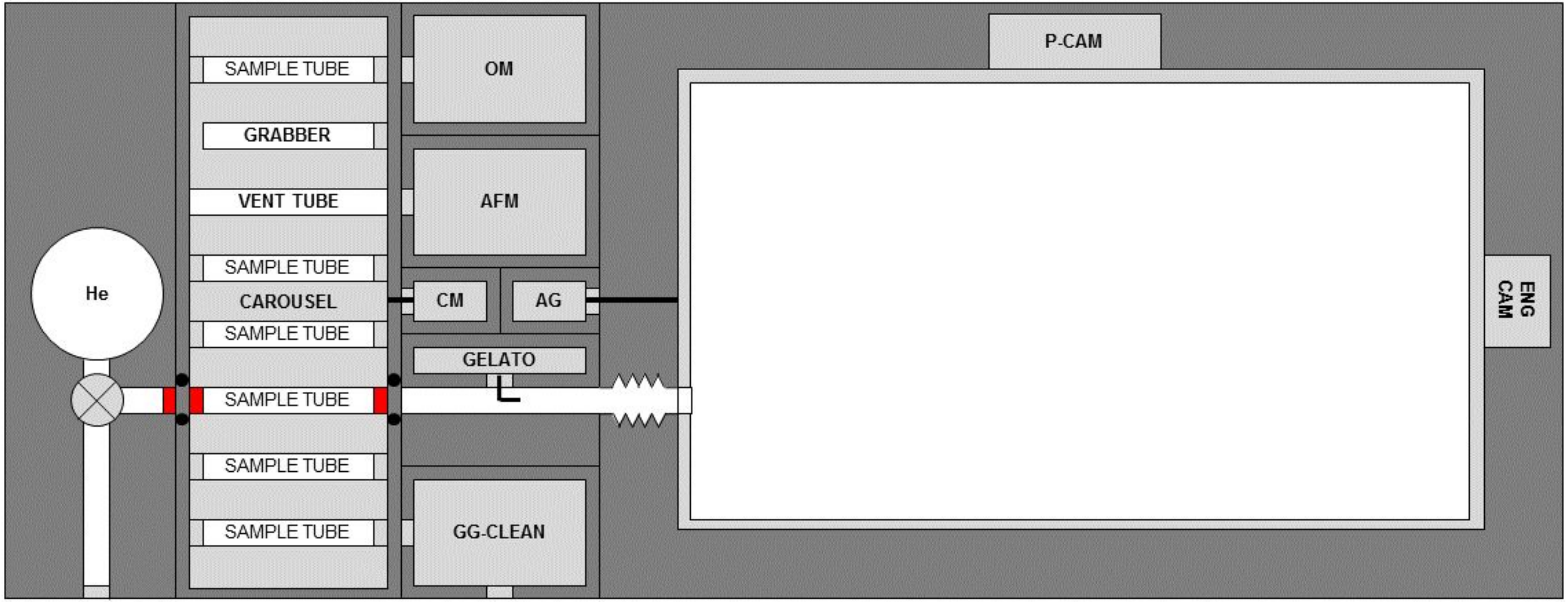
If ice layer required on dust, inject H2O

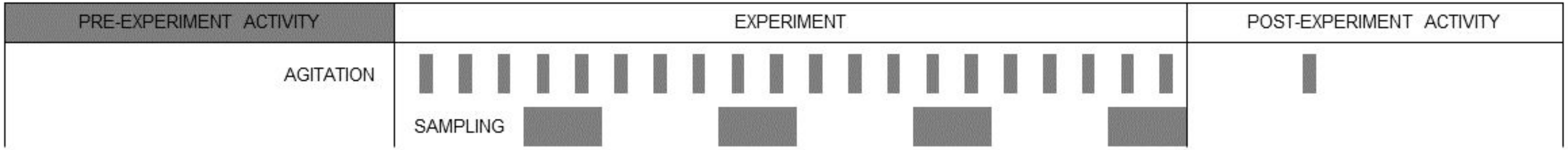


If ice layer required on dust, wait

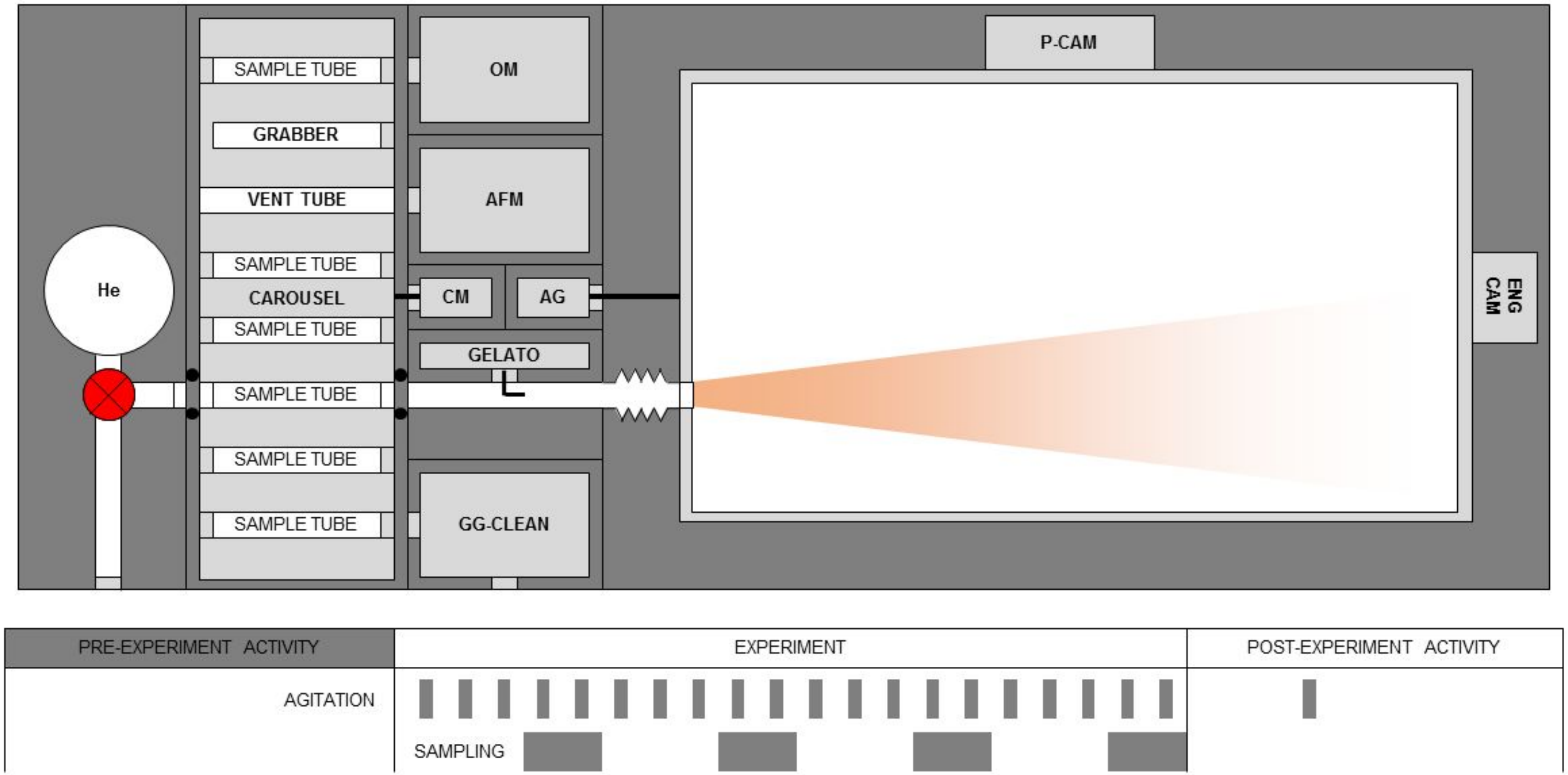


Open valves for dust injection

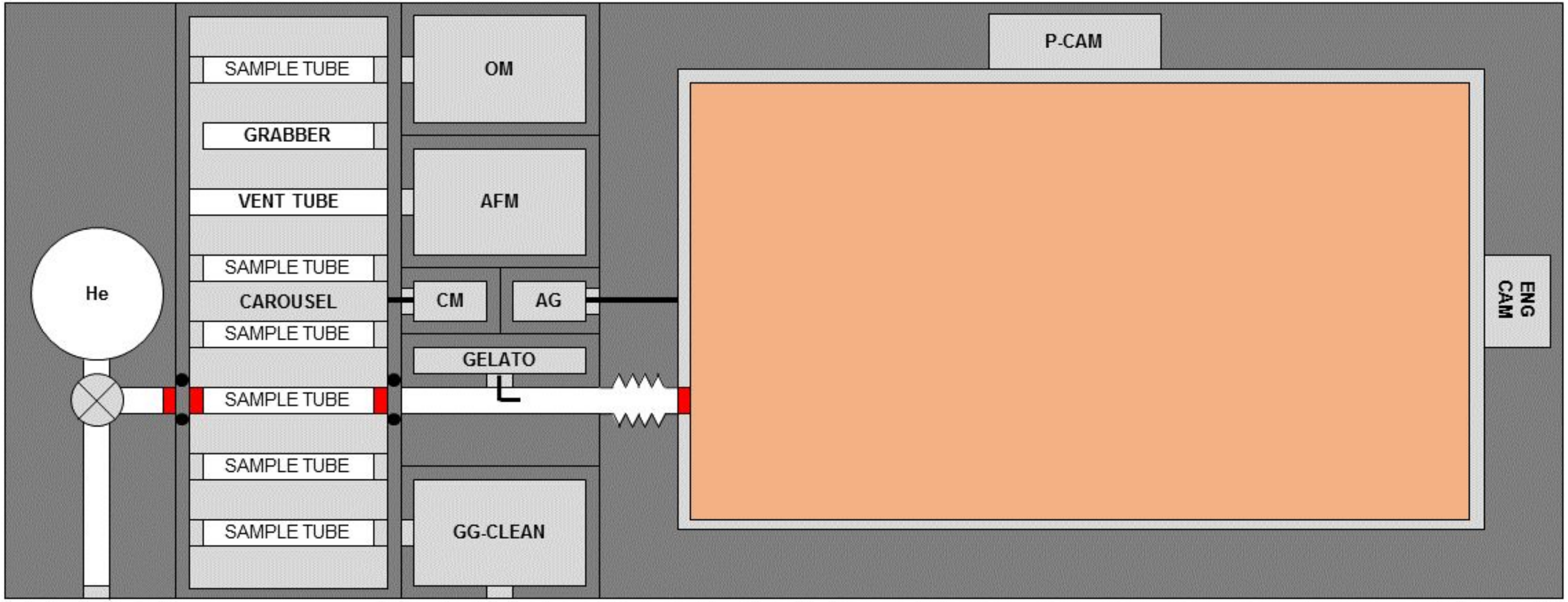


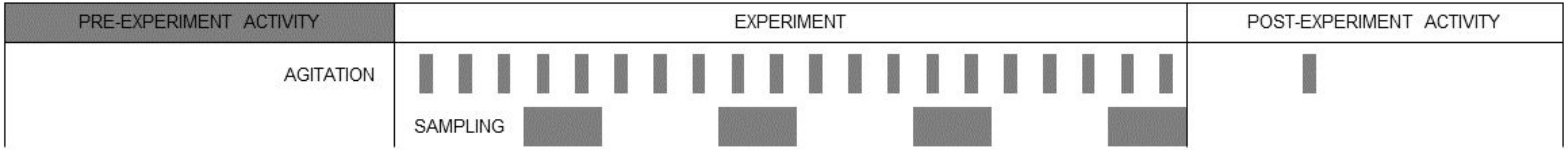


Modulate high-pressure gas flow to inject and disperse dust

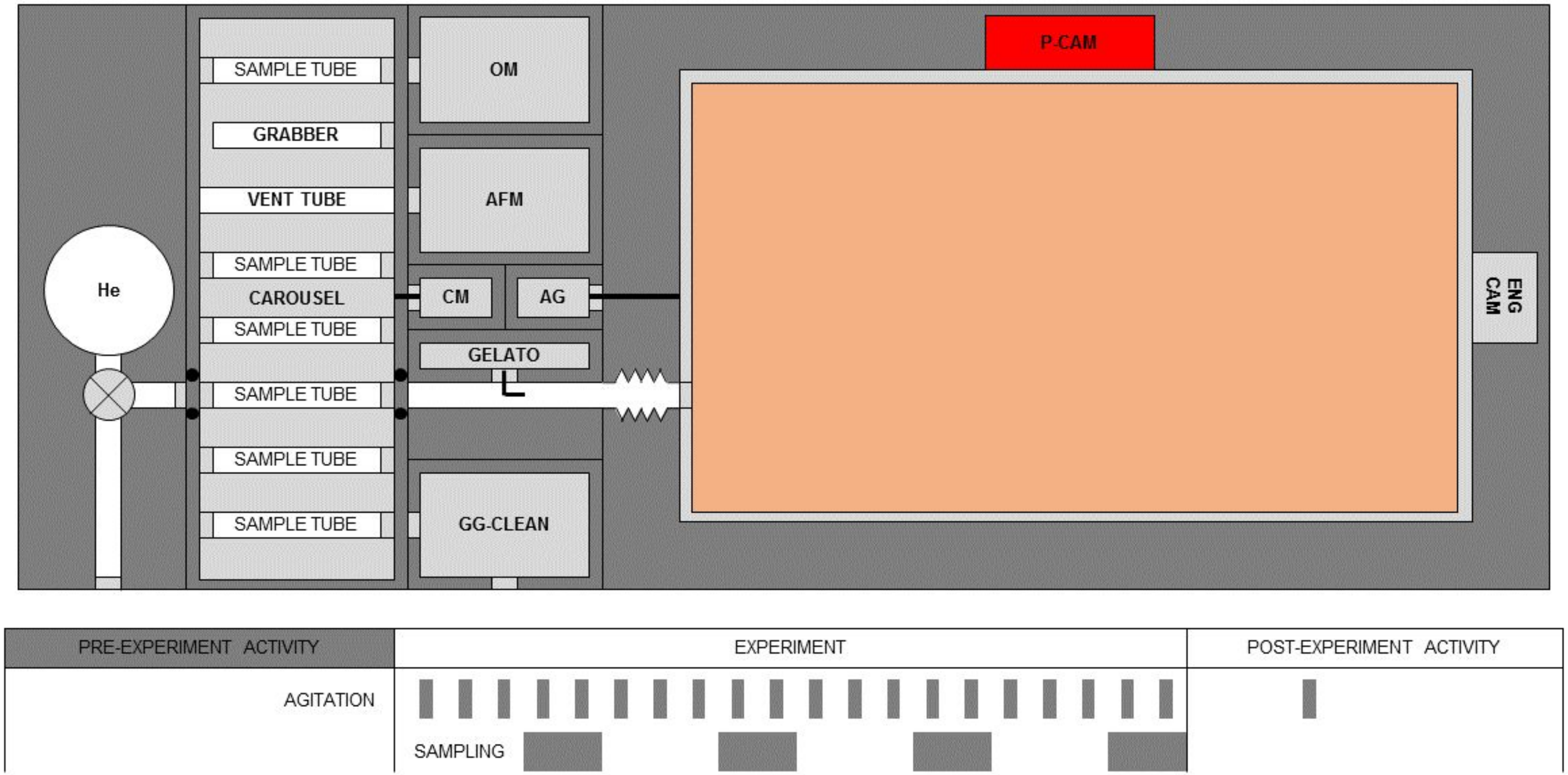


Close valves and wait for dust to disperse

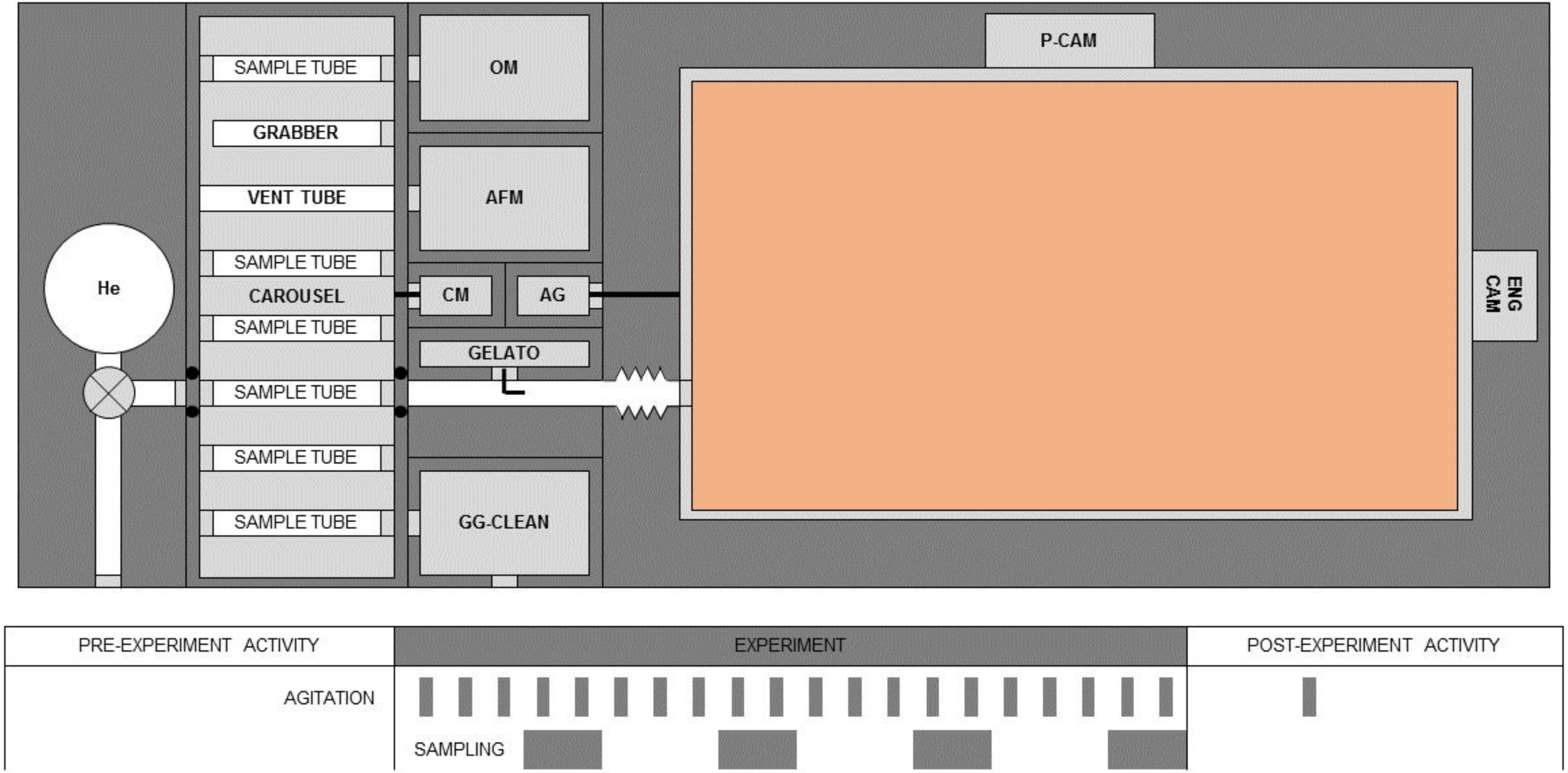




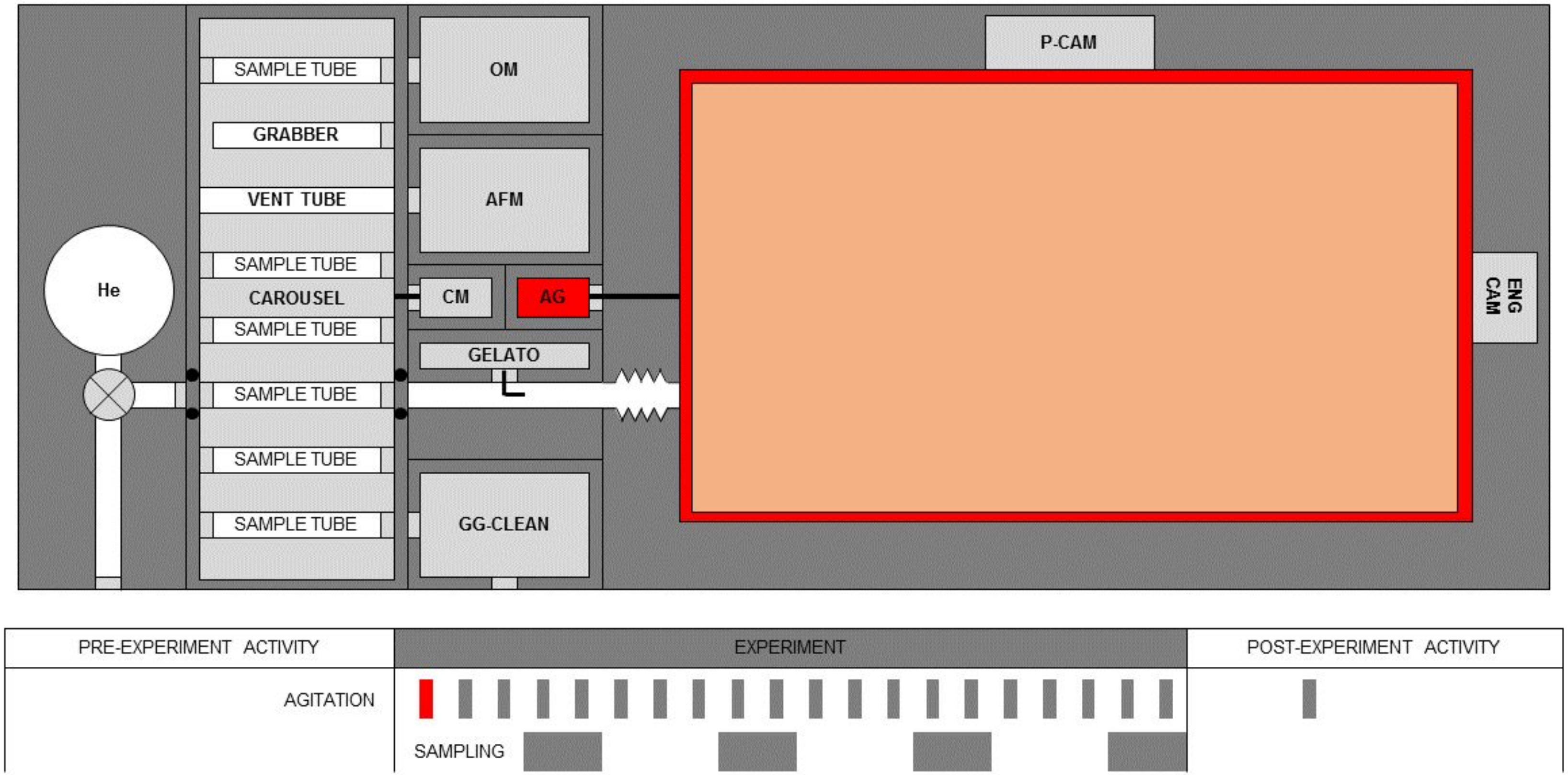
Start particle tracking cameras



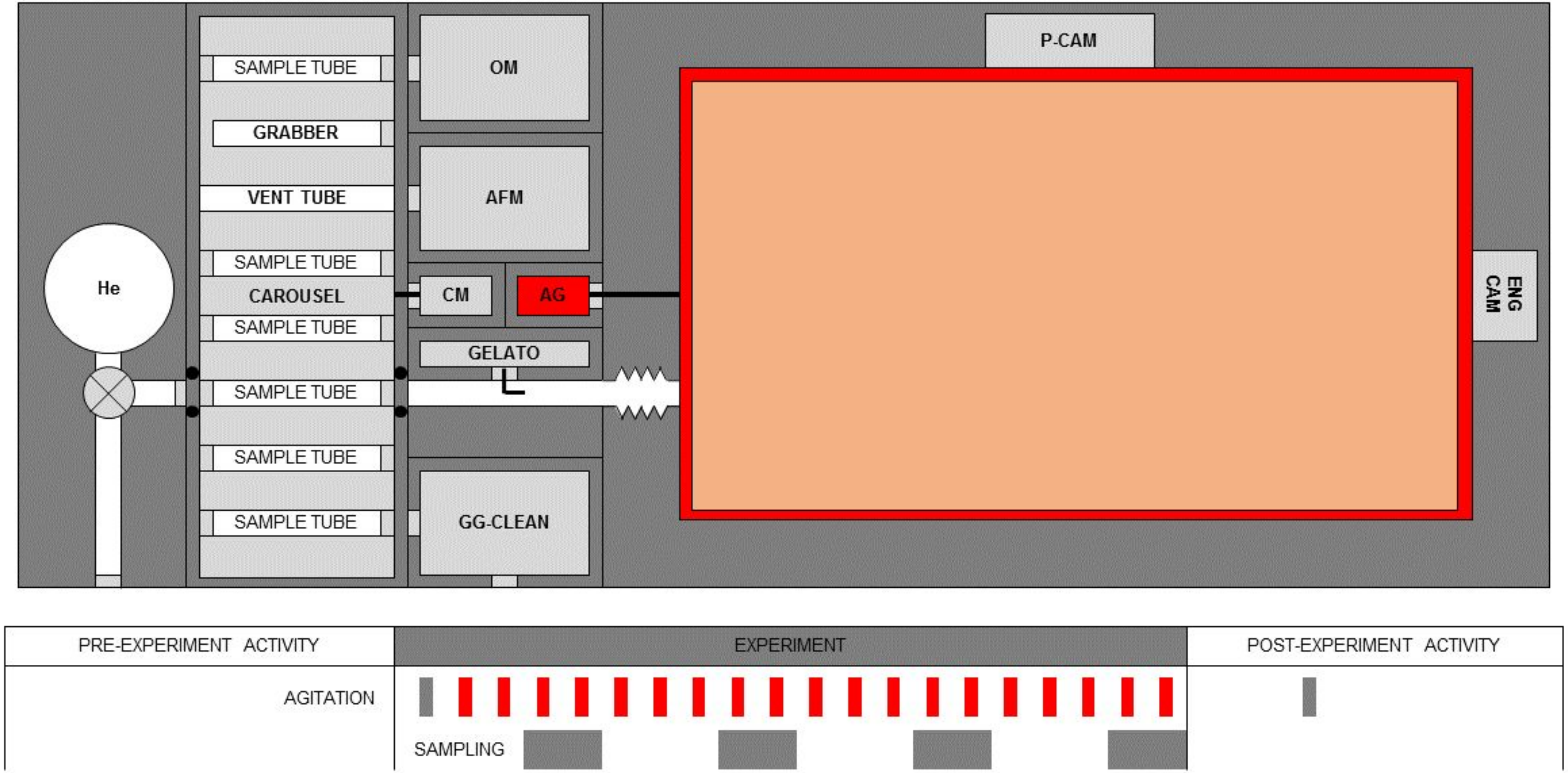
Start experiment clock. Record collisions using particle tracking cameras



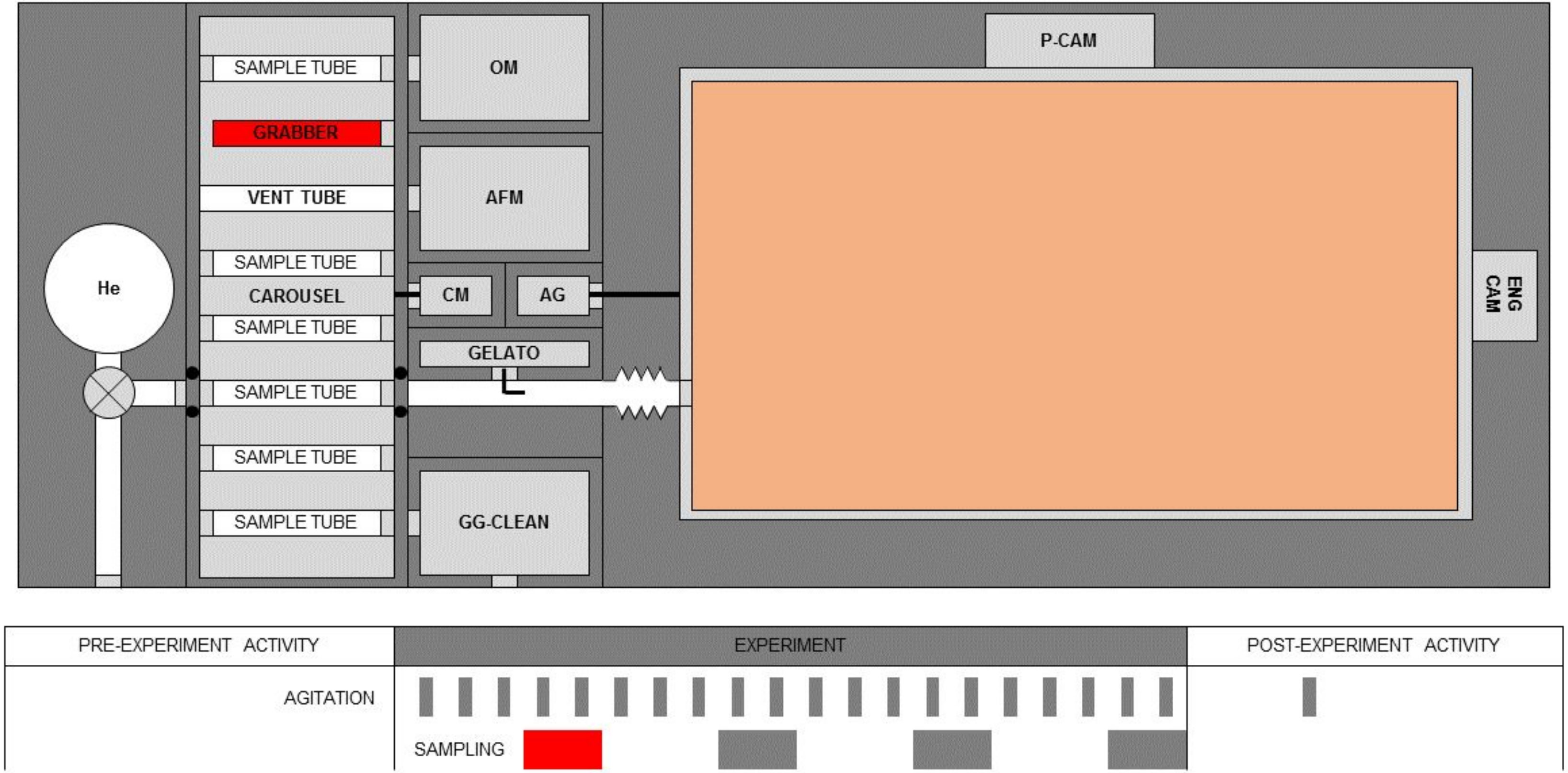
Agitate chamber using off-axis motor and low-amplitude resonator to release dust stuck to walls



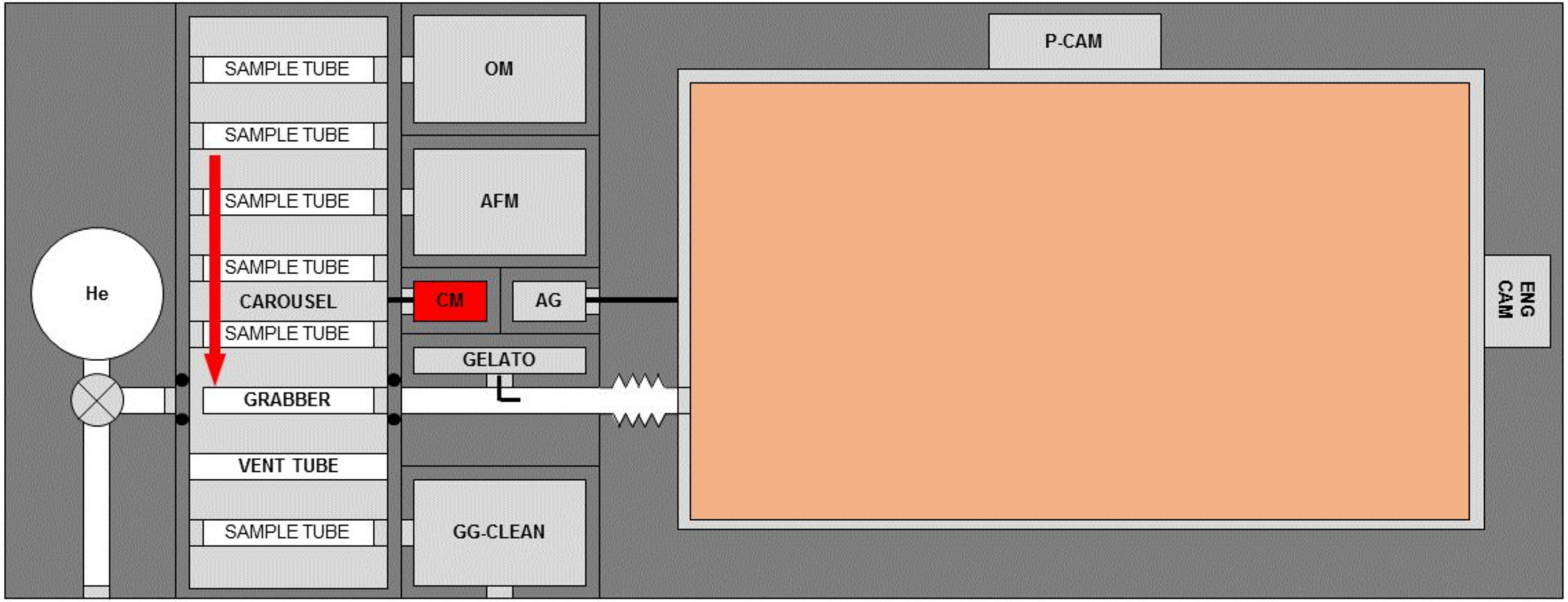
Agitations carried out periodically throughout experiment

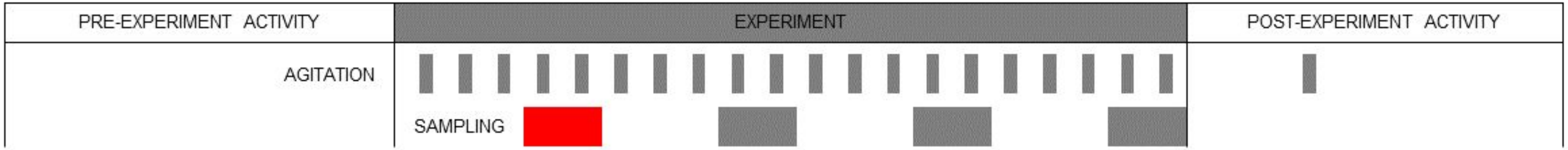


Pre-programmed sampling time reached. Identify position of grain grabber in carousel.

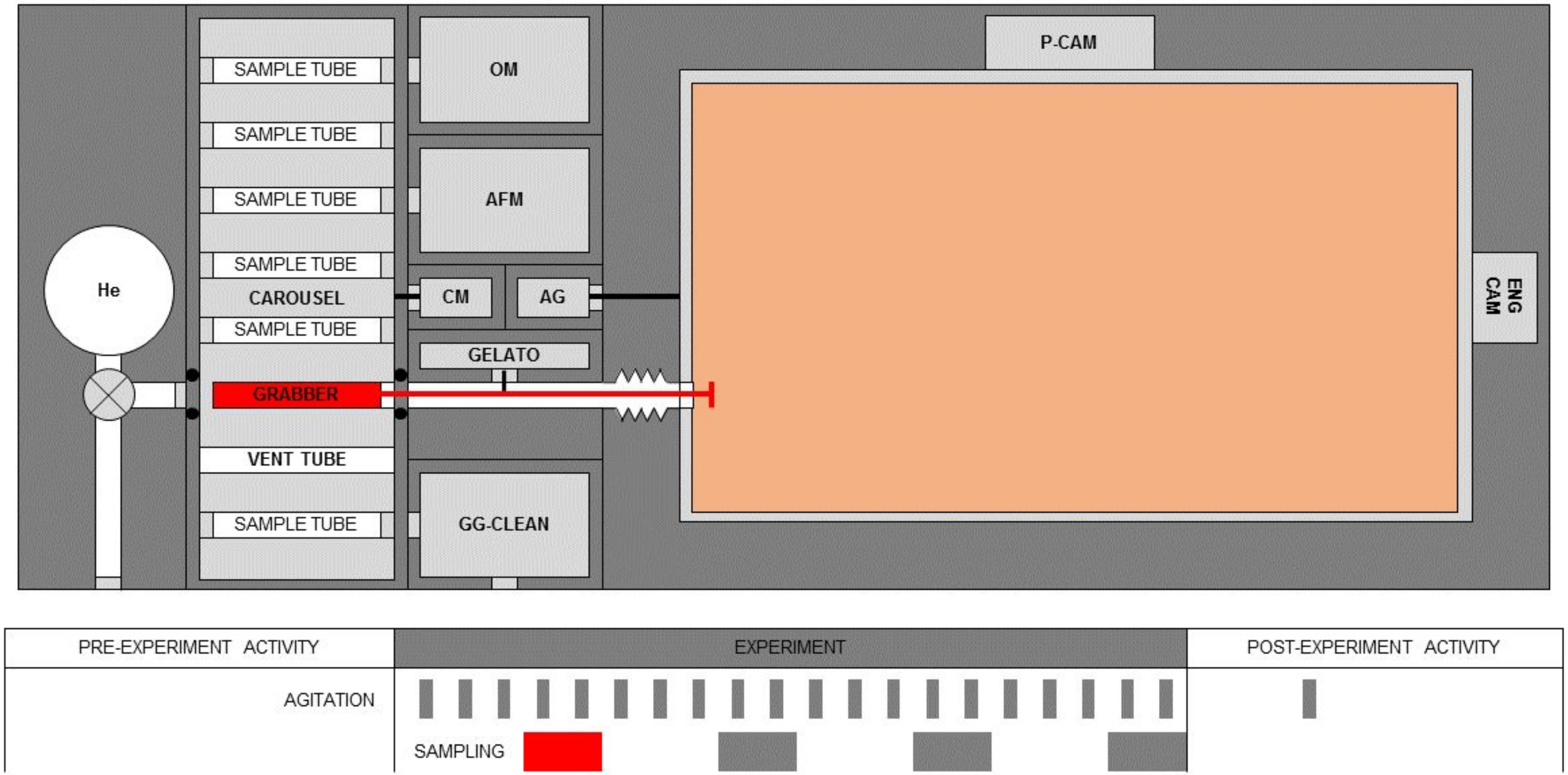


Rotate carousel to align grain grabber with injection port

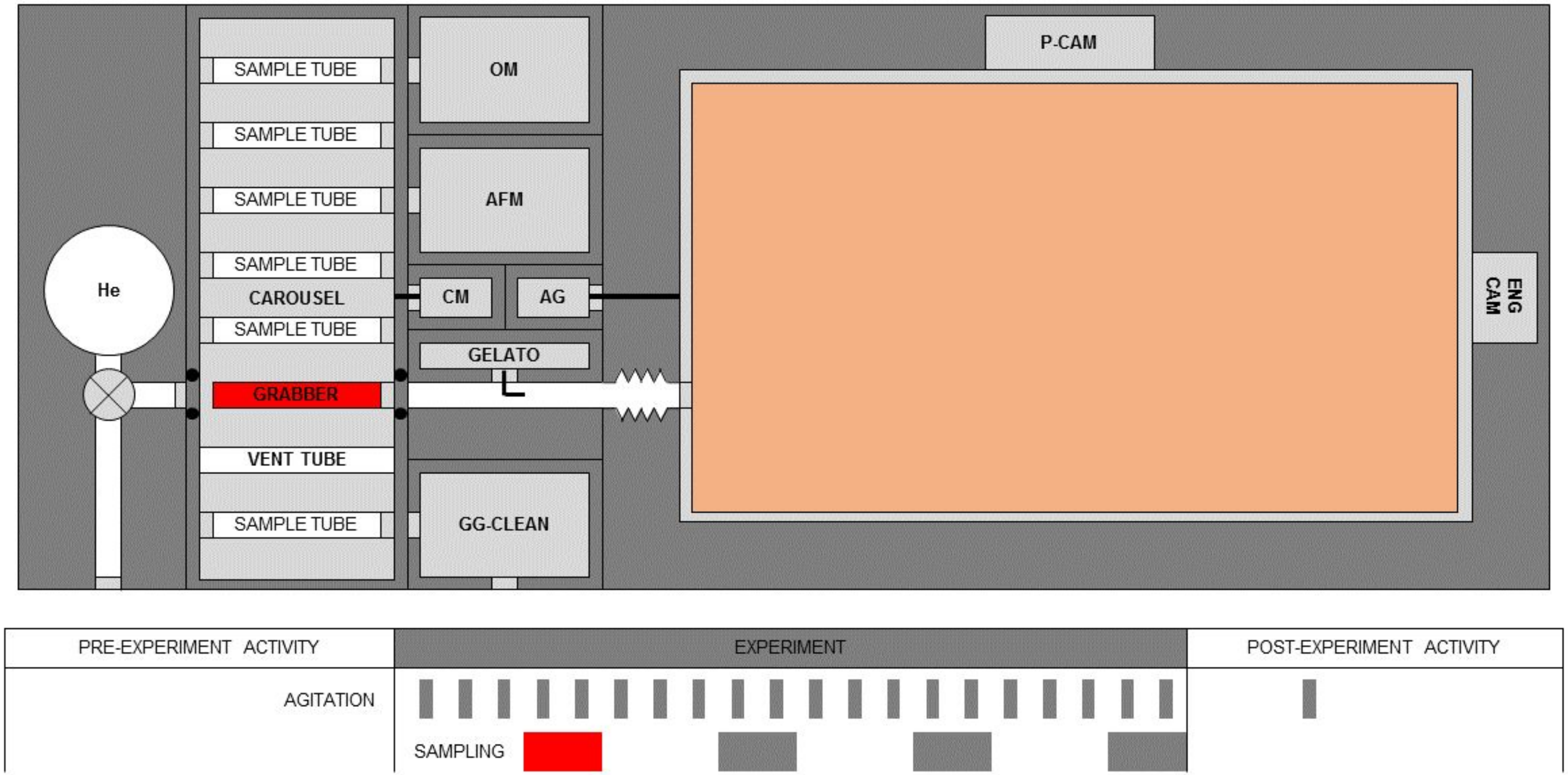




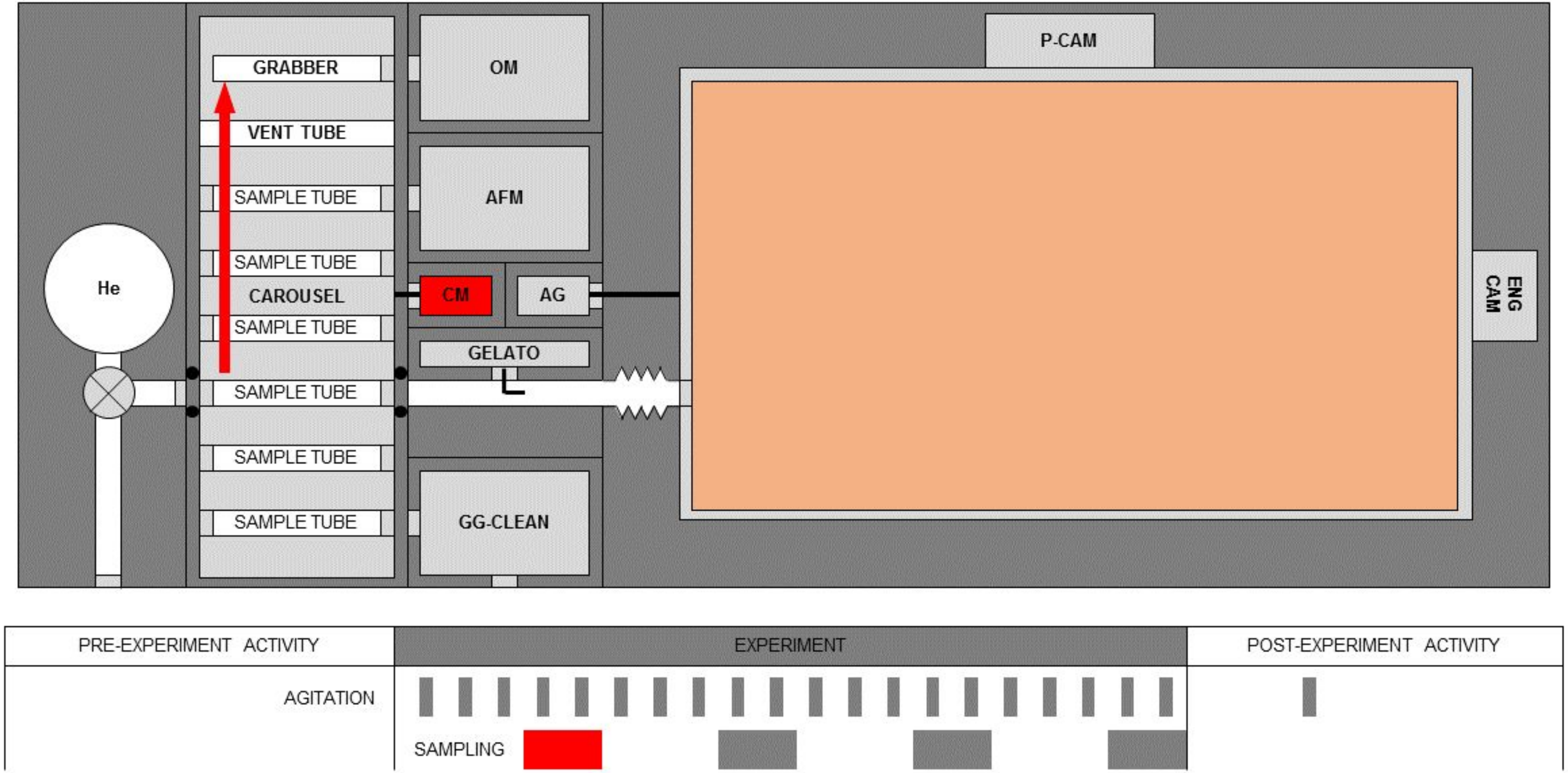
Extend grain grabber on linear telescopic actuator to sample grains



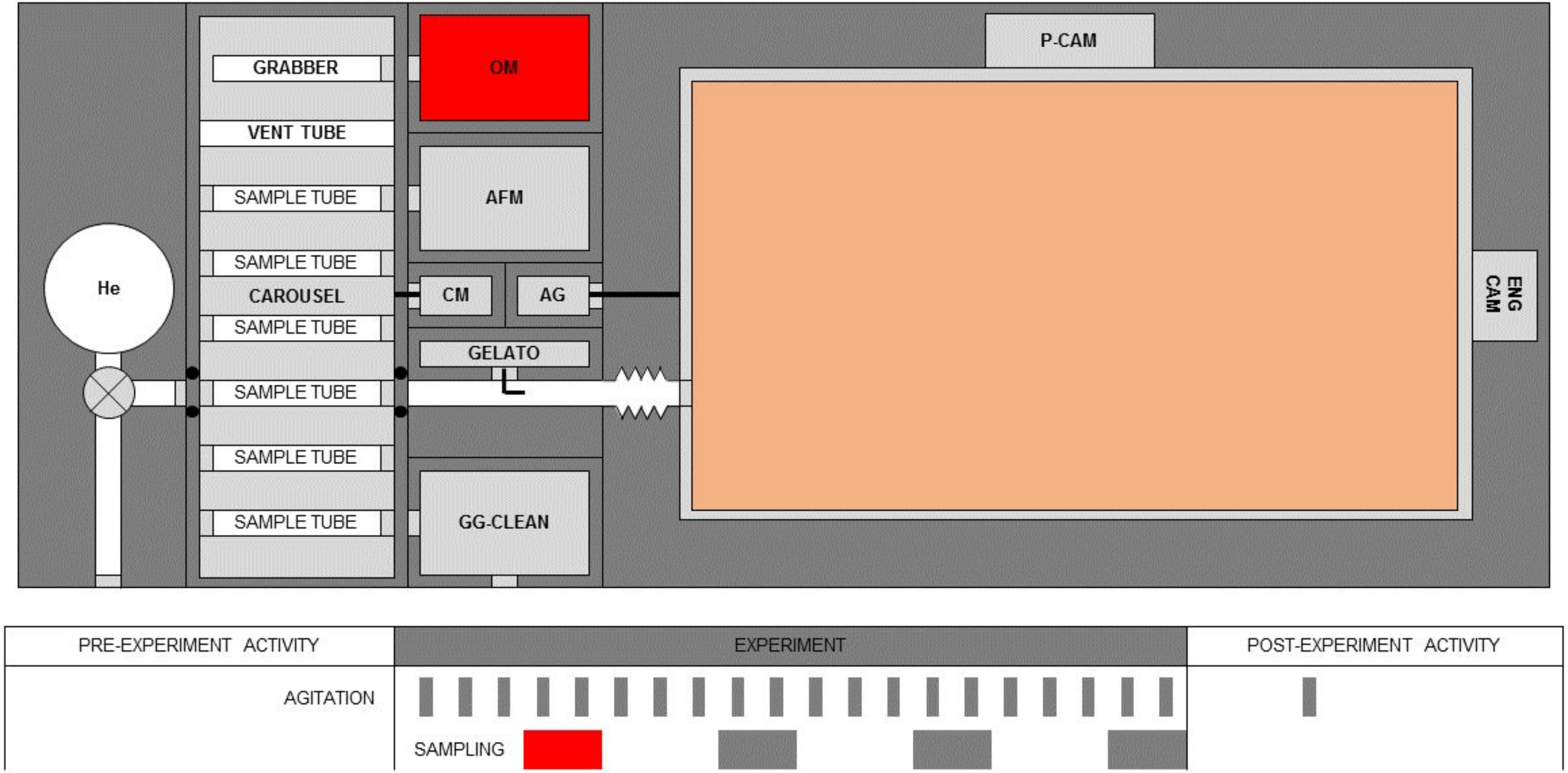
Retract grain grabber head back into carousel with dust grains attached



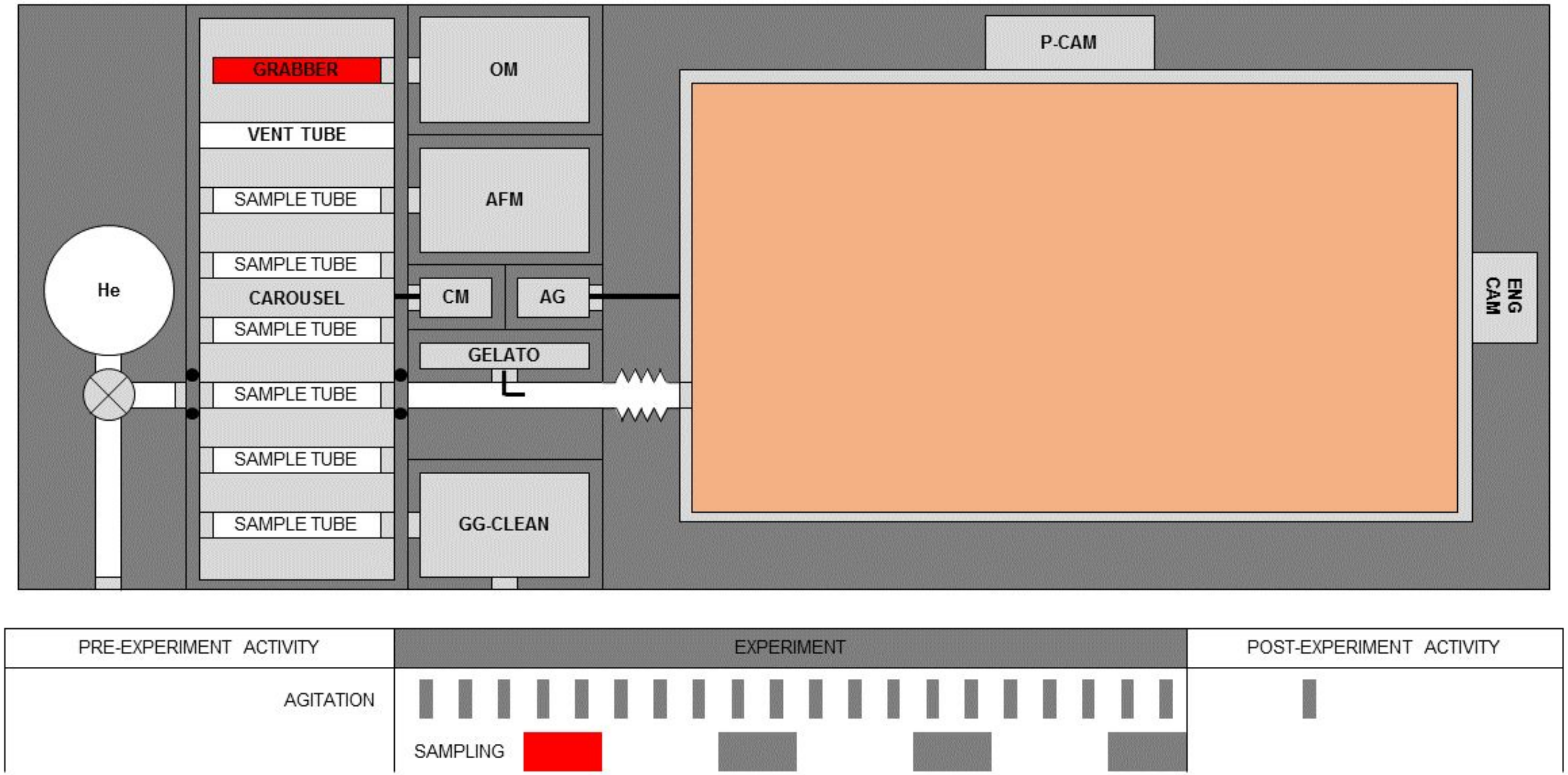
Rotate grain grabber to align head with optical microscope



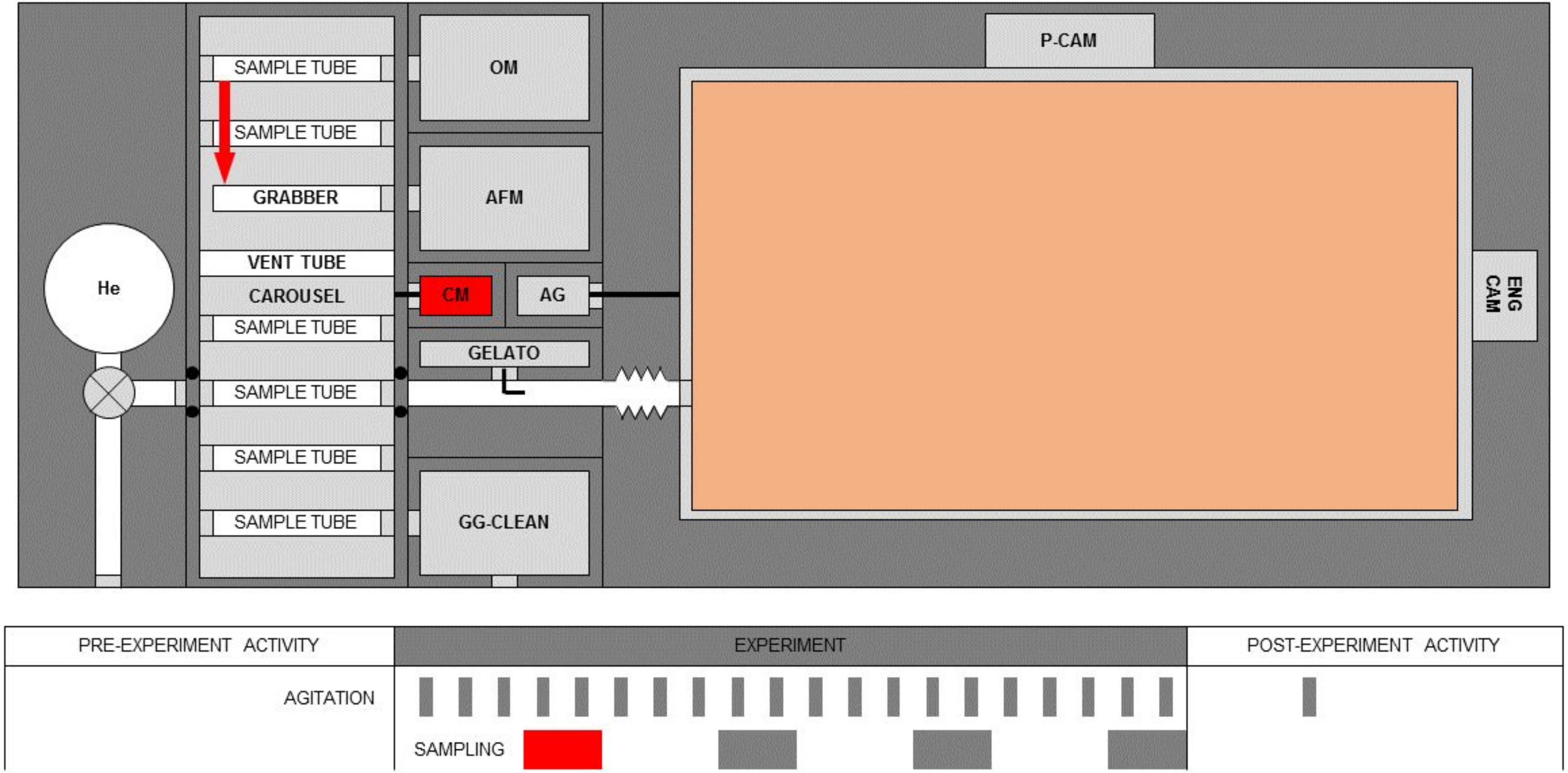
Inspect grains at close range using optical microscope (OM)



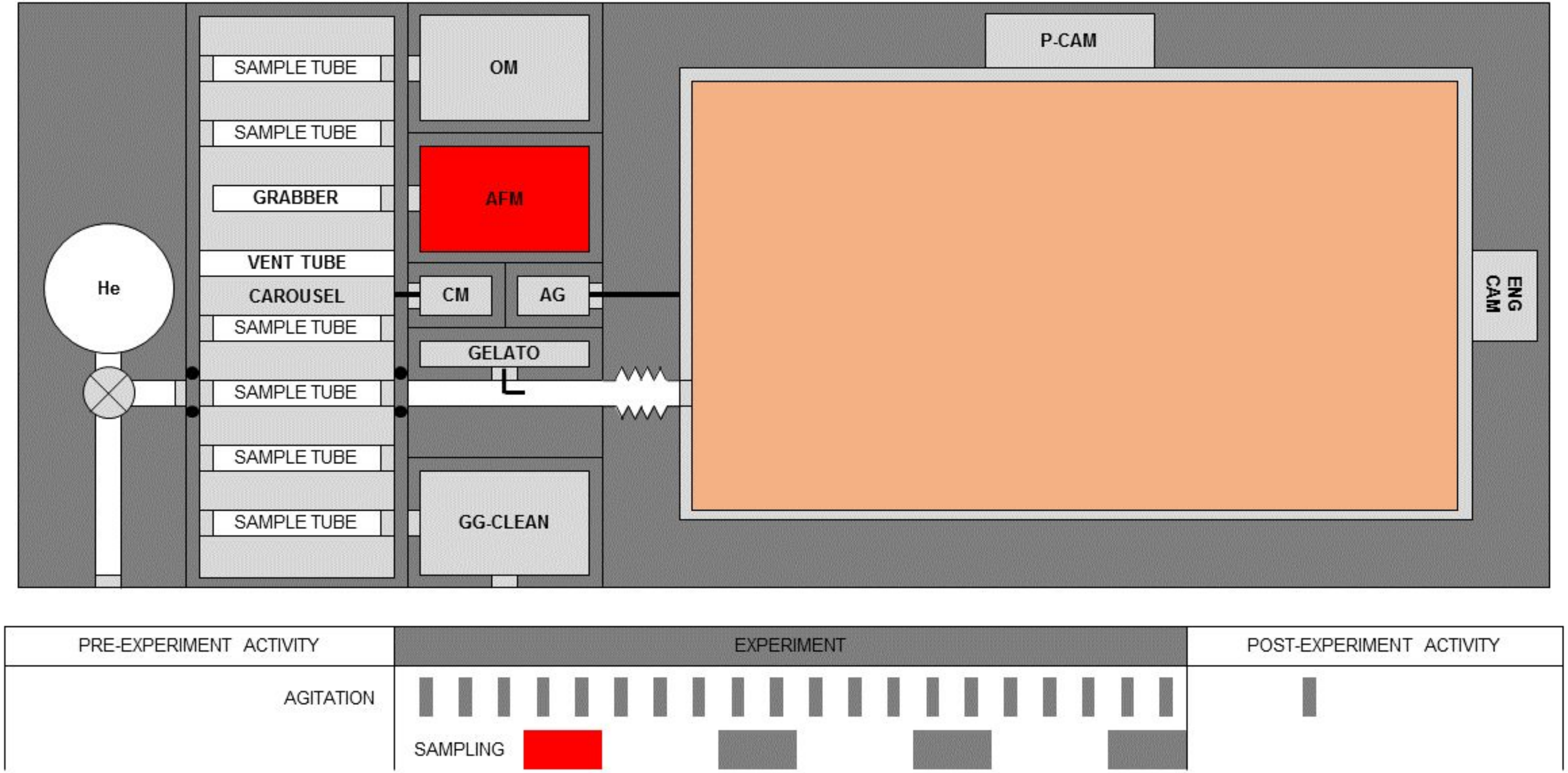
Rotate grain grabber to align head with Atomic Force Microscope (AFM)



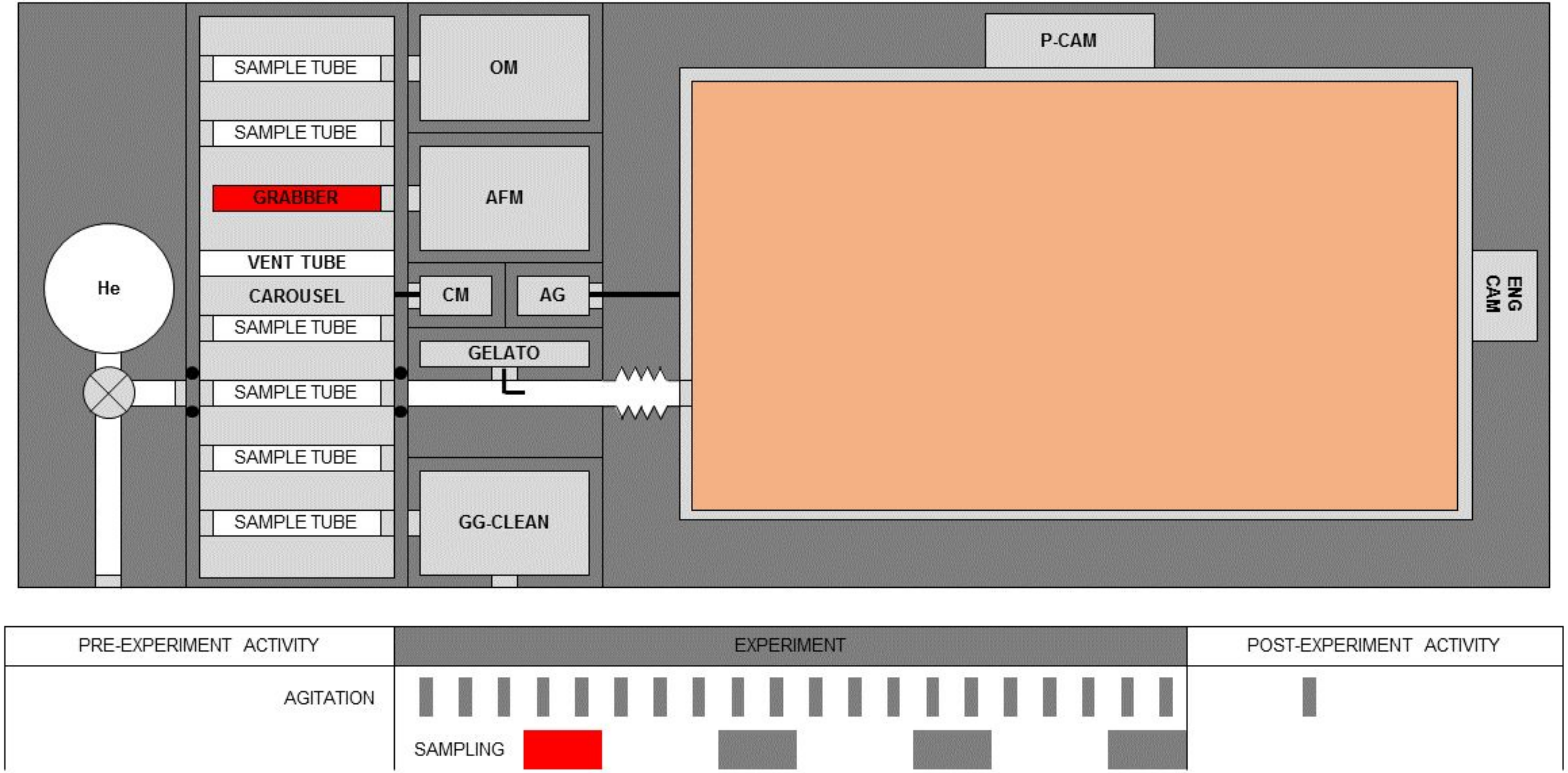
Rotate grain grabber to align head with Atomic Force Microscope (AFM)



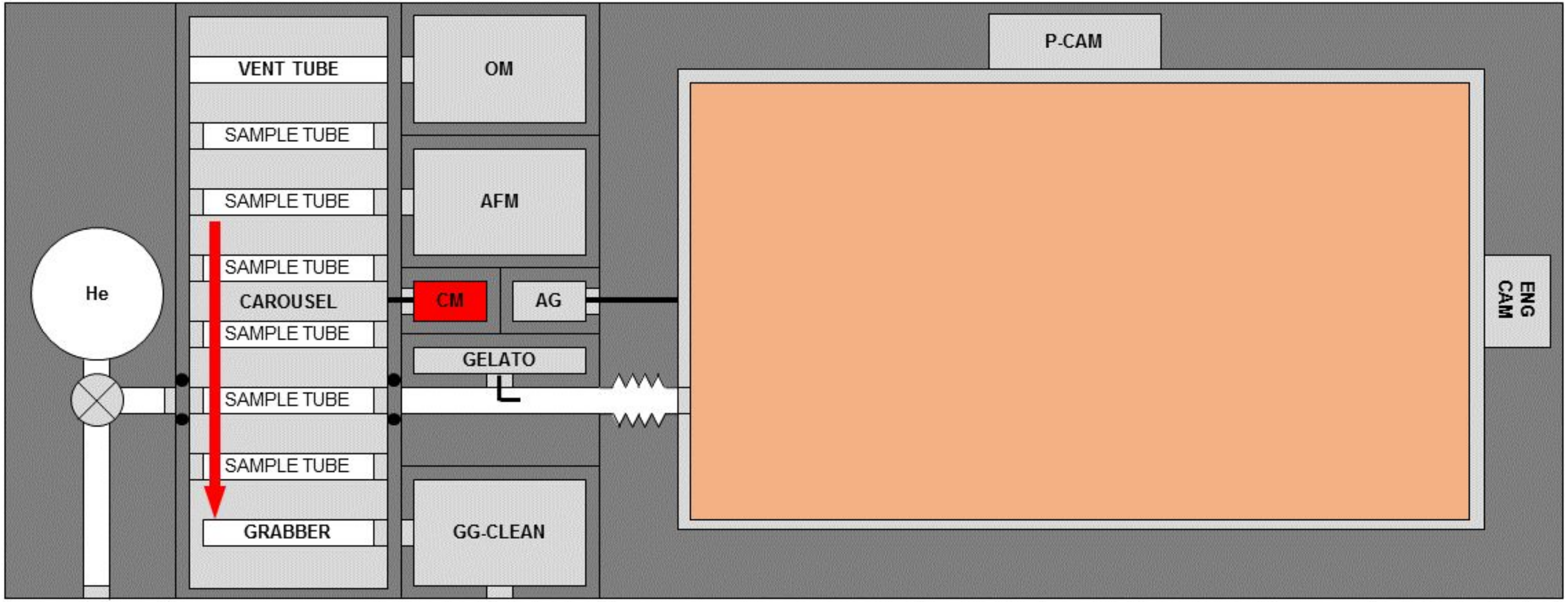
Inspect grains at close range using Atomic Force Microscope (AFM)



Rotate grain grabber to align head with Grain Grabber Cleaner (GG-CLEAN)

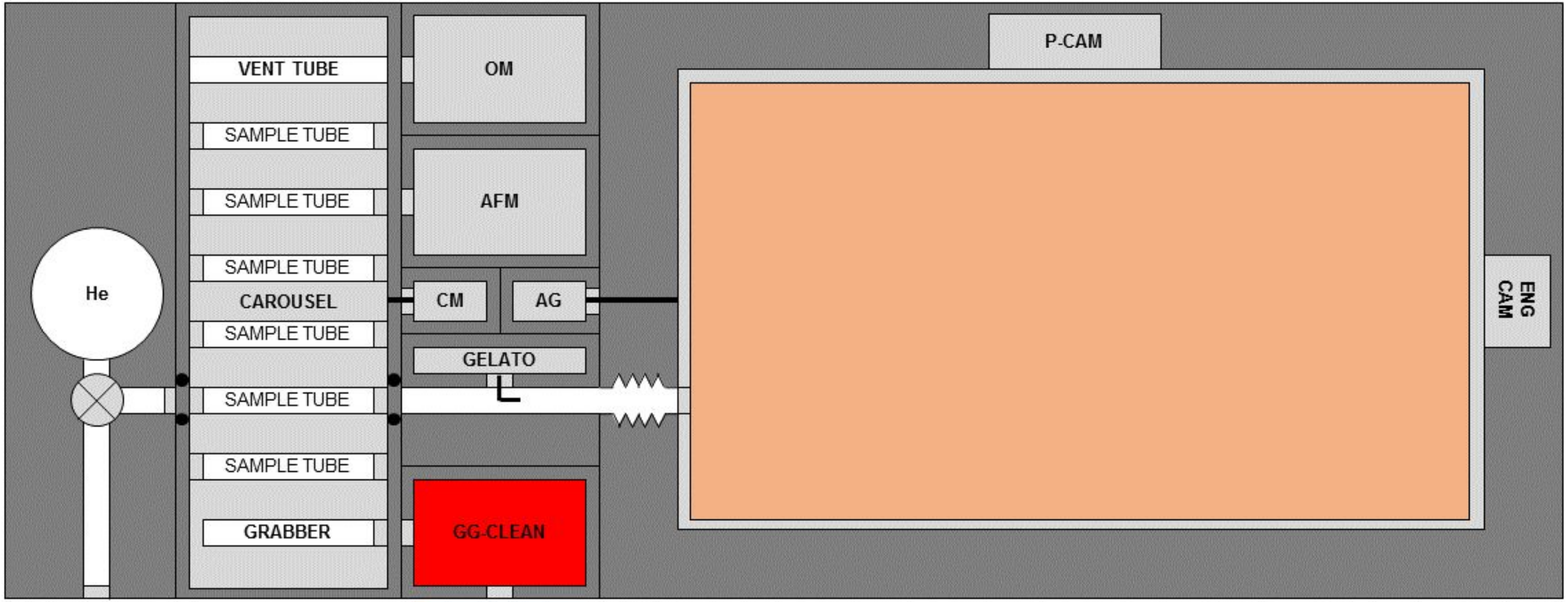


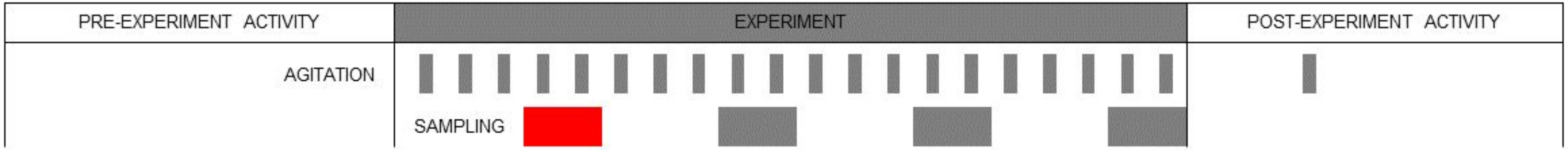
Rotate grain grabber to align head with Grain Grabber Cleaner (GG-CLEAN)



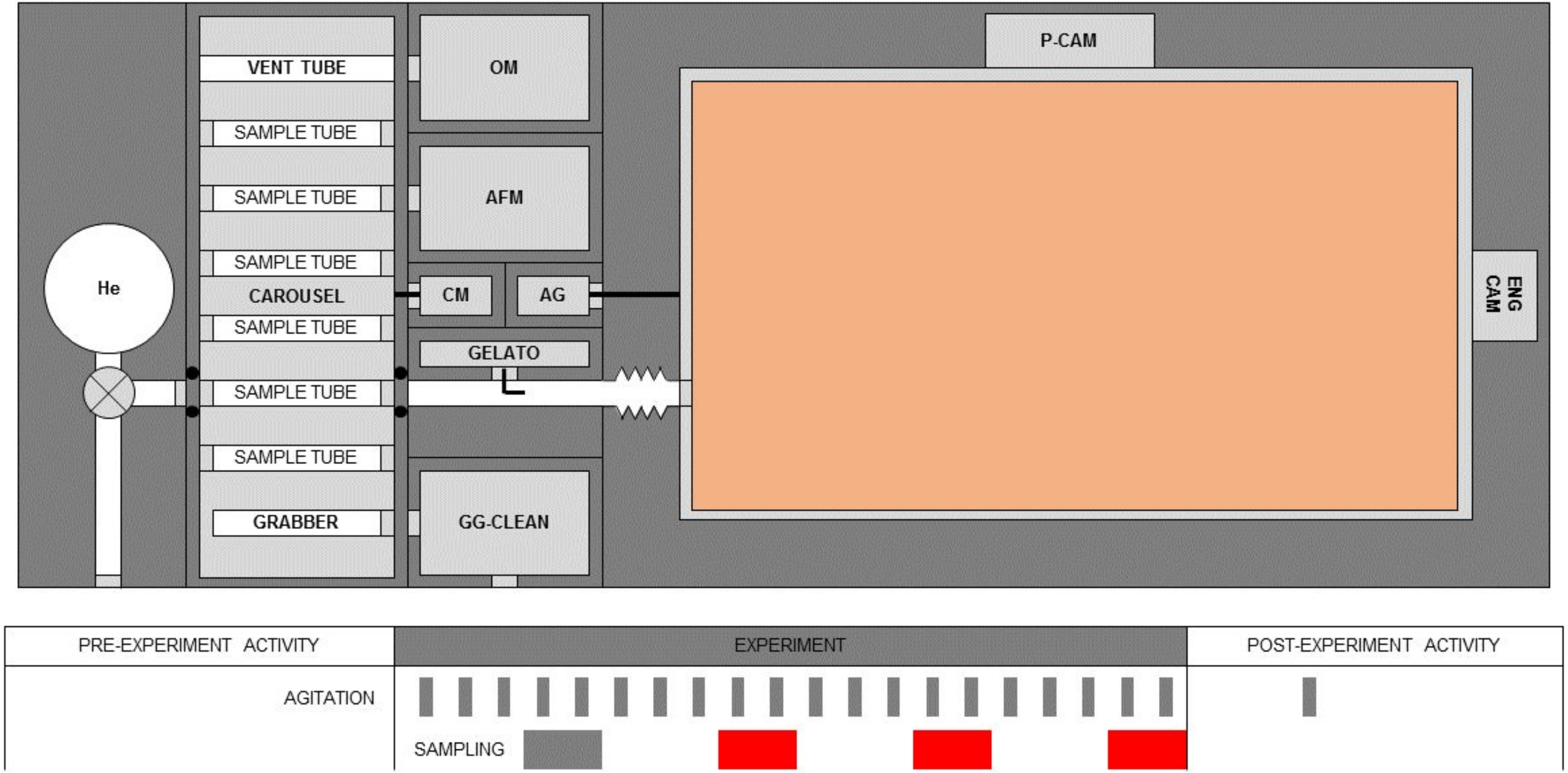
PRE-EXPERIMENT ACTIVITY	EXPERIMENT	POST-EXPERIMENT ACTIVITY
AGITATION		
	SAMPLING	

Clean grain grabber head and expel particles to vacuum

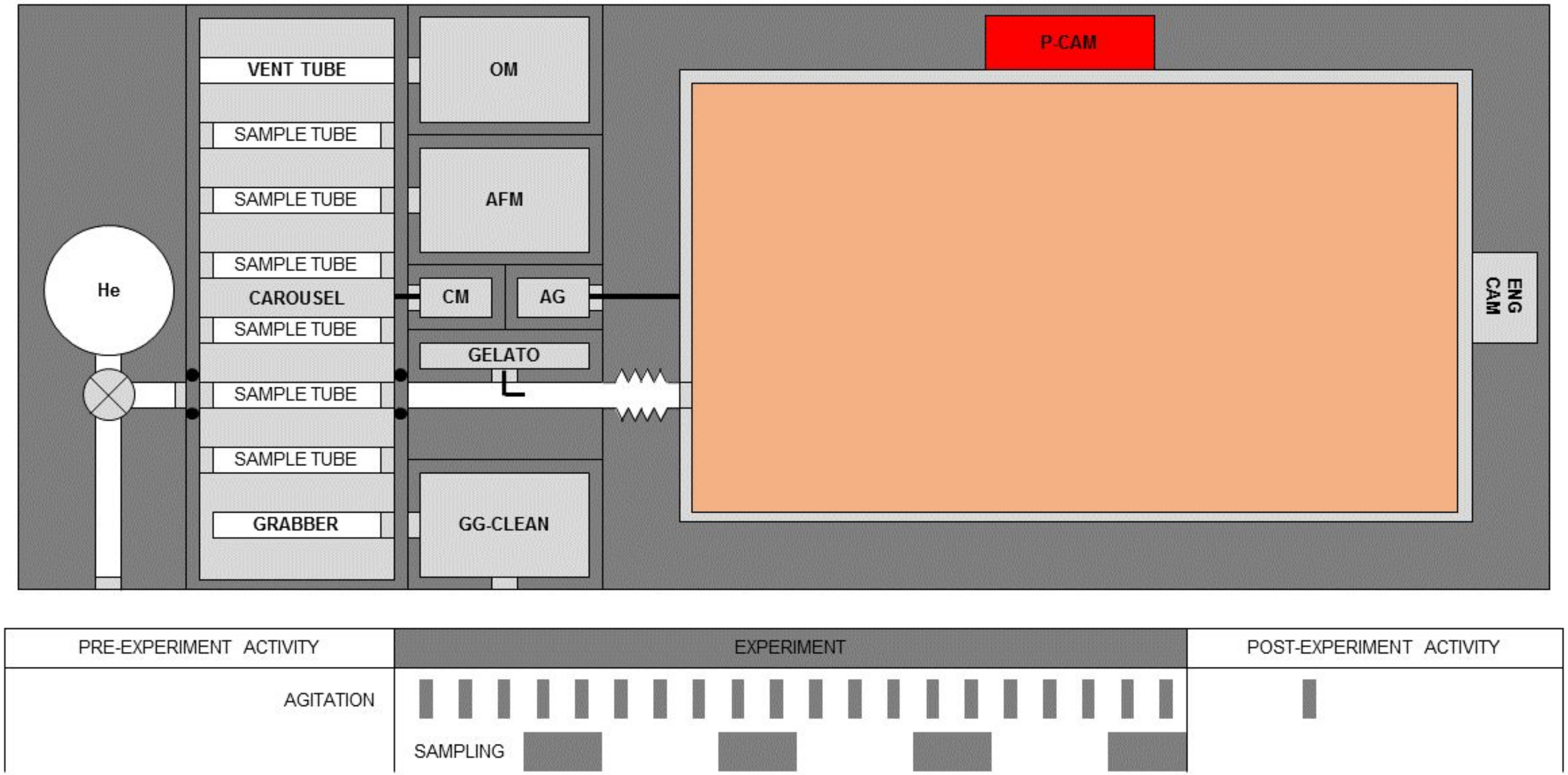




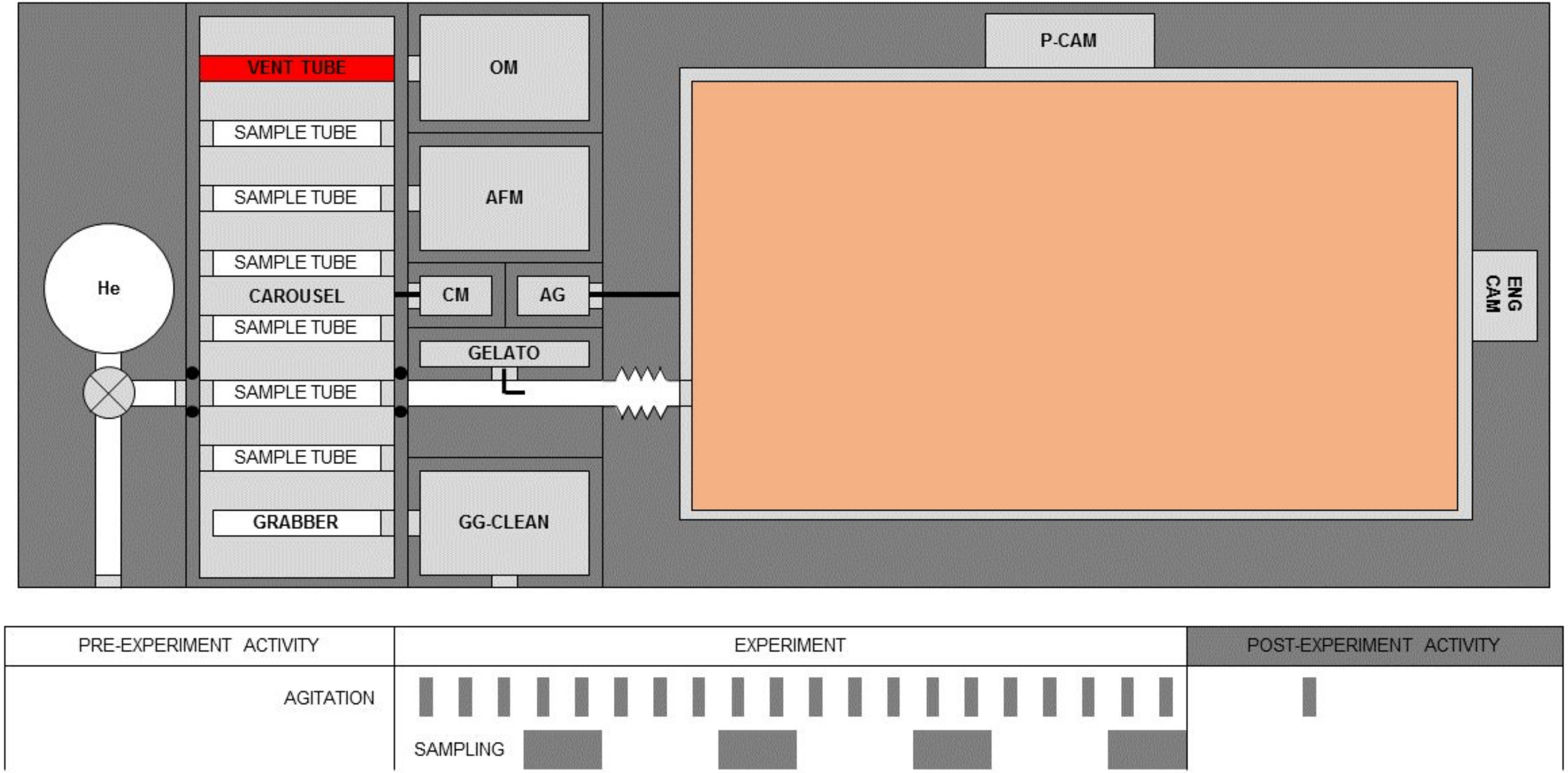
Repeat sampling periodically throughout experiment. GG cleanliness can be inspected using OM.



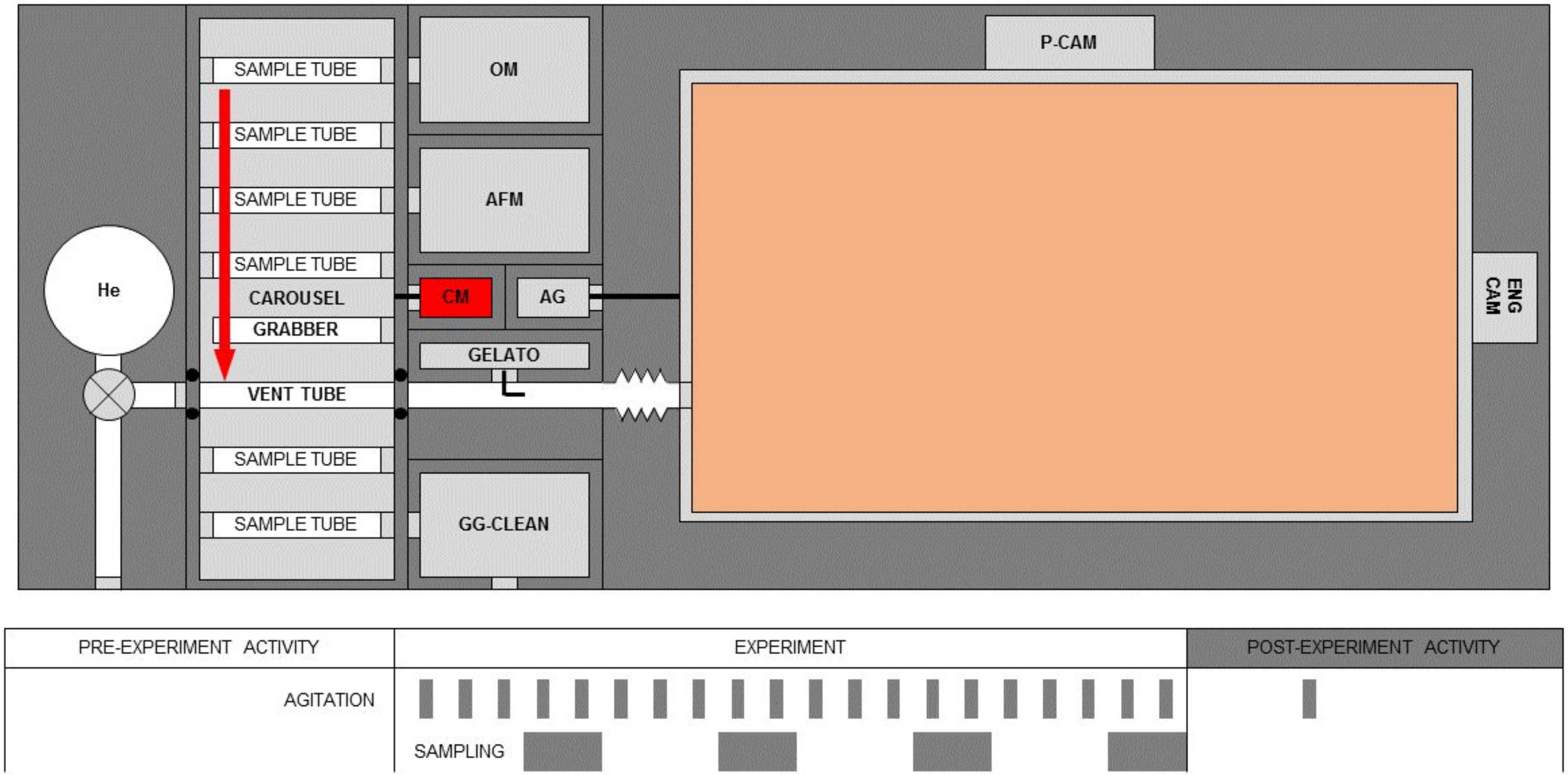
When target number of collisions reached, or experiment timeout, stop particle tracking cameras



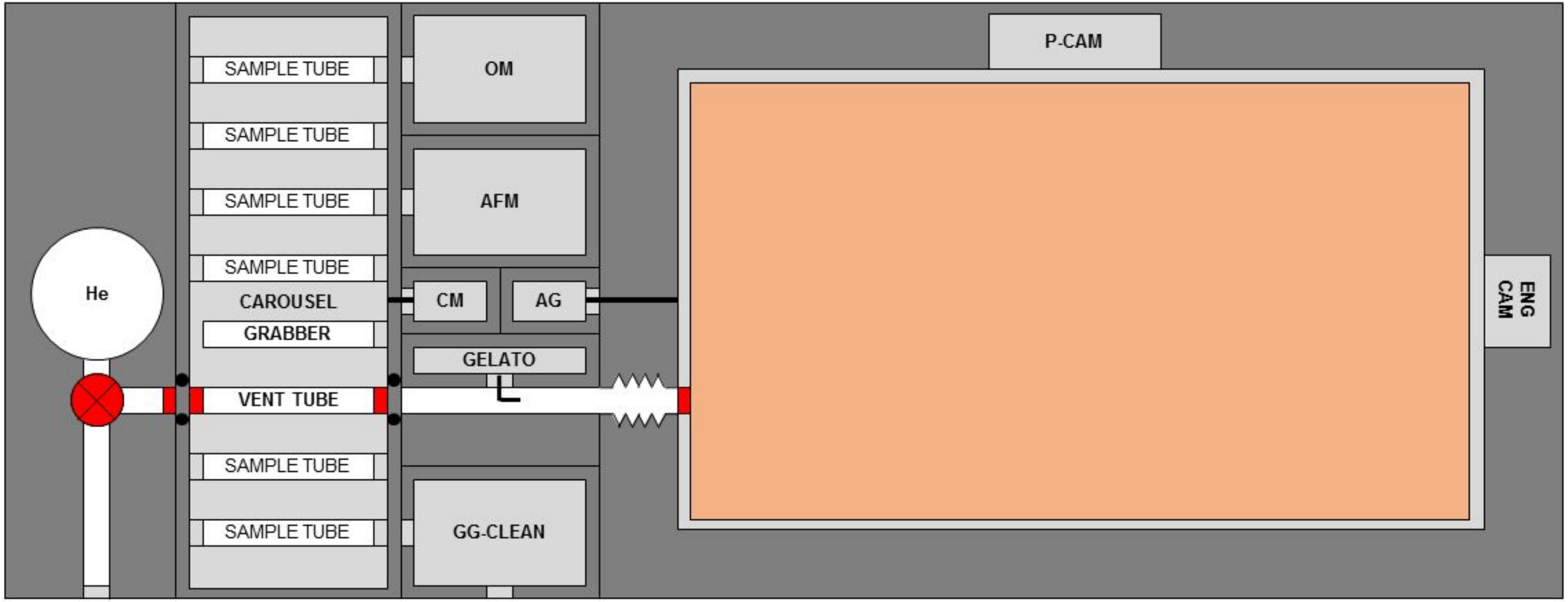
Rotate carousel to align vent tube with injection port

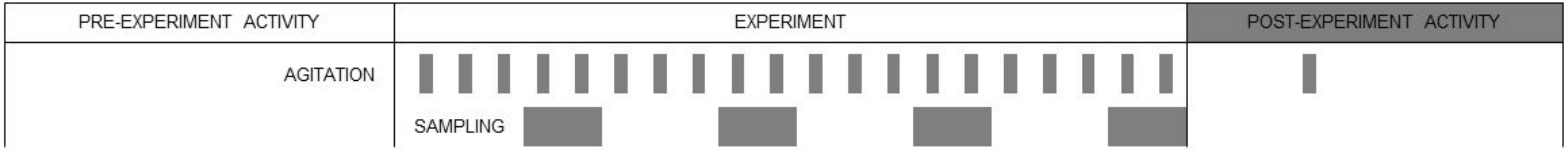


Rotate carousel to align vent tube with injection port

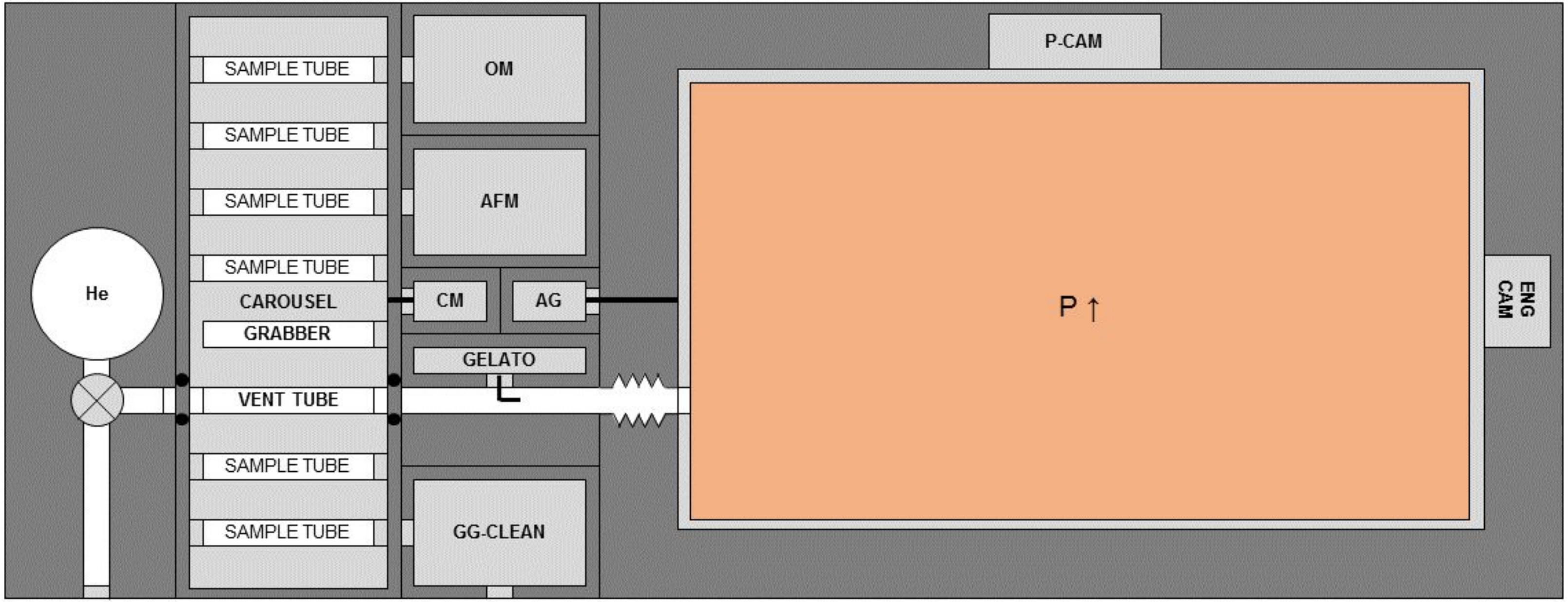


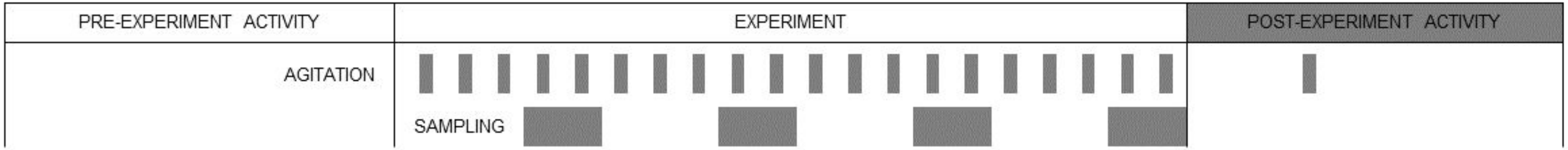
Open vent valves



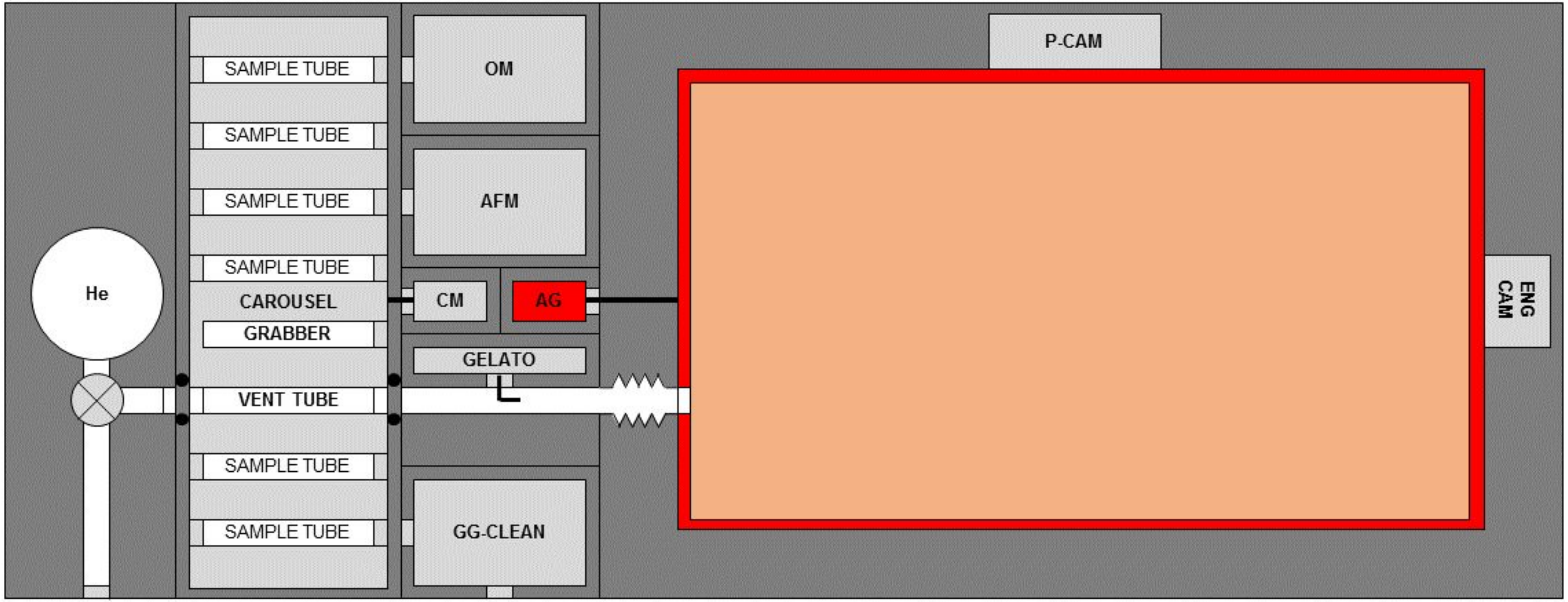


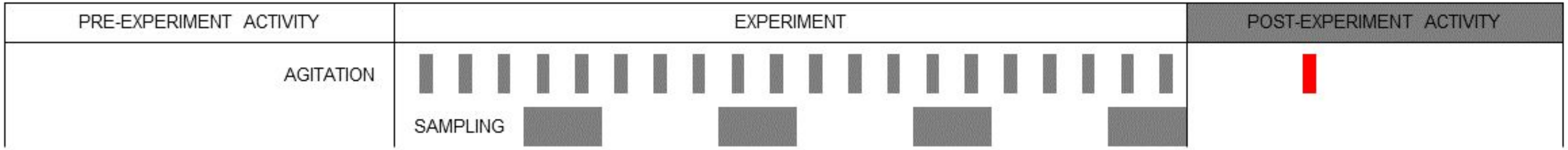
Let gas into chamber to achieve desired overpressure for dust ejection



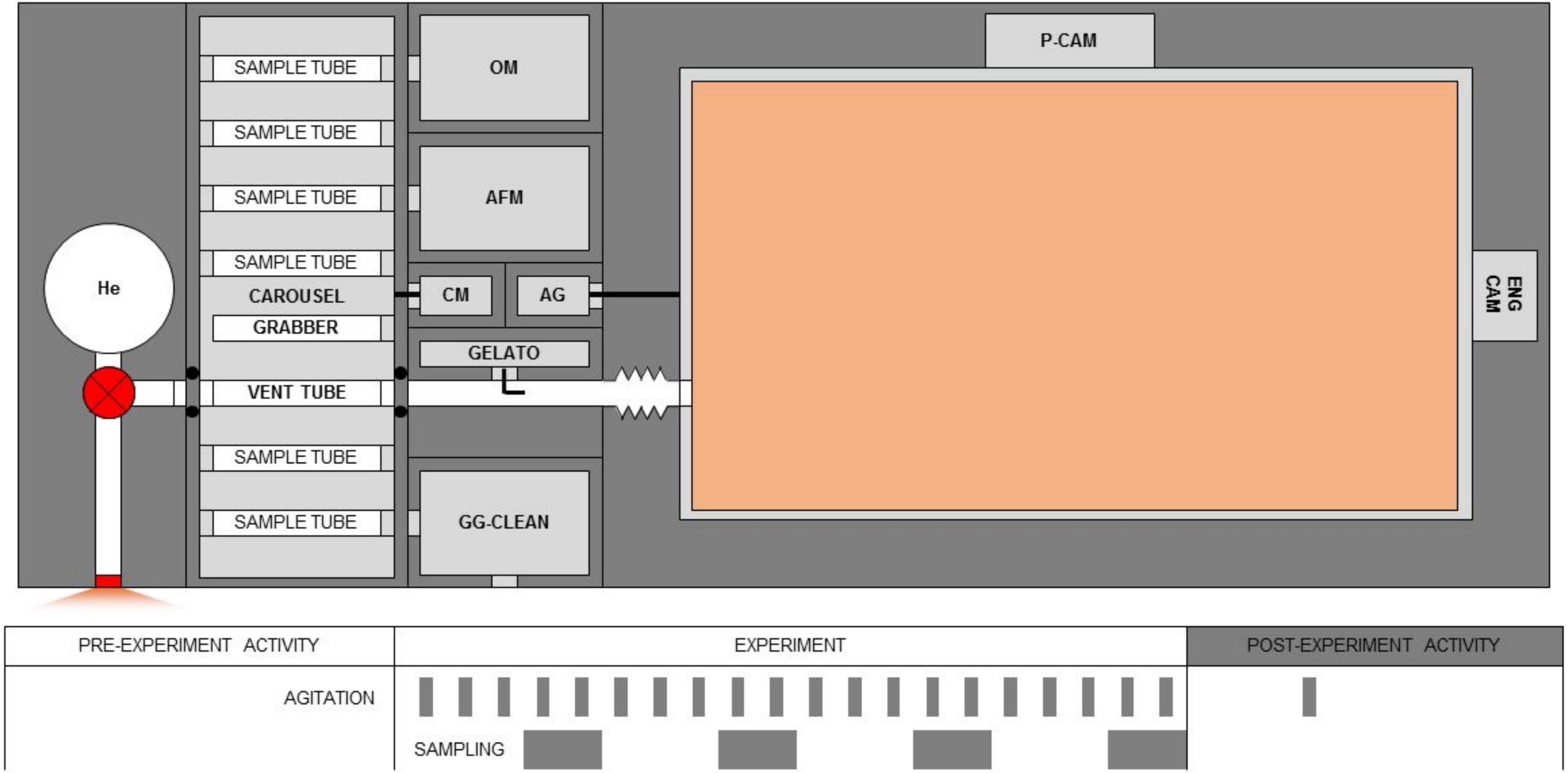


Agitate volume to release any dust stuck to walls

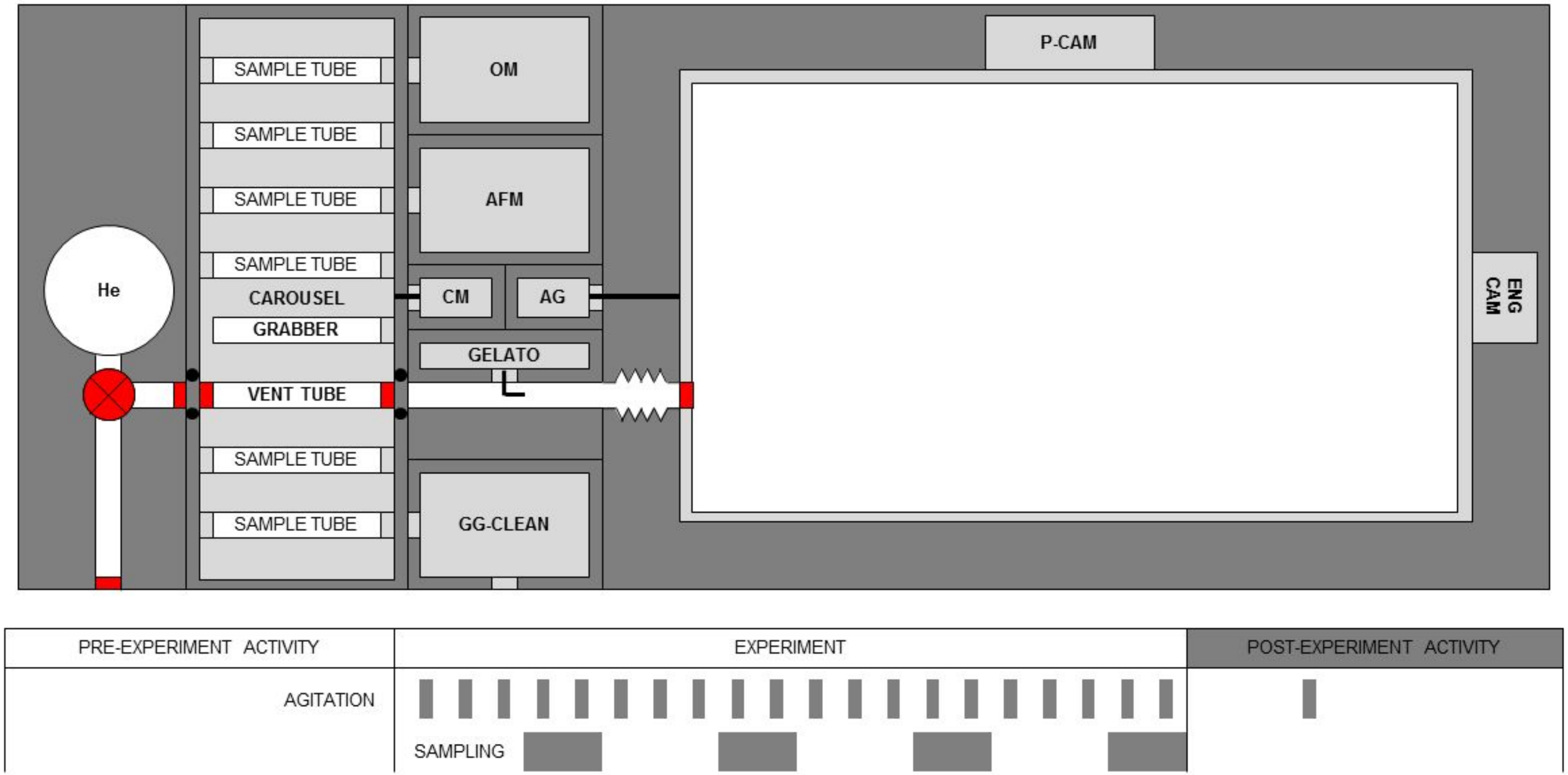




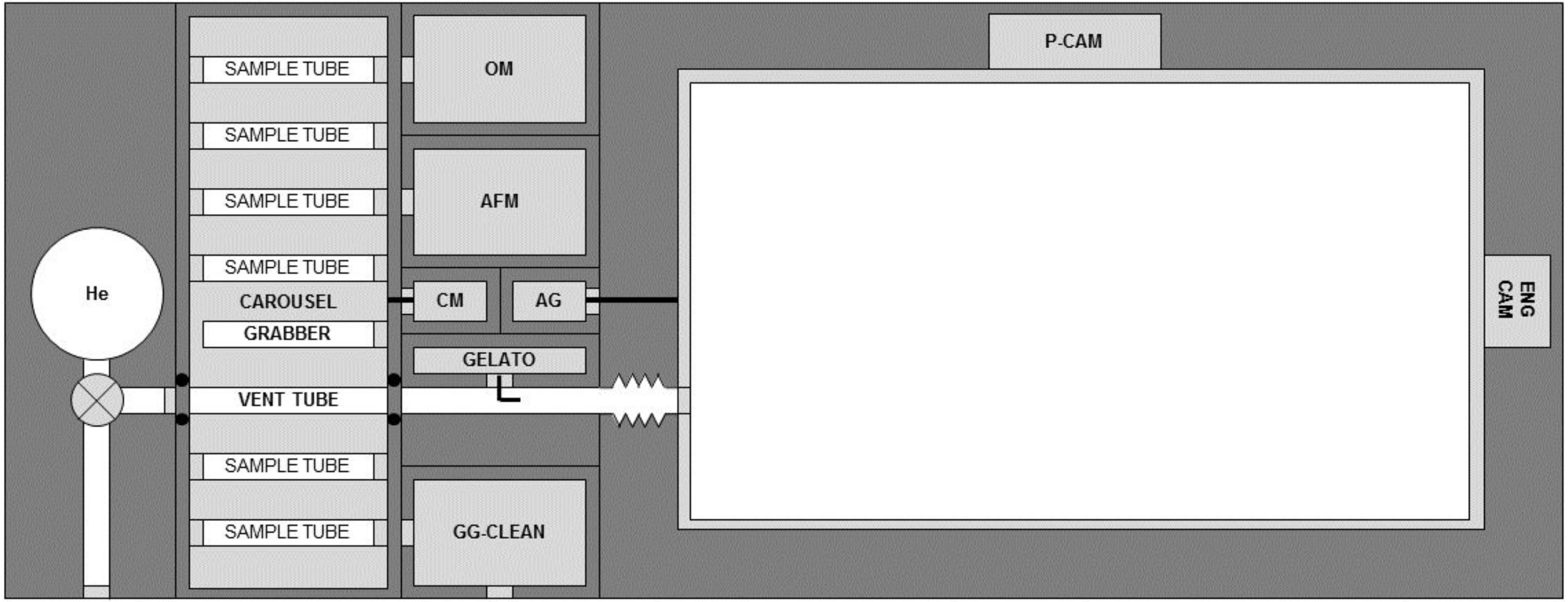
Modulate gas flow to vent dust to vacuum. Repeat as required.

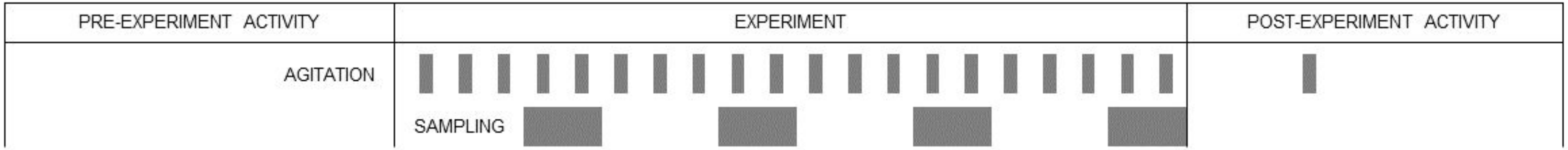


Close valves



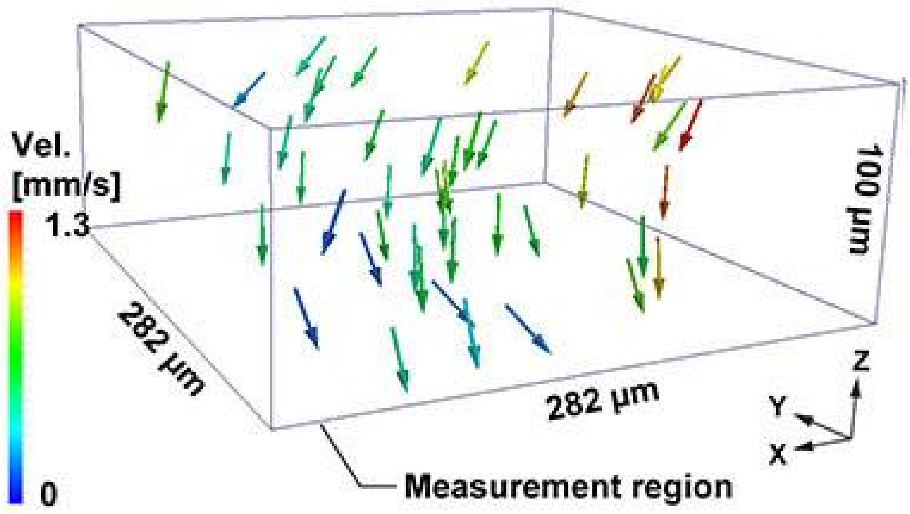
Ready for next experiment





On-board data processing

Data type	Maximum data generation rate (Mb s^{-1})
Raw	
Total raw data	**42000**
After processing	
Particle velocities	8
Particle rotation rates	9
Particle images	0.3
Total after processing	**17**



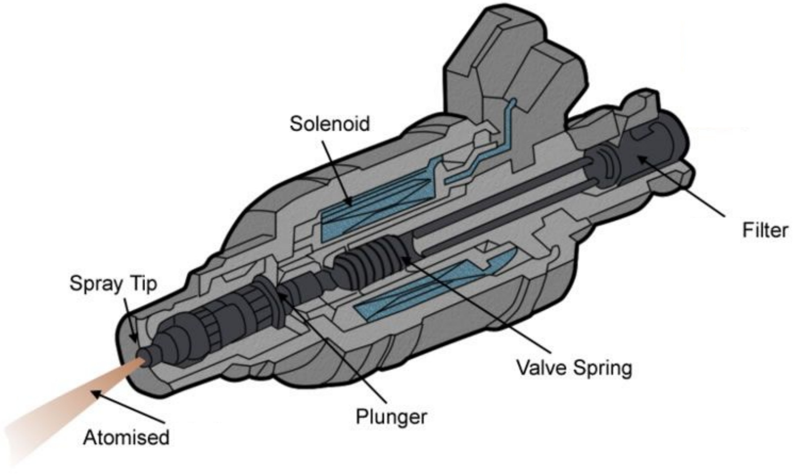
Key technology development plan - Grain Grabber

SKF

PI Motion Position

- Current TRL: 2
- Function
  - Collect sample
  - Hold samples
- Requirement
  - Reusability
  - Long stroke
- Solution
  - Linear actuator
  - Static charger
  - Piezo actuator (Curiosity heritage)
- Verification
  - Lab testing
  - Micro-g for grain adhesion

Key technology development plan - GELATO



- Current TRL: 2
- Function
  - Apply ice layer to dust particles
- Requirement
  - Diffuse gaseous H_2O
- Solution
  - Based on fuel injectors
  - Aerosol experiments
- Verification
  - Lab testing
  - Micro-g for grain adhesion

Key technology development plan - Carousel

Honeybee Robotics

- Current TRL: 2
- Function
  - Hold sample container
  - Rotate Grain Grabber
- Requirement
  - Hold multiple experiments
  - 1m radius
- Solution
  - Curiosity SAM module Heritage
  - Counter mechanism
- Testing:
  - Eath laboratory
  - Micro-G

Mission profile

Objectives, requirements, and drivers

Mission objectives

Achieve all planned science experiments

Downlink and analyse data on the ground

Main system drivers and mission requirements

- Long duration in microgravity
- Minimal external disturbances
- Thermal control
- Data rate

Detumble

- Stabilize
- Obtain attitude
- Deploy comms
- Deploy solar

Commissioning

- Eliminate rotation
- System check
- Initiate science

Experiment

- Release sample
- Take measurements
- Vent chamber

Housekeeping

- Reorbit
- Diagnosis

Launch

- Soyuz
- Sun-Synchronous
- 800 km
- Mass < 2t
- Shared ride possible.

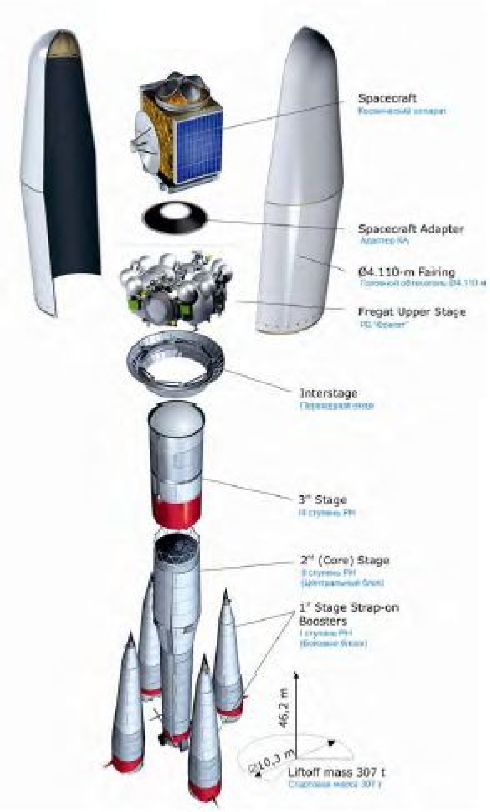
Transit

- Env. conditions on launch

Pre-flight

- Prepare grain canisters

Launcher and transfer



Launch Vehicle: Soyuz
Target: SSO 800 km
Launch Base: Guiana Space Center

Orbit	Altitude	Inclination
Injection	785 ± 12 km	98.6° ± 0.12°
Target	800 km	98.6°

Orbit

Launch site: Guyana Space Center

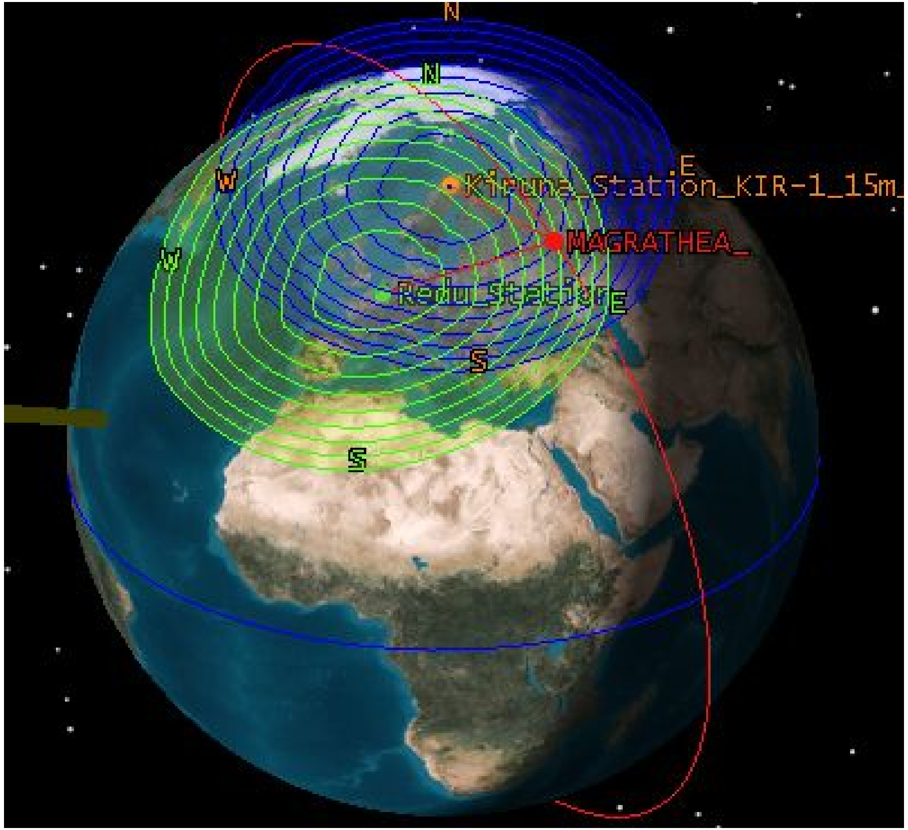
Orbit type: Sun-synchronous

Altitude: 800 km

Inclination: 98.6°

RAAN: 6:00 pm RADN: 6:00am

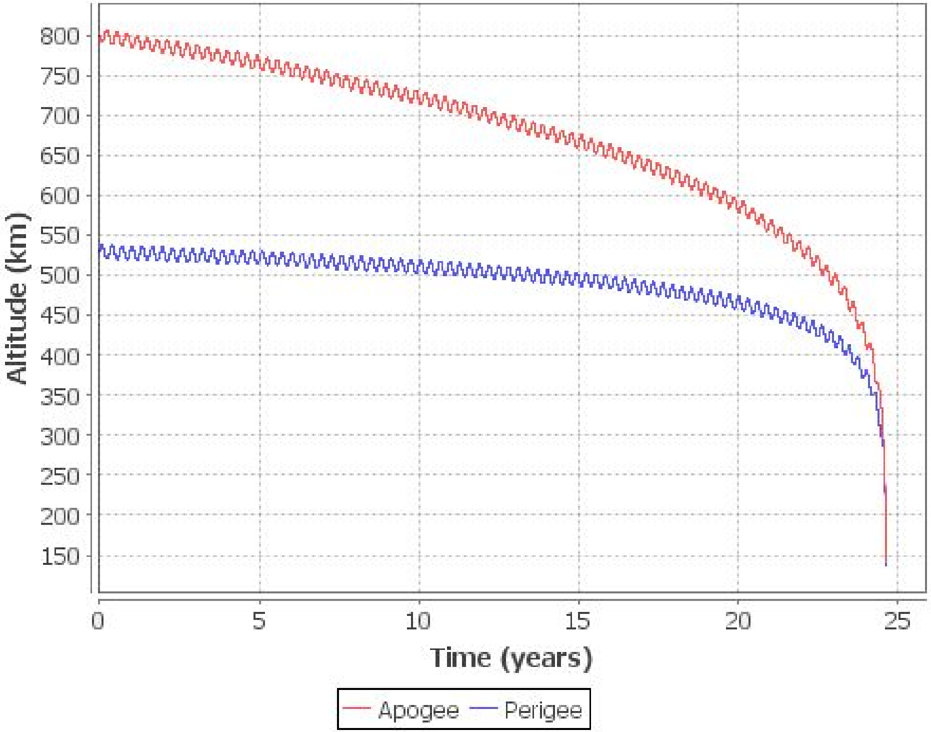
- Long access times for the downlink
- Thermal stability
- No attitude corrections to point at the sun
- Acc. from drag & Solar pressure ~10^{-7} m/s^2

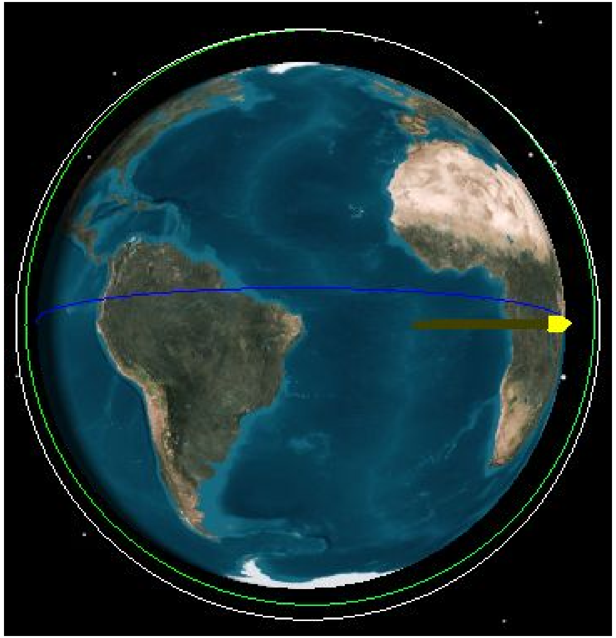


Delta V Budget

		Delta V [m/s]		Fuel mass [kg]	
Injection	37.85			15.3	
Station Keeping		1 Year	Mission 10 Years	1 Year	Mission 10 Years
	Inclination	5.1	51	1.7	17
	Drag	2.4	24	0.8	8
Collision avoidance		0.1	1	0.03	0.3
Deorbit	74.8			31.1	
Total	188			71.7	

Deorbiting



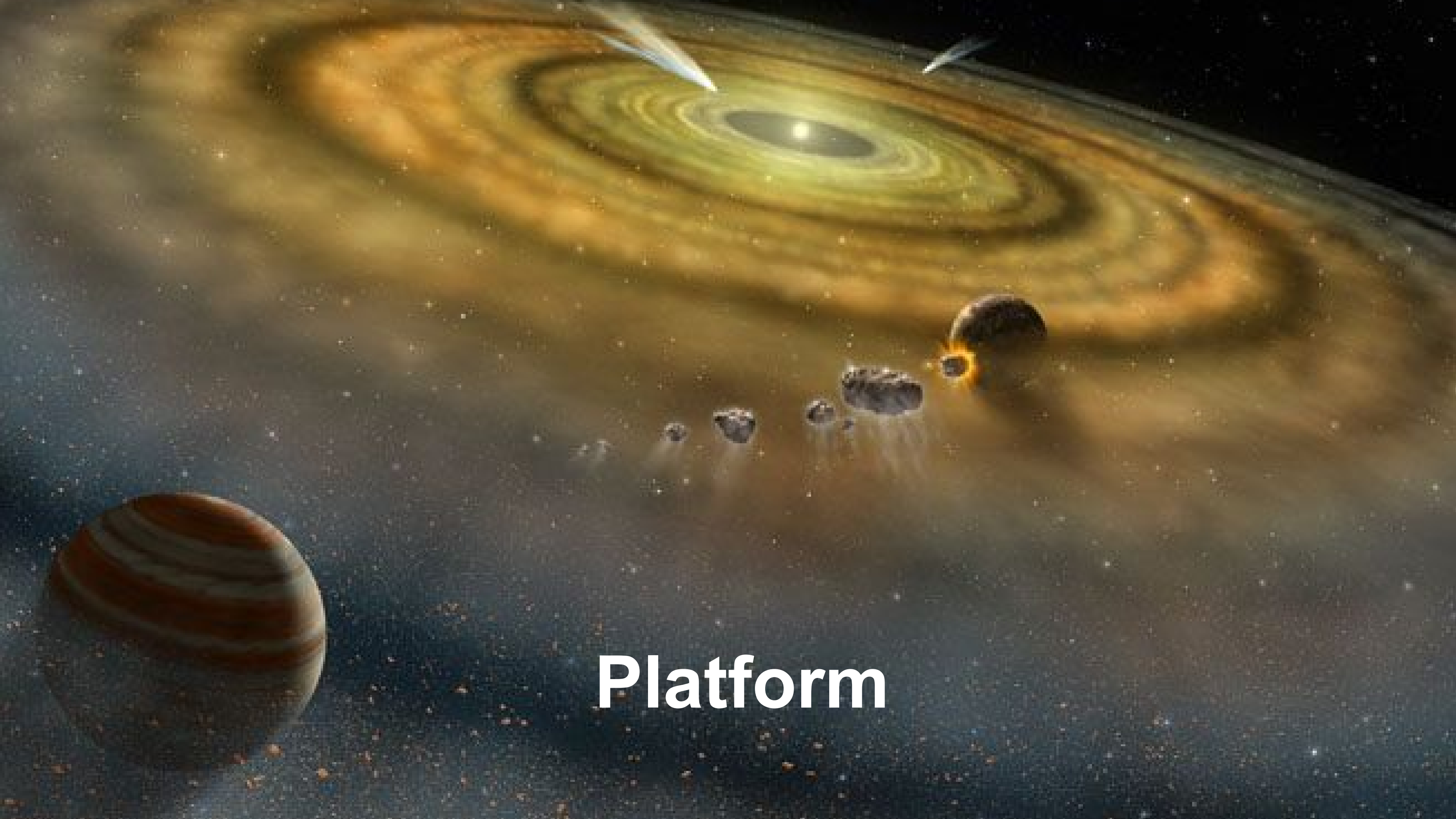


Deorbiting time: 24,5 Years
Further analysis for safe disposal has to be made

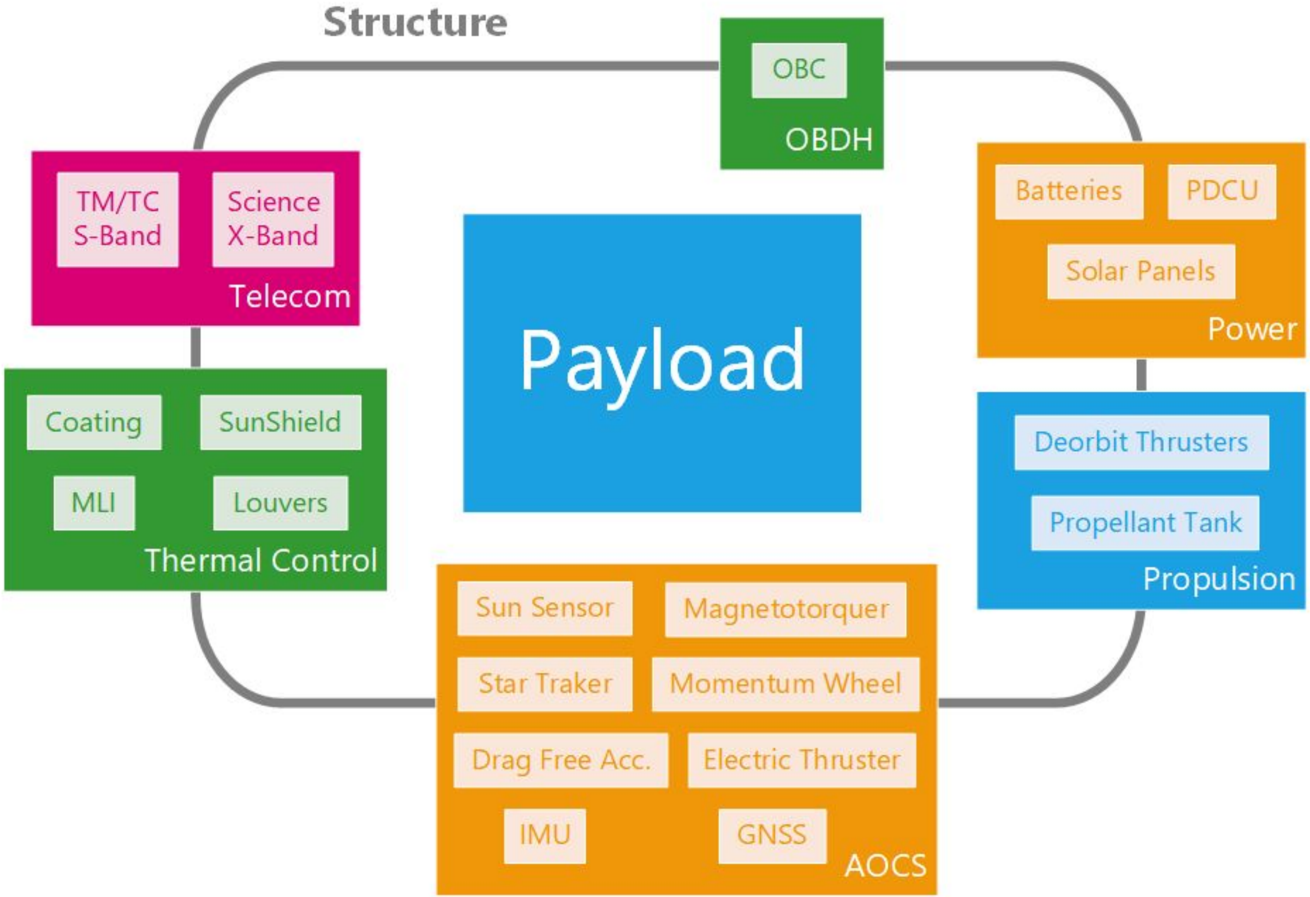
Operations and ground segment

- Redu GS - TT&C subsystem - 2.4 m antenna operating in S-Band
  - 100 kbps up, 2 Mbps down
- Kiruna GS - Scientific data downlink - 15 m antenna operating in X-Band
  - 191.4 GB downloaded per day at 175 Mbps
  - 12 passes per day to download scientific data
  - Each pass consists of 730 seconds (~12 minutes)

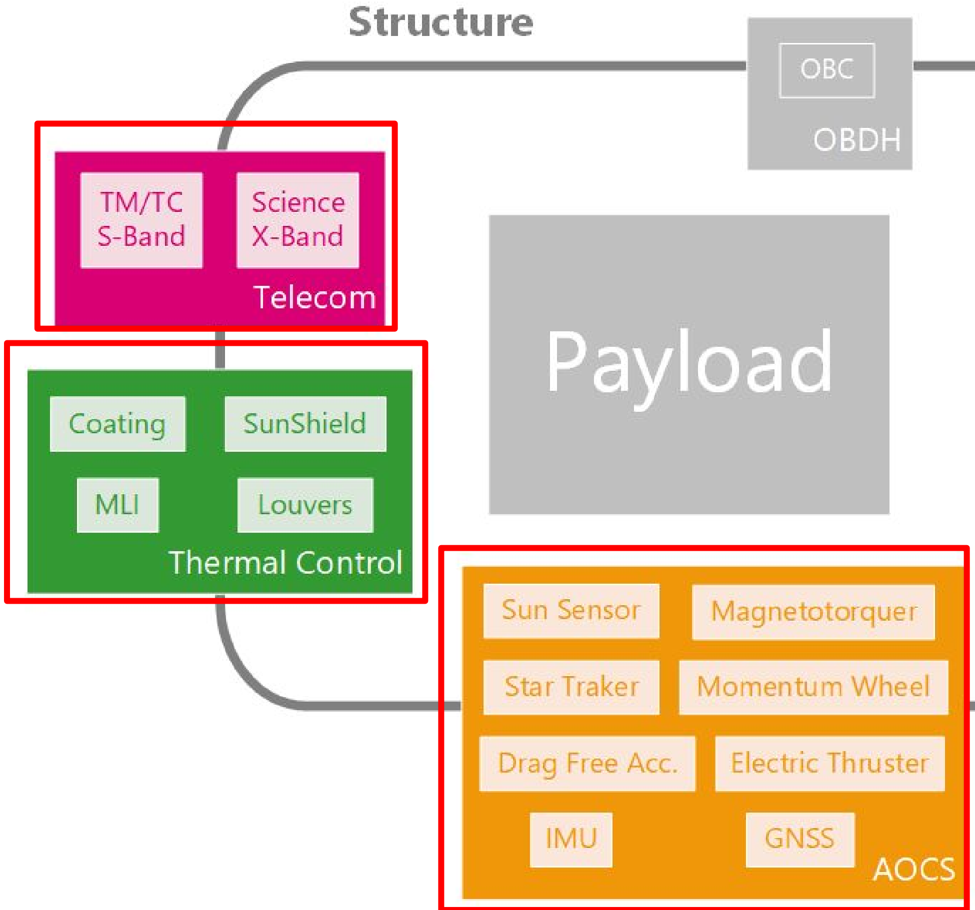
Platform



Overview of subsystems



System drivers



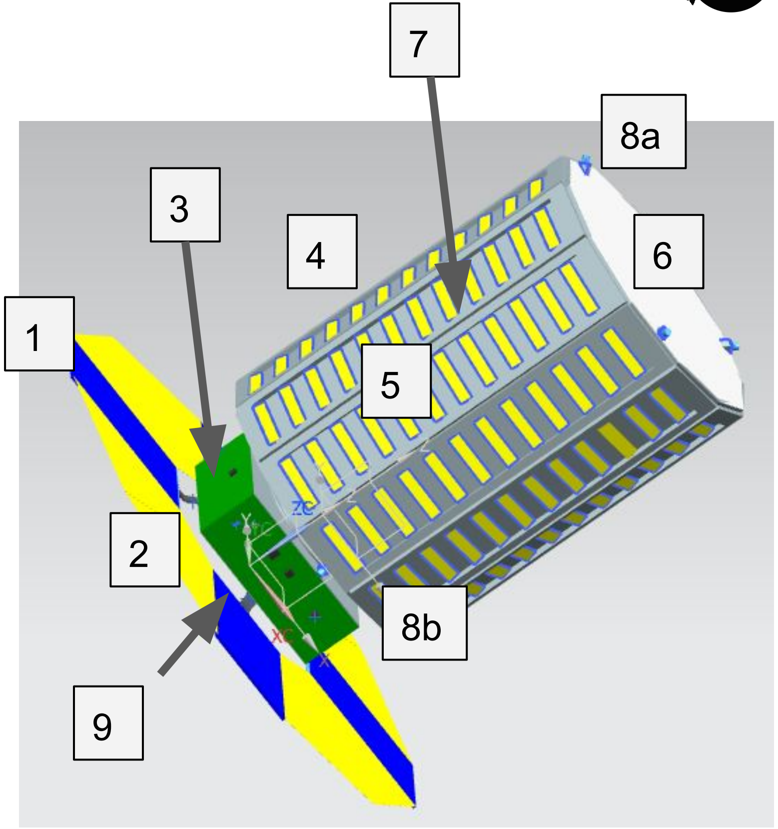
Spacecraft configuration

1. Solar panels
2. Sun shield
3. Spacecraft bus
4. Payload container
5. Louvres for thermal control
6. Quartz mirror for thermal control
7. Frame
8. Ion thrusters for attitude control (x6)
9. Hydrazine thrusters (x4)

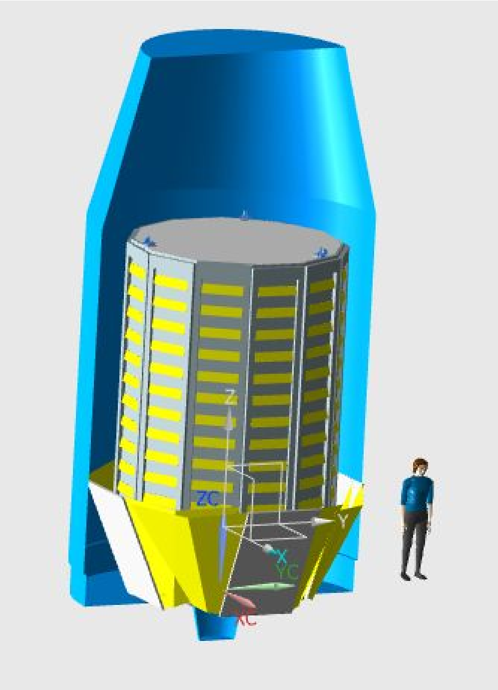
Spacecraft dimensions:

H: 4400 mm
W: 2800 mm
L: 2800 mm

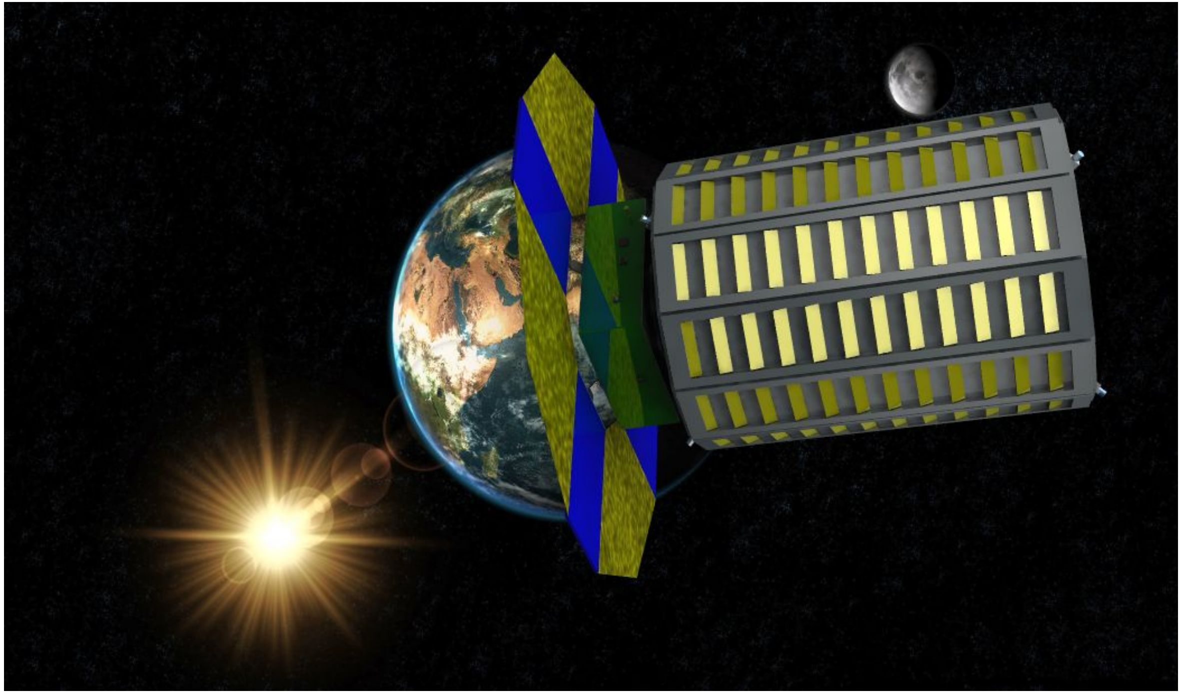
Sunshield: ∅ 5000 mm



Spacecraft configuration



Spacecraft in stowed arrangement compared with the Soyuz fairing usable volume and a human for scale

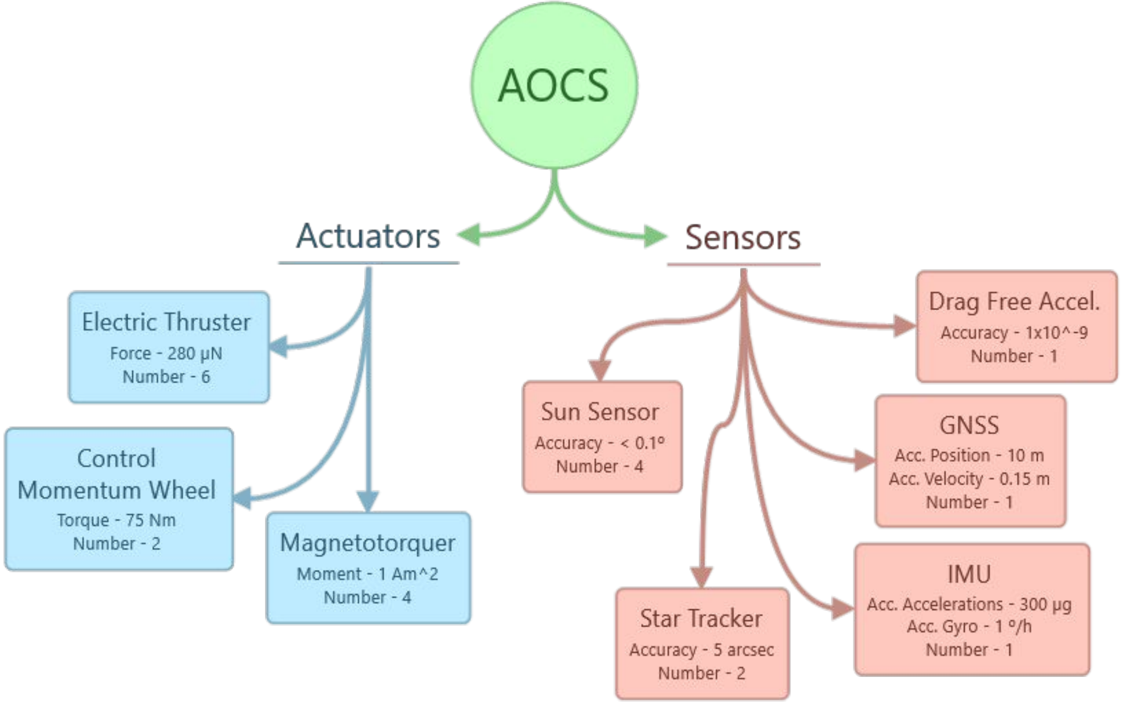


Magrathea - concept model

Propulsion subsystem

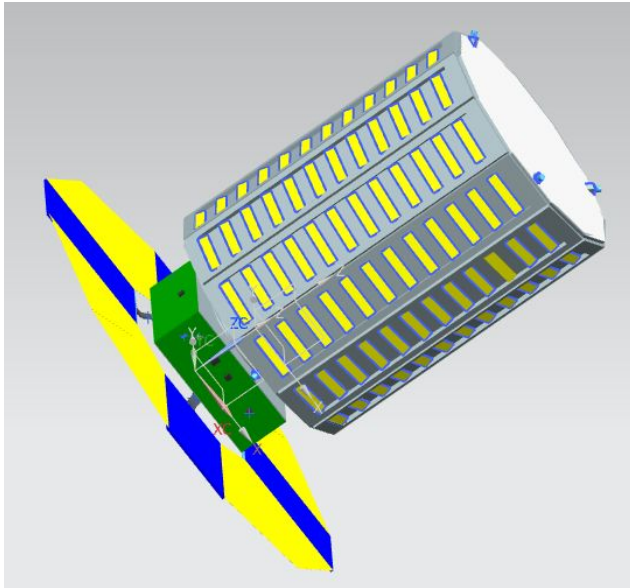
- **Functions**
  - Orbit injection and correction maneuver
  - Detumbling phase
  - Station keeping
  - Debris avoidance
  - End of life maneuver
- **Driver**
  - Safe deorbiting at EOL
- **Solution**
  - 4 x 20 N monopropellant hydrazine
  - Isp = 220 s
  - DeltaV = 164 m/s
- **Technology readiness**
  - TRL 9

AOCS subsystem



- **Functions**
  - Minimize disturbances to experiment
  - Drag-couter control attitude
- **Driver**
  - Counter all external forces
  - Pointing capability for communications
- **Technology readiness**
  - TRL9

Thermal subsystem



- **Functions**
  - Provide required temperatures for experiment and bus
  - account for IR emission from Earth
- **Solution**
  - MLI
  - Sun shield
  - Coating
  - Louvres
  - Heaters
  - Optical surface reflector
- **Maturity**
  - TRL9 but high criticality

Thermal Model	Bus		Experiment Chamber	
Case	Cold	Hot	Cold	Hot
Equilibrium temp. with louvers/ heaters [K]	263 (-10°)	293 (20°C)	161	190

Power subsystem

- **Functions**
  - Sustain all the equipment of the spacecraft (payload and SM) with required power

Subsystem	Power (W)
Payload	373
Platform	489
Total (margin 20%)	863

- **Solution** (900W)

Battery Cells
N°cells = 10
Energy = 100 Wh
Mass = 1.25 kg

Solar Arrays
Power max = 900 W
Area = 6.3 m^2
Mass = 16.4 kg

Power Distribution & Control Unit
Power max = 900 W
Efficiency = 97 %
Mass = 0.6 kg

- **Technology readiness**
  - TRL9

C&DH subsystem

PAYLOAD OBDH : Sirius C&DH

Performance

Processor software = 32-bit OpenRISC fault-tolerant processor
Mass memory storage = 124 GB

BUS OBDH : Data Handling VPDHS

Payload
Storage capacity = 4 GBytes
Storage capacity flash = 16 GBytes non-volatile
Power consumption = 15W

- **Functions**
  - On board science data reduction and particle tracking
  - Data storage
  - Housekeeping data handling

- **Technology readiness**
  - TRL9

Communications

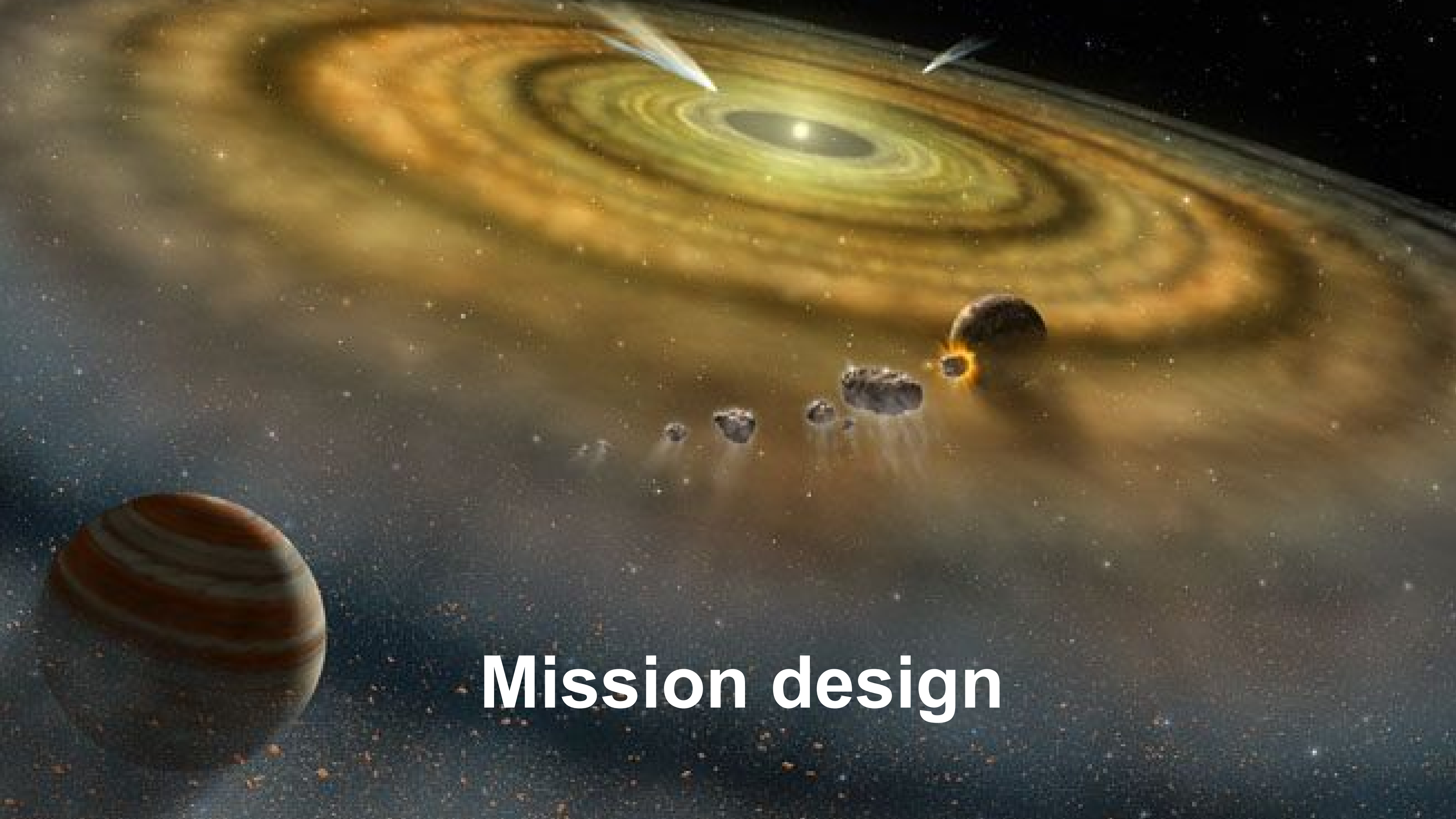
- **Requirement**
  - Download all the scientific and housekeeping data

	Value	Unit
Data rate	175	Mb/s
Daily data volume	191.4	GB
Data downlink/pass	16	GB
Data downlink/day	191.6	GB

- **Solution**
  - Two S-Band patch antennas and transceivers for TT&C (housekeeping)
  - X-Band horn antenna and transmitter for data downlink
  - Use of different ground stations for each purpose
- **Technology readiness:** TRL9

Main budgets

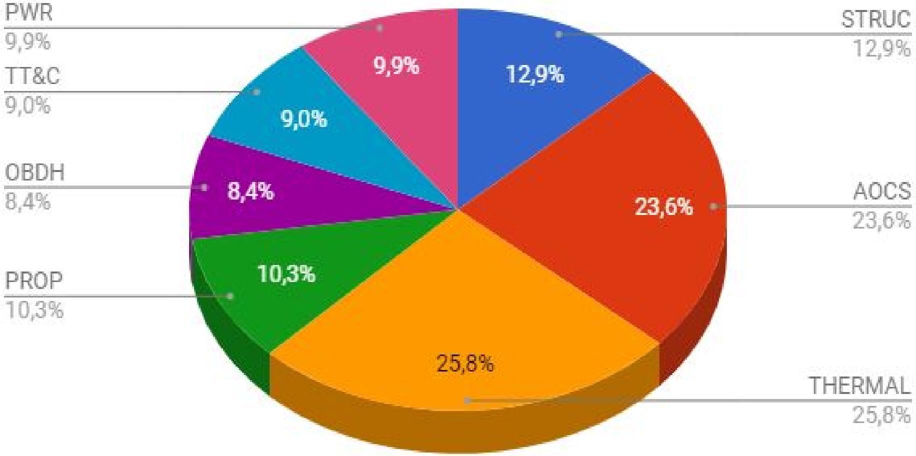
Subsystem	Margin	Mass (kg)	Power (W)
Payload	35%	289	454
Telecom	20%	23	66
OBDH	20%	3	18
Power	20%	29	27
AOCS	20%	84	266
Propulsion	20%	37	24
Thermal	20%	121	36
Structure	20%	373	0
Propellant	20%	75	0
Total		Wet: 1033	891



Mission design

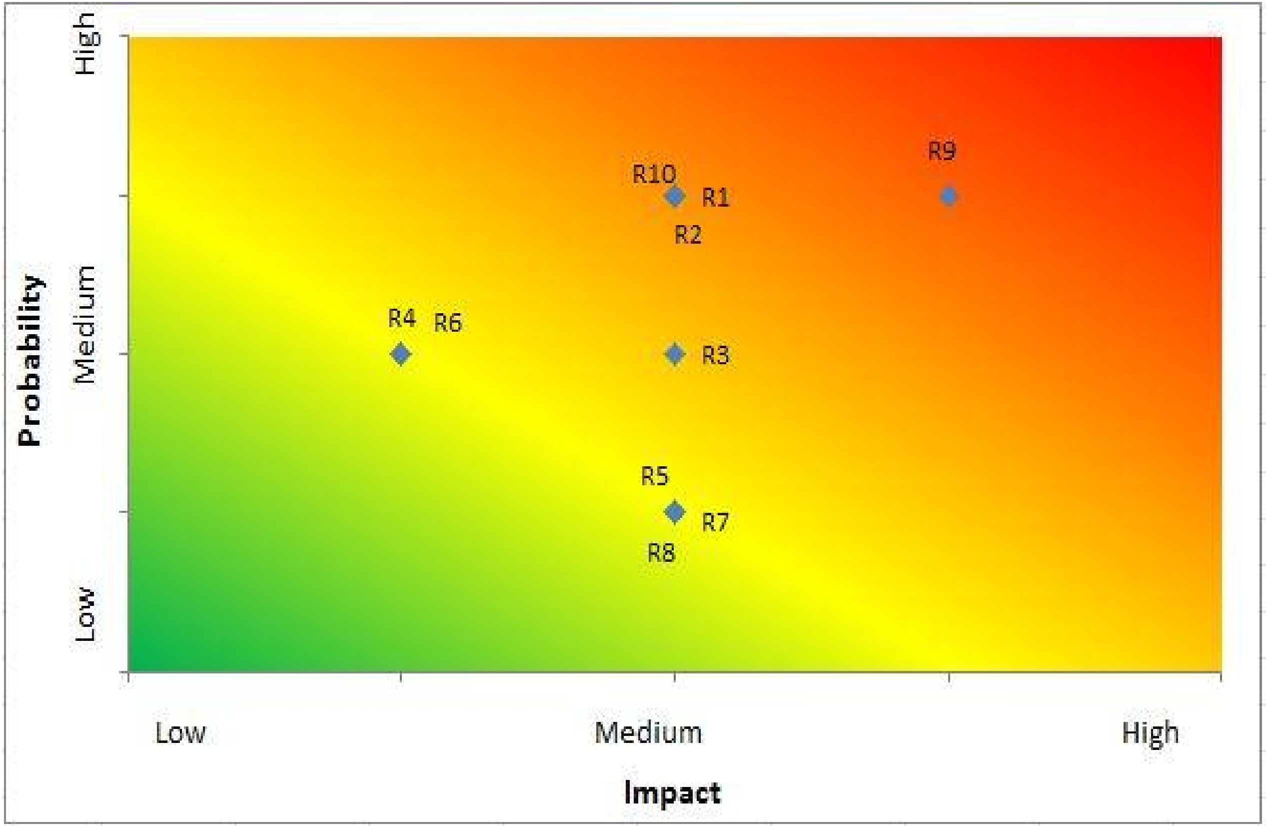
Cost Analysis

Spacecraft Elements	
Element	MEUR
Instruments	88
S/C Bus	135
Mission and Programmatic elements	**MEUR**
Total Spacecraft cost	223
ESA Programme Level	27
Integration, Assembly & Test (IA&T)	22
Ground Operations(MOC,SOC)	31
Flight software	20
Launch vehicle(Soyuz)	75
Margin	10%
Total with margin	438



S/C Bus cost

Risk Analysis



R1: Chamber agitation
R2: Chamber contamination
R3: Louvre blocking (thermal)
R4: Thermal chamber instability
R5: Solar radiation
R6: Debris impact
R7: Chamber venting
R8: Water condensation
R9: **Technology development (Sample handling and processing SS - TRL2)**
R10: Wall sticking

Development schedule

FRR : Flight Readiness Reviews

PHASE D: PRODUCTION AND QUALIFICATION

CDR : Critical Design Review

7 years

PHASE C: DETAILED DEFINITION

SRR : System Requirements Review
PDR : Preliminary Design Review

1 year

PHASE B: PRELIMINARY DEFINITION

PRR : Preliminary Requirements Review

2 years

PHASE A: FEASIBILITY STUDY

Total : 11 years
> Expected launch date : 2030

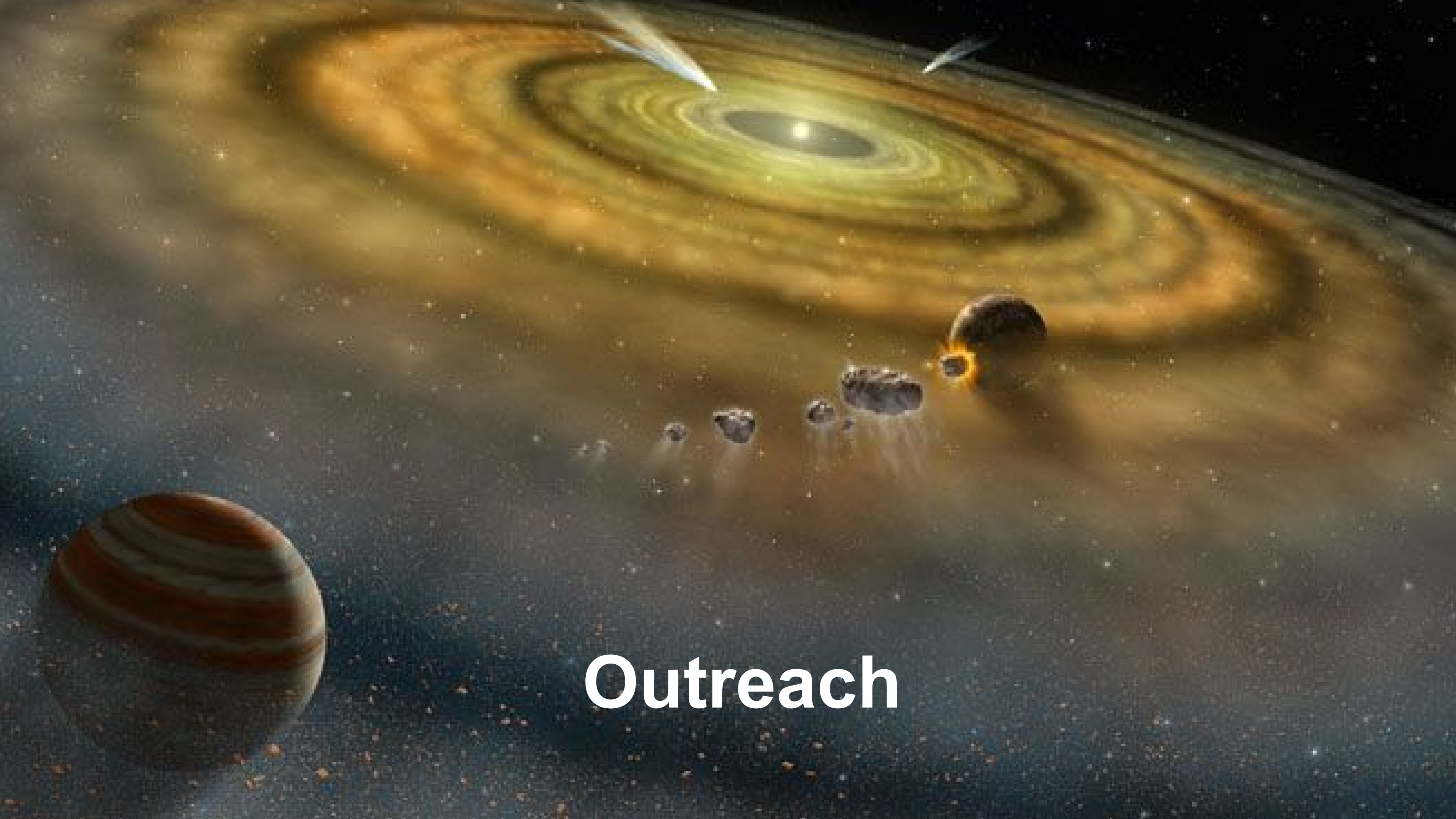
MDR : Mission Definition Review

1 year

PHASE 0: MISSION ANALYSIS

Descoping options

- Reduce number of experiments according to science priority
- Remove ice-layer generation capability (GELATO)
- Remove Atomic Force Microscope



Outreach

Outreach - Middle school

Outreach - College

MAGRATHEA
BUILDING PLANETS

drop your
thesis!

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drop your thesis!

fly your thesis!

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drop your thesis!

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orbit your thesis!

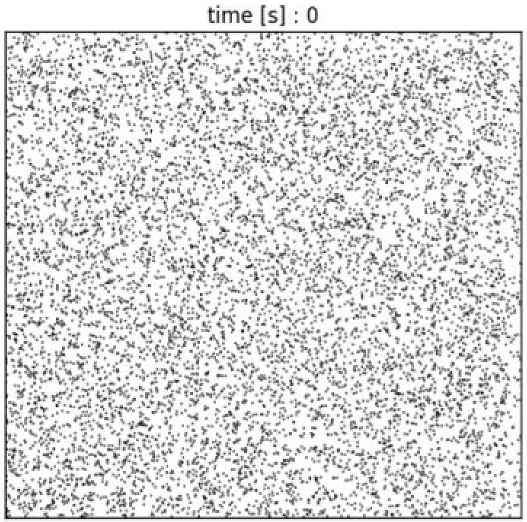
Thank you for the Alpbach summer school!

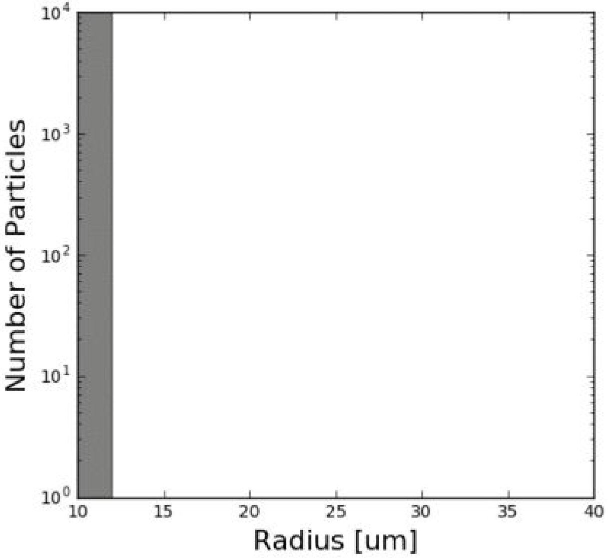
Appendix slides

Long experiments provide insight on grain growth

Long experiments provide meaningful statistics on:

- Collision type
- Requirement for sticking
- Physics of collisions





Measurement requirements (old version)

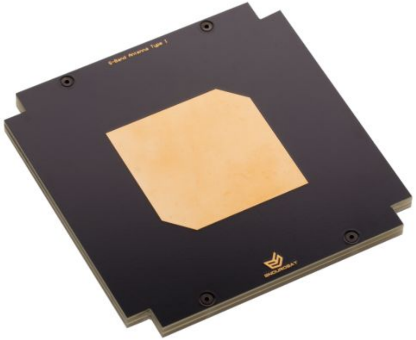
Science requirements		Measurement requirements (M1 - M8)		
		Min.	Max.	Precision
Understand how the following parameters affect dust grain growth in protoplanetary disks	**S1:** size (r_{eff})	0.5 µm	1 cm	± 0.1 µm
	S2: collision type	Classify collision type according to Guttler et al. 2010		
	S3: shape			± 0.1 µm
	S4: rel. velocity	1 µm s^{-1}	5 mm s^{-1}	± 10 %
	S5: rotation rate	0 rev s^{-1}	60 rev s^{-1}	± 1 %
	S6: composition	N/A - compositions selected before launch		
	S7: porosity (φ)	0	1	± 1 %
	S8: ice mantle	N/A - icy mantle produced during grain injection		

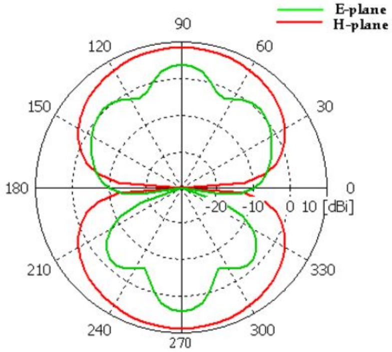
Particle tracking camera

Measurement requirement	Specification	Solution
Need to resolve 1 cm^2 in spaces of 3 μm	Size of pixel	Side of 5.5 μm, total surface of 30.25 μm^2
Need to measure 1 cm^3	Number of pixels	11.56 MP (3400x3400)
Need to resolve rotations	Frames per second	120 fps
Need to see the volume	Field of view	8.265°

Antennas

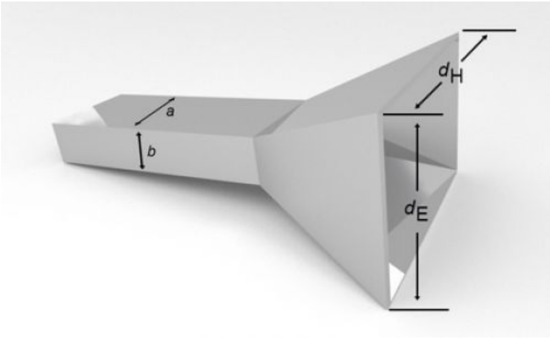
- **TT&C**: two S-Band patch antennas and transceivers

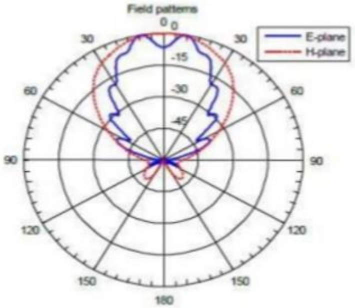




- Gain: 8 dB
- Half Power Beam Width (HPBW): 71°
- Transmitted power: 20 dBm

- **Data downlink**: X-Band horn antenna and transmitter





- Gain: 10 dB
- Half Power Beam Width (HPBW): 55°
- Transmitted power: 37.8 dBm

Link budget

	S up (100 kbps)	S down (2 Mbps)	X down (175 Mbps)	Unit
EIRP	32.23	-2	17.78	dBW
Path losses	156.96	157.36	169.1	dB
G/T	-22	9.62	37.29	dB/K
EB/NO	29.87	13.85	30.14	dB
Required EB/NO	8	8	14	dB
Margin	21.87	5.85	16.14	dB

Thank you tutors!

Thank you tutors!

Thank you tutors!