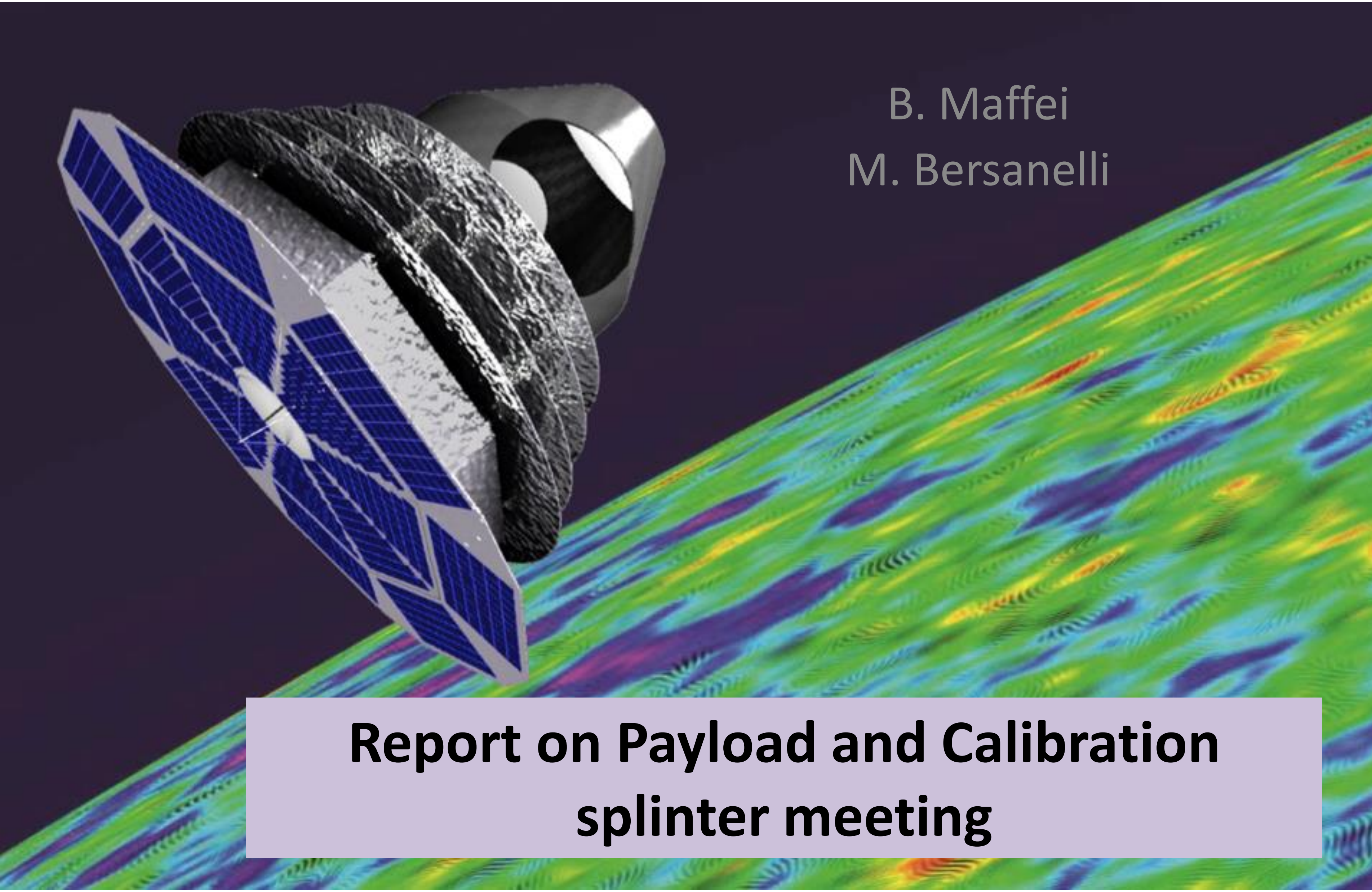


B. Maffei
M. Bersanelli

Report on Payload and Calibration splinter meeting

Payload requirements in order of priority ?
(at least from ESA perspective)

- Costs
  - 550 M€ + EU National agencies ? + External collaborators ?
    - Cannot take into account externals for the proposal
    - Probably 650M€ max
- High TRL and low risk scheme
  - Need to pass the “technology screening”
- Dimension envelope
  - Ariane 6 fairing cylinder of 4.6m diameter x 4m high
  - 2m diameter, 2 m height available for payload
- Mass
  - Safely assume that we cannot go beyond Planck mission
  - COrE+ 2014: 1958 kg; Planck was 1500kg
- Power consumption
  - Will dictate if we need deployable solar panels or not (added risks)
  - COrE+ 2014: 2073 W; Planck was 1700 W
- Data rate
  - COrE+ 2014: 2.4 Mbits/s

Payload trade-off – Sub-systems cannot be treated independently

Size and configuration of the telescope
- No more than 1.5m diameter primary
- Rather 1.2m
- Cannot use CTR configuration

No HWP (at least as the first element)
(Cost, Dimensions & Mass)

Complex scanning strategy
- Impact on solar panels size
- Impact on data transfer

(Cost, Power, Data transfer)

FPU and number of detectors
Technology (EU)
(Cost, Power, cooling power, Data transfer, dimensions, mass, TRL)

Descope ?
Impact on Science?

Cooling chain
- Passive / active
- Choice: impact on signal, ….

(Cost, Power, dimensions, mass, TRL)

Ground Tests and calibration
- Impact on in-flight calibration

(Cost, Schedule, Risks)

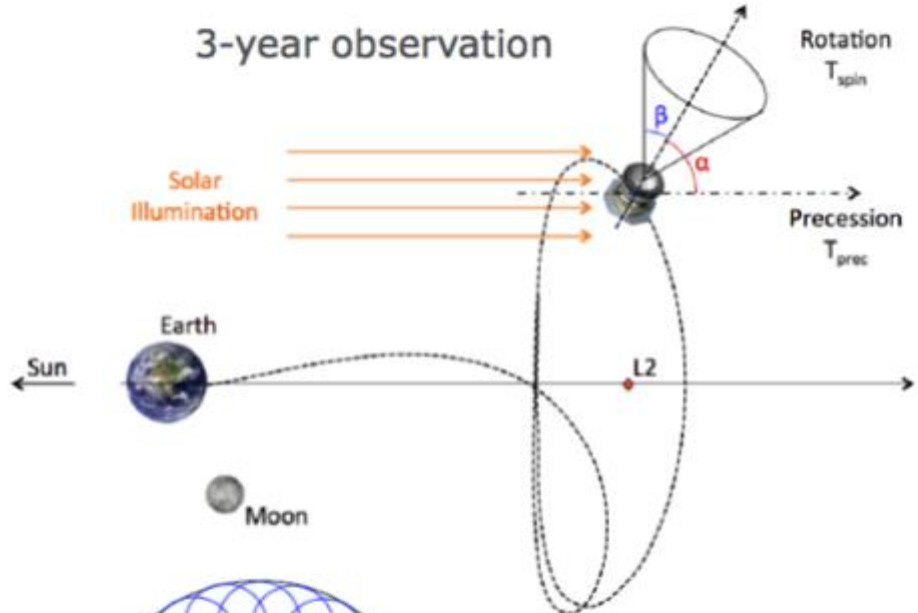
CDF baseline

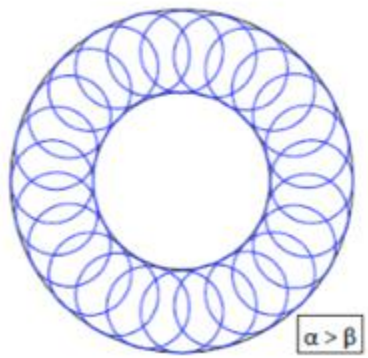
- use of cold HWP in front of telescope is a fundamental difference in Litebird and Core+ designs which is a design driver (e.g. limited angular resolution, frequency range)
  - Neither team convinced of need for HWP
    - resolution must be achieved by realistic simulations w/ and w/out HWP
    - Cannot be done within the timescale of the CDF
- Fundamental requirement of the European team is high angular resolution (aperture > 0.8 m), both for B-mode science and additional science
- it was agreed to study a single configuration with no HWP and an effective aperture ~1.2 m
  - Use prior knowledge as much as possible (Planck, NGCryoIRTel)
  - Assume use of European technology
  - Ignore details of focal plane (treat as "black box")
    - Allowing for reimaging optics inside black box
  - Include a cold baffle to reduce straylight and act as partial cold stop
  - high spin rate (2 rpm) to mitigate low frequency noise

Mission description

- Orbit: Large amplitude Halo orbit around L2 (like Herschel). No scientific need for a small amplitude Lissajous orbit (like Planck)
- Launch Vehicle:
  - H-II/H-III launcher, sizing for fairing volume (4.6 m Ø X ~4 m h cylindrical part)
  - Ariane 6.2 sizing for mass performance to L2.
- Full sky coverage with scanning law consisting of three combined rotations:
  - Spin @ 2 RPM around axis at β = 45 deg wrto optical axis
  - 4-day Precession of spin axis with α = 50 deg wrto Sun line
  - Daily Sun-SC line rotation

3-year observation





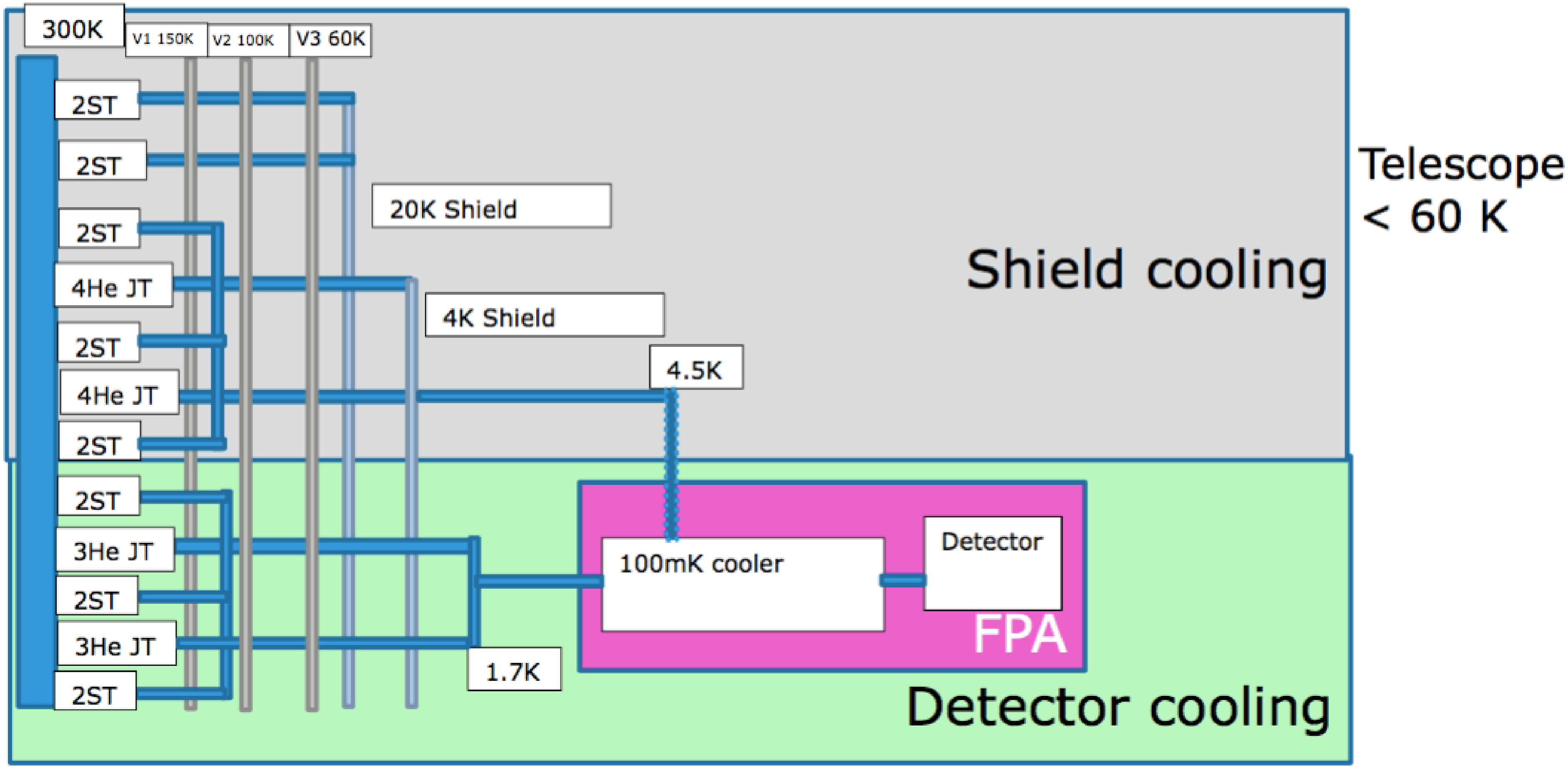
Communication

- Science Data Volume (includes compression of factor 4)
  - Option 1 (O1) (2 RPM): 4.8 [Mbps] → 414.72 [Gbit/day]
  - Option 2 (O2) (1 RPM): 2.4 [Mbps] → 207.36 [Gbit/day]
- Too high for X-band (band limited to 10 MHz), K-band downlink required (as Euclid)
- 4h downlink/day assumed with 35-m Cebreros, data rate ~15 Mbps
- 0.2 m Parabolic K-band HGA
- Mechanical steering required as Electrical steering will imply too high power
- 15 W RF power and TWT-based amplifiers

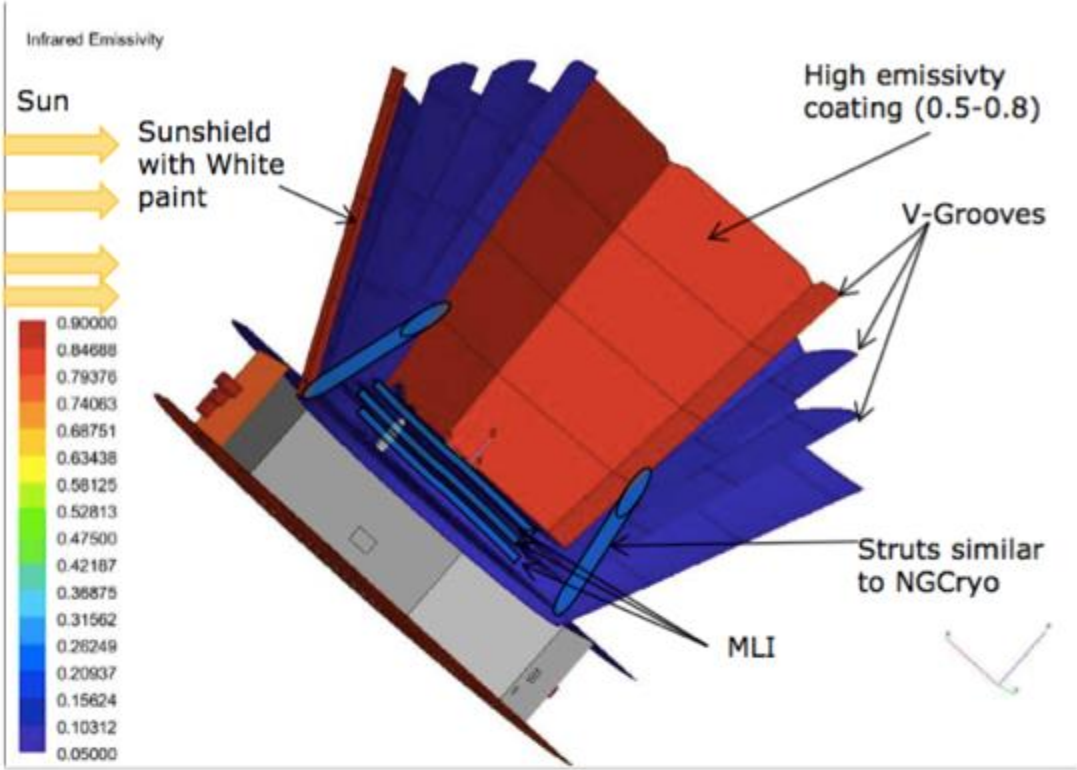
X/X/Ka DS TRSP

K-Band TWT

Cryogenic architecture – Baseline



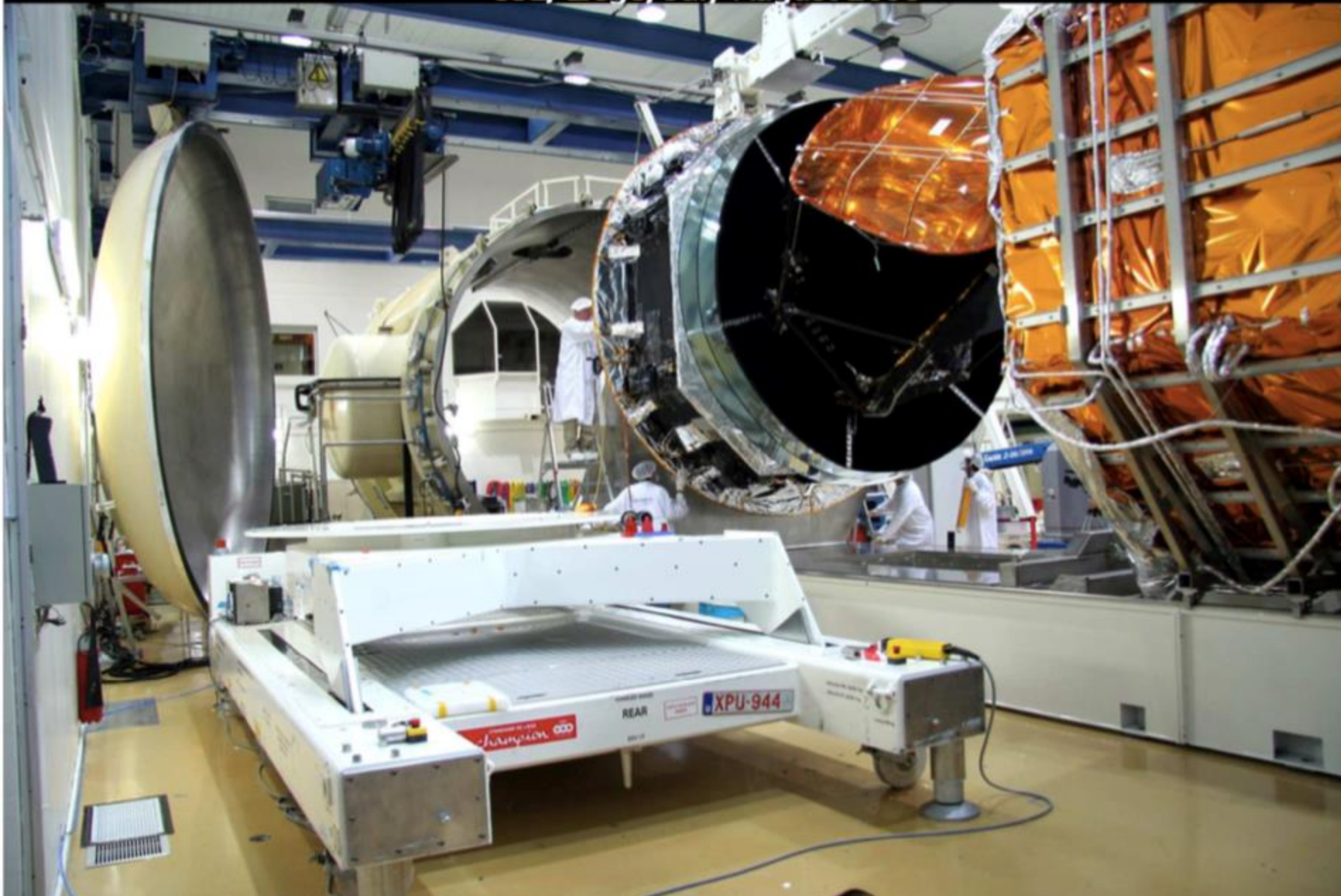
Cryogenic architecture – Baseline



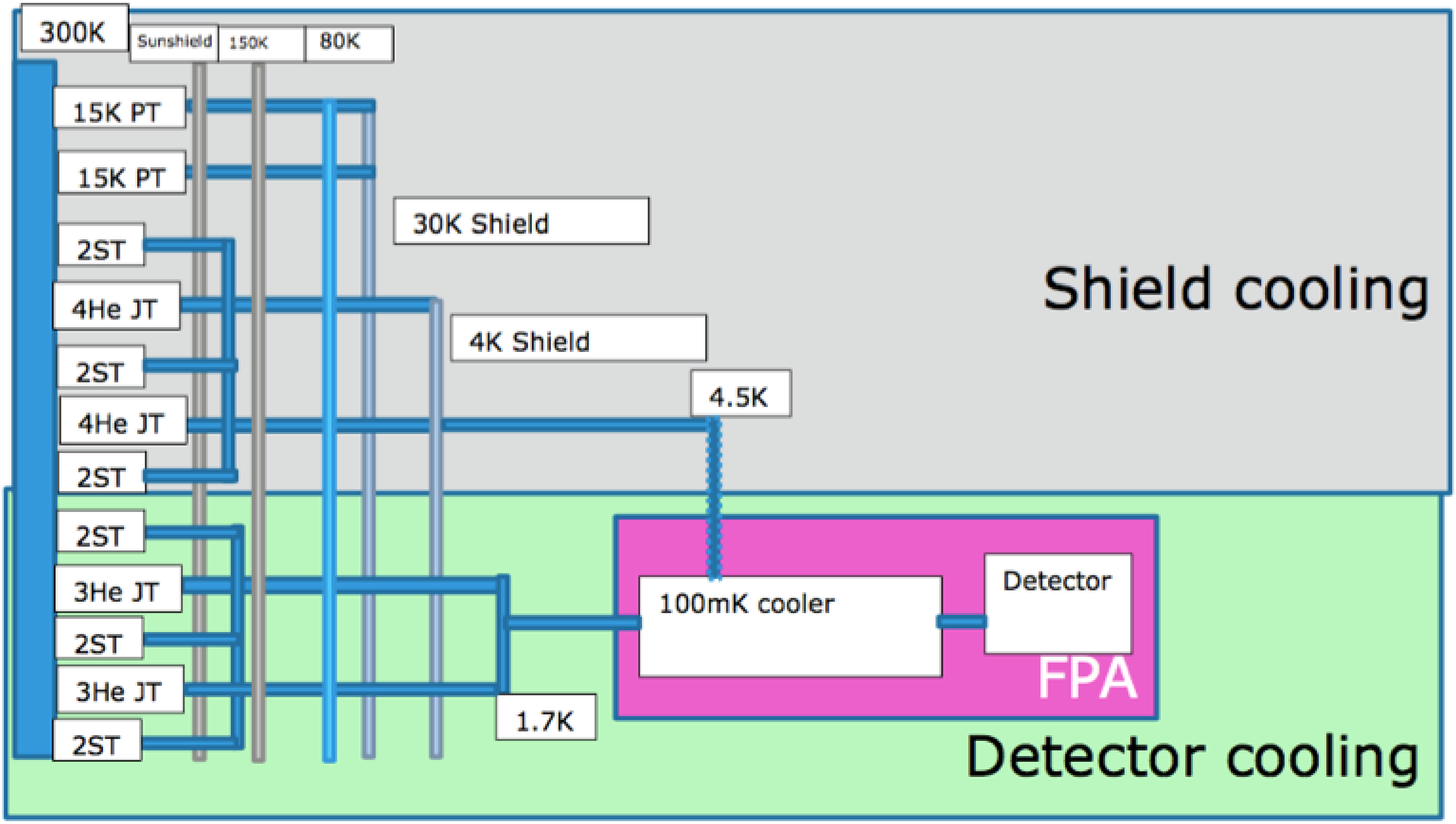
- + Payload available volume: ~2m diam / 2m height
- + Has more heritage (Planck), predicted V-Groove temp ~45K
- – Requires cryo-testing with Helium shrouds (high cost)

Active cooling looks feasible, but low margins on 4K/2K cooling stages ➔ further optimisation will be required

CSL, Liege, July-August 2008

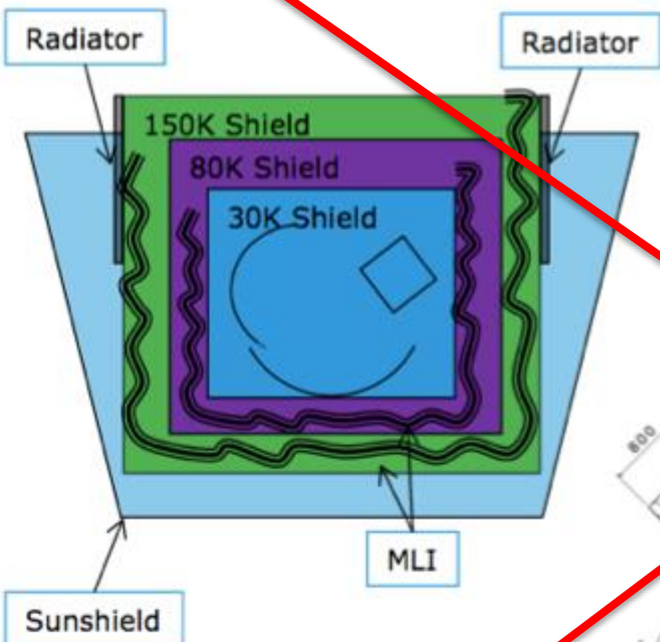


Cryogenic architecture – option 1



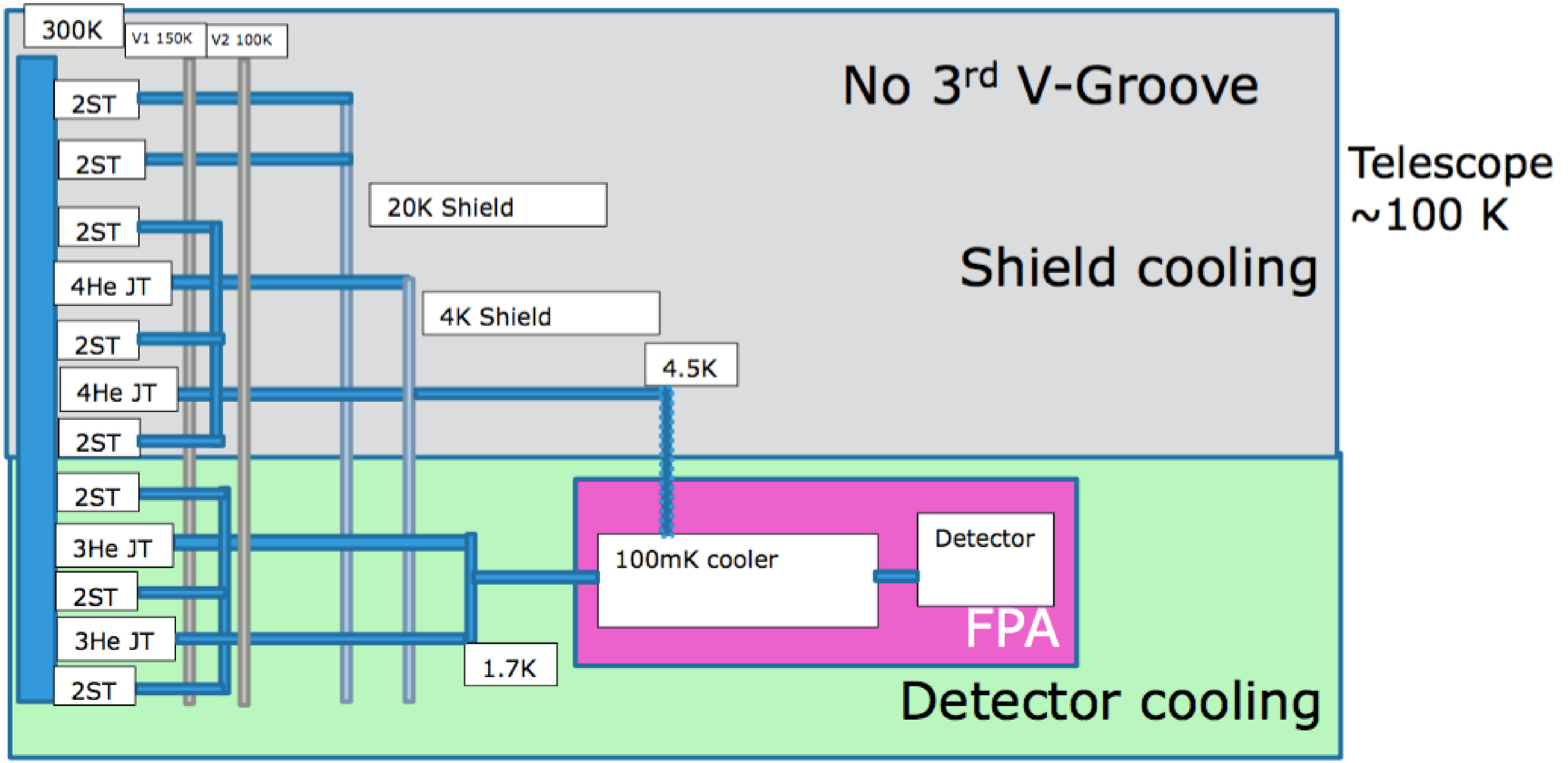
Telescope
~ 30 K

Cryogenic architecture – option 1

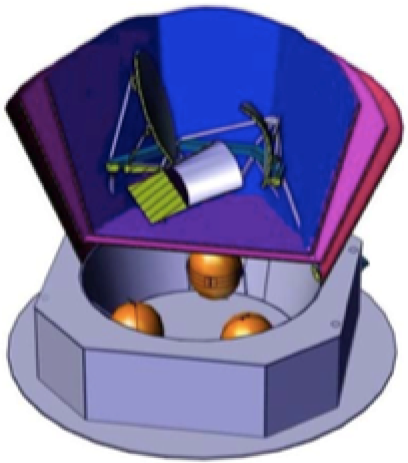


- – Limits Payload available volume to ~2m diam / 1.5 m height
  Max aperture ~ 80 cm
- + Does not Require System level cryo-testing with Helium shrouds
- – Telescope testing @30 K required
- – Requires ~300 W additional cooling power vs option 1
- – Requires dis-connectible support structure
  Relies on 15 K Pulse Tube qualification (ATHENA)
  Cooling power marginal vs heat load; requires optimisation

Cryogenic architecture – option 2



Cryogenic architecture-option 2



- Two V-grooves, passive cooling down to 100K only ➔
+ No testing required in LHe chamber in CSL (Telescope and System)
- Higher Telescope temperature ➔ higher background

- Load on the active cooling at 20K increased ➔ additional 20K JAXA shield cooler or ESA 15K PT might be required
- Active cooling looks feasible, but still low margins on 4K/2K cooling stages ➔ further optimisation will be required

Will need to think seriously about the impact as this is a way to cut cost !

G. Morgante

- Need for a system engineering from the start !
  - Contrary to Planck where this was set up towards the end
- Margin management
  - critical without system coordination
- Testing is never too much !
  - Anticipate testing with different models
  - test subsystems together

How to achieve 20K ?

- Sorption cooler based on Planck heritage performed well
  - Expertise “lost” in the US who provided Planck 20K cooler
  - Could be developed in Europe with Planck expertise: Possible backup solution.
- Pulse Tube Cooler could be the solution
  - Advantages
    - Lower base temperature (15K)
    - Lower mass
    - Also provide cooling power at 100K
  - Disadvantage
    - Mechanical cooler → vibrations
    - But should be low enough (TBC)
    - and KID detectors are less prone to microphonics vs TES

Y. Pennec – Air Liquide

ALAT 15K PTC

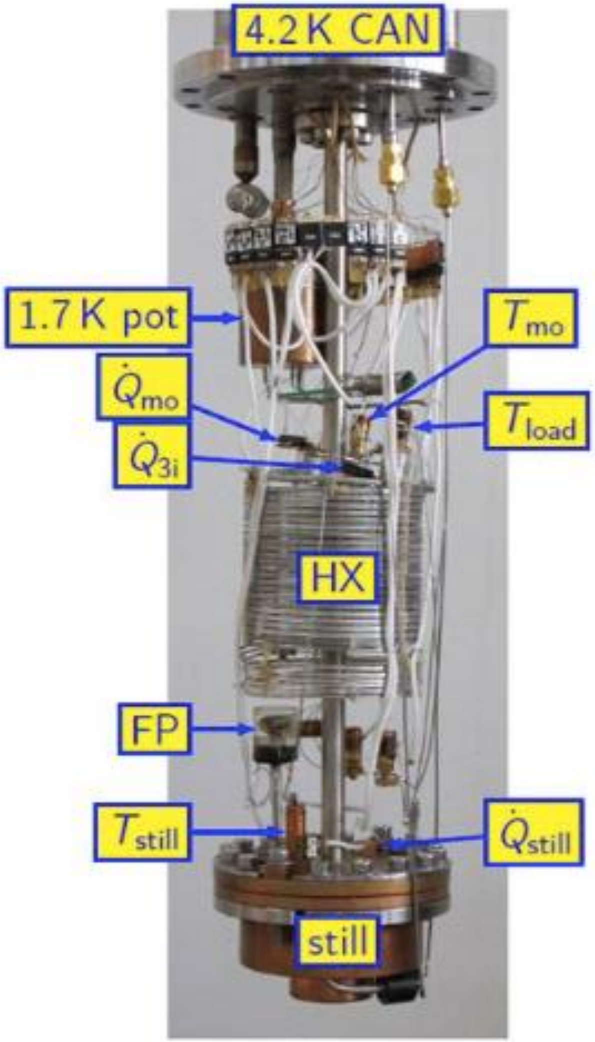
Leveraging on ALAT long heritage

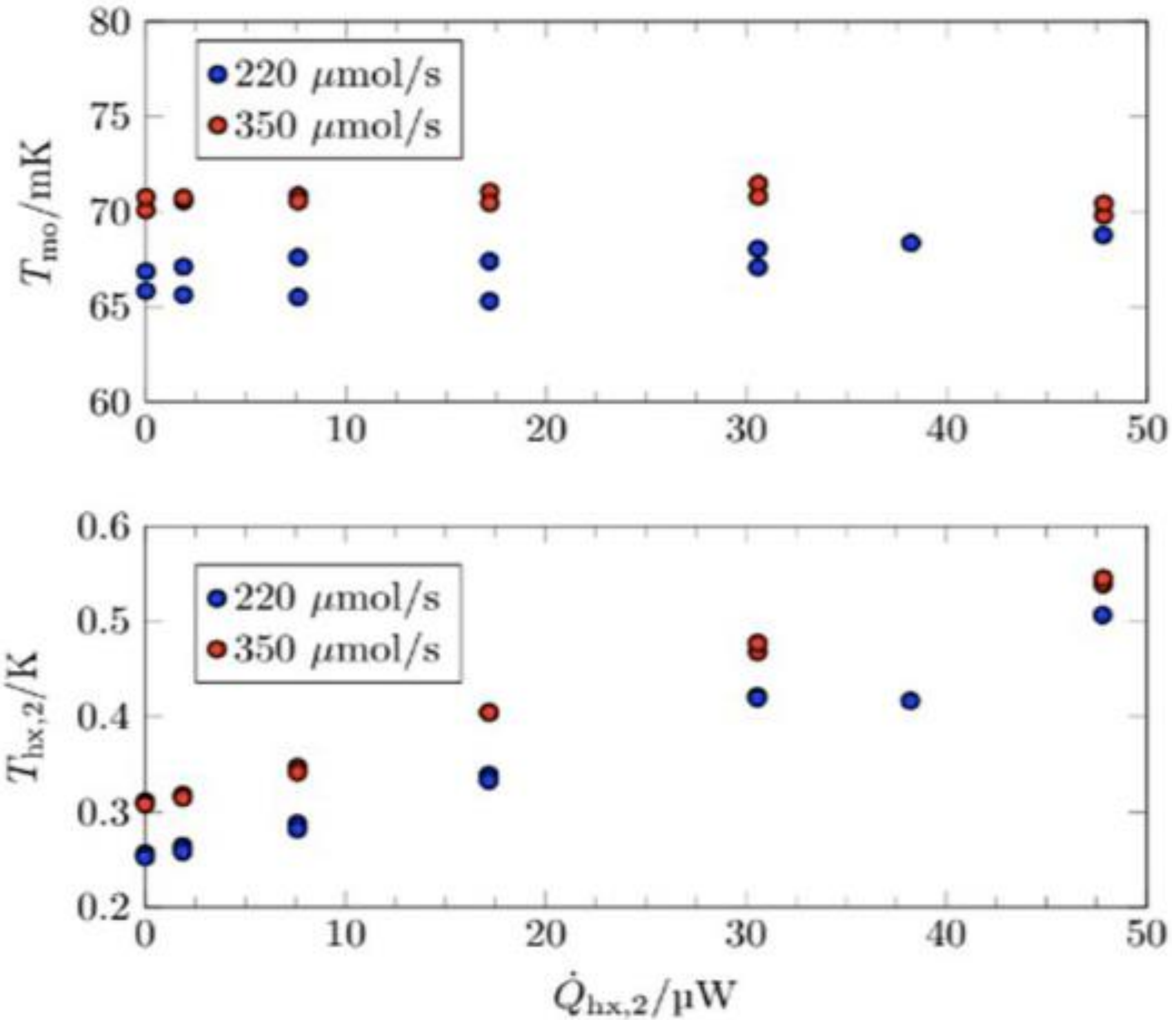
- 1st stage based on TRL8-LPTC
- 2nd stage cold finger based on the 20-50K
- Novel low temp regenerator
- Mass 2.5 Kg CFA + 10 Kg Compressor
- TRL 5 Soon to be developed to TRL6 by Air Liquide
- 450mW @ 15K + 5W at 100K

THALES cea

G. Vermeulen

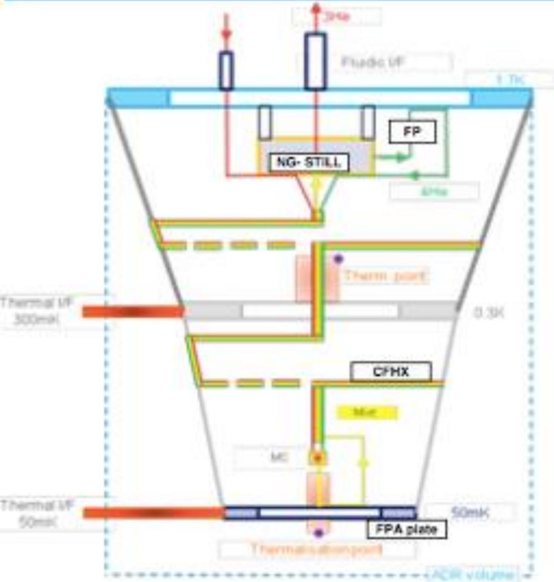
CNRS CCDR TRL 4 UNIT



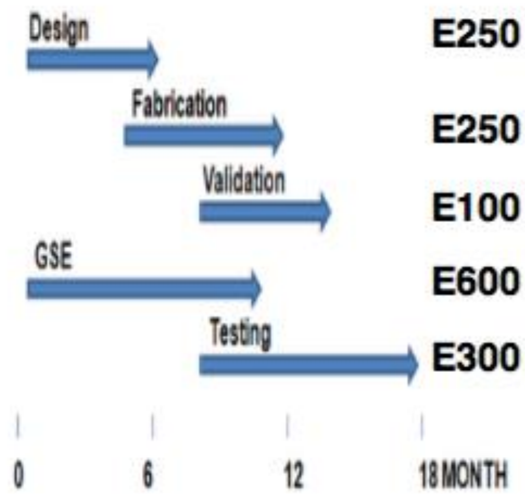


Plan only - not yet funded !

ALAT-CNRS CCDR: ROAD TO EM TRL 5/6



1	Dimensions	Less than 350x200x150mm^3
2	Weight	TBD
3	Mechanical Interface	X-IFU
4	Base Temperature	50mK/100mK
5	Cooling Power at Base Temperature	600nW
6	Base Temperature Stability	< 3uK/10mn
7	Intermediate Stage Temperature	300mK
8	Intermediate Stage Temperature Stability	TBD
9	Cooling Power at Intermediate Stage	13uW
10	Reject Stage operating temperature	1.7K
11	Reject Stage Power Consumption	<8mW
12	Magnetic Straight Field radiated	<10^-4 T
13	Thermal and Vacuum stress range	-50C -> 60C
14	Launch Vibration stress range	Ariane Standard



Project Lead and Scientist: Dr. Yan Pennec
Project Manager: Pascal Barbier
Scientific Advisor: Dr. James Butterworth (Planck Alumni)
Senior Mechanical Engineer: Gerald Fruh (Planck Alumni)
Mechanical Engineer: Eric Patras
Mechanical Engineer: Gaetan Coleiro
Structural Engineer: Samuel Ducarouge
Fabrication Technician: Dominique Chazot (Planck Alumni)
Fabrication and Test Technician: Guillaume Dorel
Engineer PA/QA: Benoit Barthélemy
Expert System Engineer: Thierry Wiertz (Planck Alumni)
Director: Pierre Crespi (Planck Alumni)

Comments from Y. Pennec

- Heritage from Planck is invaluable
  - V-Groove + Dilution + Structure
- Cryo chain for CORE feasible but extremely challenging
- Do not underestimate mechanical design constraints
  - launch locks/Isolators/Dampers/Supports
- CCDR is ready for an EM level development (funding?)

- Priority: define realistic cryostat
- Critical inputs: define thermal loads
  - Depends on detector technology
- Main issue is not 100K/40K telescope
- The scary bit: mass of the focal plane
  - 30 kg as for the M4 proposal would be extremely challenging (and probably very costly)
  - 3 – 5 kg more reasonable

Cryogenic chain comment / conclusions & Actions

- Open Dilution Refrigerator (Planck) a possibility ?
  - Price of ^{3}He might not be such a big issue in comparison to the cost of developing the CCDR
  - It will depend on the cooling power needed
    - FPU mass and dissipation
  - Has a limited lifetime
- Actions to go forward
  - Define the cooling needs and the **mass** of the FPU
    - M. Bersanelli, Joel Ullom et al: Evaluate Mass of focal plane with horns with Aluminum platelets, coated silicon (or combination)
  - J. Delabrouille: to ask CNES for thermo mechanical structure basic design
  - To be given as input to Y. Pennec to refine thermal/cryo analysis

What we learned from Planck

- Systematic effects must be attacked, first of all, in hardware
- Know the instrument and simulate its behaviour using its physics
- Know the data and look for residuals
- Physically-based simulations and data-driven analysis must be combined to understand residual systematic uncertainties

How should we handle systematic effects budget for COrE?

A three-steps approach

1. Define the global budget

- Should come from scientific objectives
- At what level we define it? (Maps, power spectra, cosmological parameters?)

2. Break down the budget

- Define list of known sources of systematic uncertainties (*main categories: optics, detectors, electronics, thermal…*)
- Make a reasonable guess on how the global budget should be broken down → first guess on requirements

3. Assess performance

- Possible objective for phase A study
- Simulate residual effects coming from known systematic effects assuming a given mission design
- Assess impact on scientific products
- Iterate with payload and instrument design if necessary

Ground Calibration

M. Bersanelli:
Large heritage from Planck
Challenge: ~ 100 times more channels, ~30 times deeper

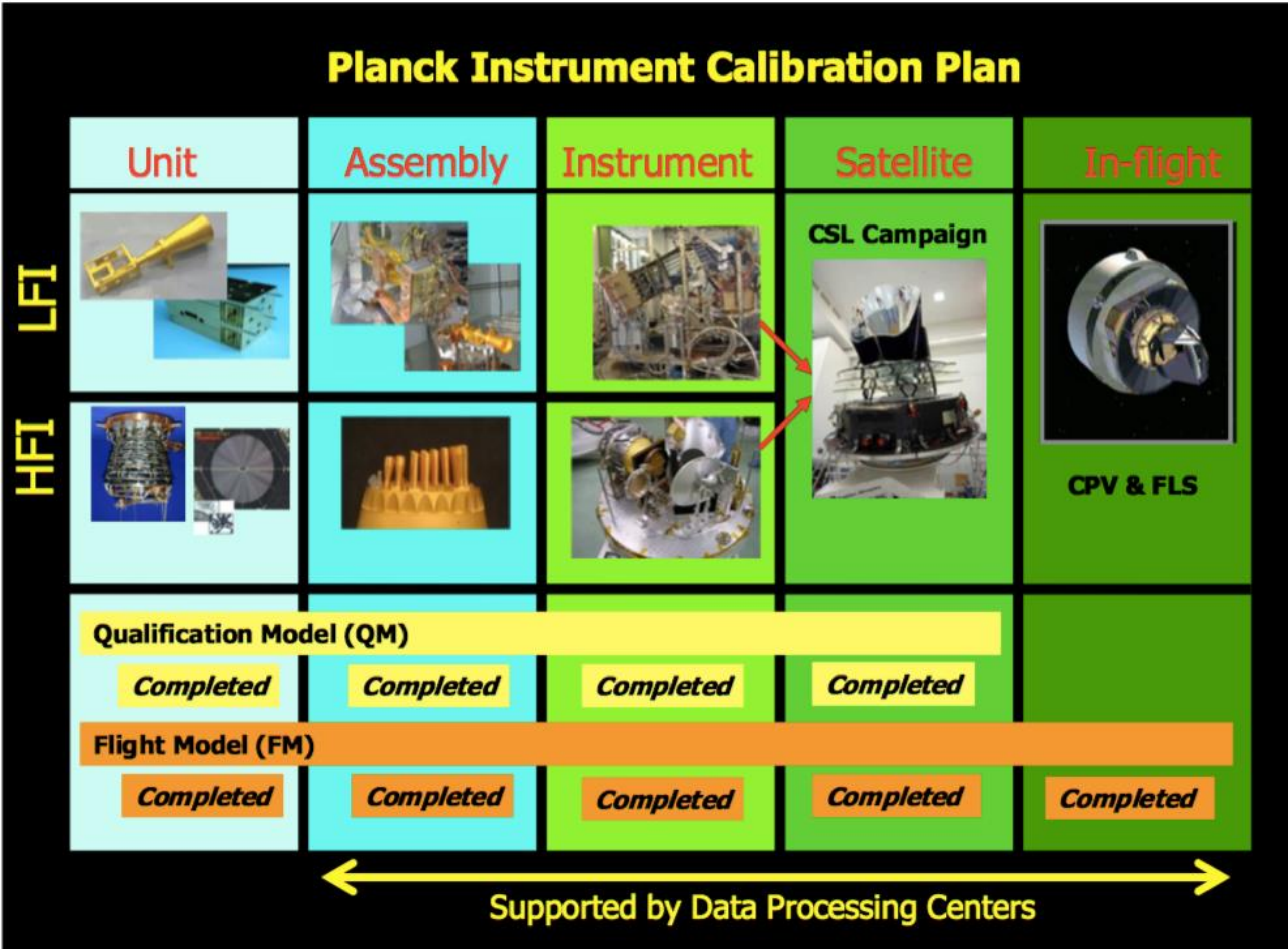
Model Philosophy

From Planck

esa

- Structural Model
- Cryogenic Qualification Model (CQM)
  - P/L QM, with a full structure (as for Planck), SVM dummy with fittings for the PLM coolers and "PLM warm units", to be used for the cryogenic test qualifying the chain of cryo stages
- SVM Avionics Model (AVM)
- Protoflight Model (PFM)
  - New, no refurbishment from other models
- RFQM (refurbished CQM), tbd. depending on achievement of optical verification

- Mirror models:
  - QM, SM and FM: QM for the CQM and then the RFQM
- Flight spares


Planck Instrument Calibration Plan
Unit
Assembly
Instrument
Satellite
In-flight
LFI
HFI
CSL Campaign
CPV & FLS
Qualification Model (QM)
Completed
Completed
Completed
Completed
Flight Model (FM)
Completed
Completed
Completed
Completed
Completed
Supported by Data Processing Centers

COrE Calibration

Classes of instrument parameters

1. **Photometric calibration:** Conversion of telemetry units to physical units (KCMB). Gain factors fwill be measured on the ground at several stages. The final calibration will be performed in-flight.

2. **Relative calibration:** stability of the gain, 1/f noise, noise spectra, zero-level stability. The redundancy of the scanning strategy will help on this.

3. **Thermal effects:** systematics induced by thermal fluctuations in the 0.1 K, 1.7 K, 4 K, 20 K, and 300 K stages; cooler induced microphonics. Thermal susceptibility of detector response. Verify that temperature sensors H/K provide sufficient monitoring of instrument thermal configuration and stability.

4. **Detector chain non-idealities:** detector (TES ot KIDs) characterization, detector time-response; non-linearity of the detector response; nonlinearity of ADC converters; impact of cosmic rays; sensitivity to microphonics, temperature susceptibility, cross-talk.

5. **Spectral calibration:** filter characterization (module level), detailed bandpass measurements. These measurements will be done on the ground, as no sweeping sources is planned on the satellite. In-flight verification of the measured bandpasses will be possible through observation of diffuse and point sources with steep spectra.

6. **Optical calibration:** main beam determination, near side-lobes, far side-lobes (both total intensity and polarization). Direct measurements of the main beams and near lobes in-flight from planets and strong polarization sources. Cross-polarization, reflection. Alignmant. Pointing.

7. **Polarization-specific calibration:** polarization efficiency and polarization angle of each detector; These will be measured both on-ground and in-flight.

8. **Noise characterization:** detailed measurements of the noise properties (noise power spectrum, 1/f noise, possible non-gaussianity) and their time evolution.

COrE Optical calibration

Objective of test/ measurement	Requirements	On-ground (at what stage)	In-flight	Instrument model verification
Optical coupling at FPA	*FWHM (Edge taper): 30dB* *Losses < 0.1dB* *Reflections: VSWR > 40dB* *Cross-polarization: <30dB*	*- Single detector* *- Module* *- Instrument*	*N/A*	*Compare to GRASP simulations* *Feeds/lenses prototypes*
Main beam determination *Both total intensity and polarization*	*FWHM per freq (value spread)* *Ellipticity <* ***1.1***	*- Single detector* *- Module* *RFQM (With telescope)*	*Direct measurements of main beam exploiting signals from ALL external planets* *Strong polarization sources: polarized beams*	*Compare to GRASP simulations* *Beam variation in-band*
Sidelobe determination *- near side-lobes,* *- far side-lobes* *Both total intensity and polarization*	*Rejection needed for: Galaxy,* *Sun, Earth, Moon* ***20dB lower than Planck***	*RFQM (With telescope)*	*Intermediate sidelobes down to -35 dB to -40 dB with Jupiter will be possible in-flight*	***Trade off edge taper with angular resolution*** *Compare to GRASP simulations* *Beam variation in-band*
Internal straylight	*Limit background on detectors from* *- FPA environment* *- P/L environment* *- Baffle*	*- Single detector* *- Module* *- Instrument* *- CQM* *- PFM (at CSL)*	*May be able to test during cooldown*	*Thermal model* *Emissivity* *Baffle*
Filter characterization	*- Band definition (from comp sep)* *- Bandwidth (sensitivity)* *- Consider CO lines (and other moloecules)*	*- Unit/Module level* *- CQM (cryo conditions)*	*N/A*	*Filter models* *Filters prototypes*

Planck Telescope: alignment

- Mechanical alignment
- Photogrammetry
- Specific RF component added on FPU for ground tests
  - Extra horn + diode at 320 GHz (RTH)

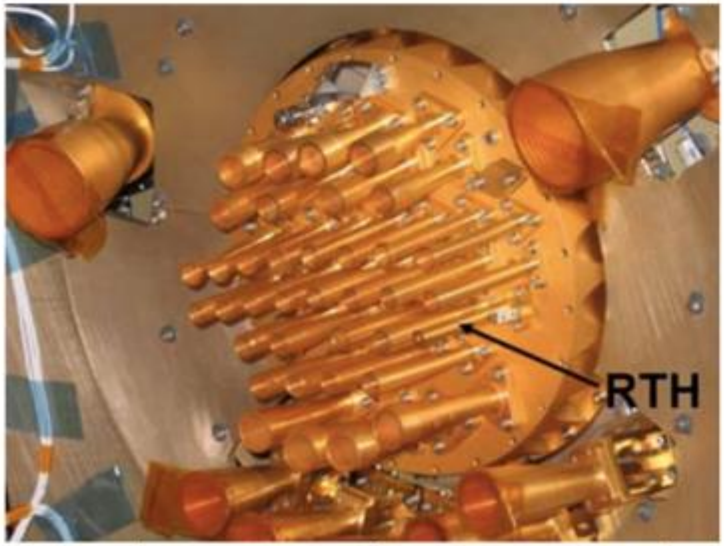
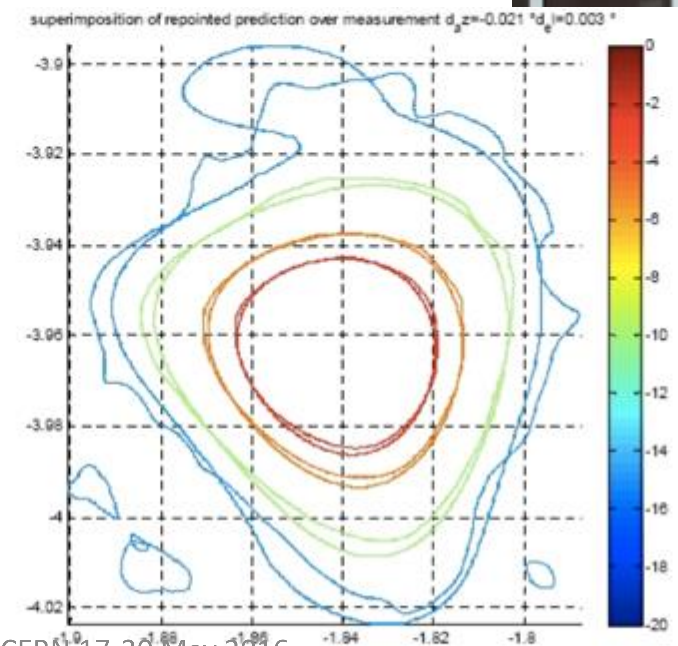


Fig.3. The 320 GHz Reference Test Horn in Planck's Focal Plane



Planck RFQM & Optical Calibration

Planck RFQM campaign:
QM mirrors and representative FPU and limited number of frequencies
At room temperature

Frequency	AZ max RF (°)	EL max RF (°)
30	7.78	-1.85
70	6.09	2.53
100	5.40	-1.10
320	3.88	1.05

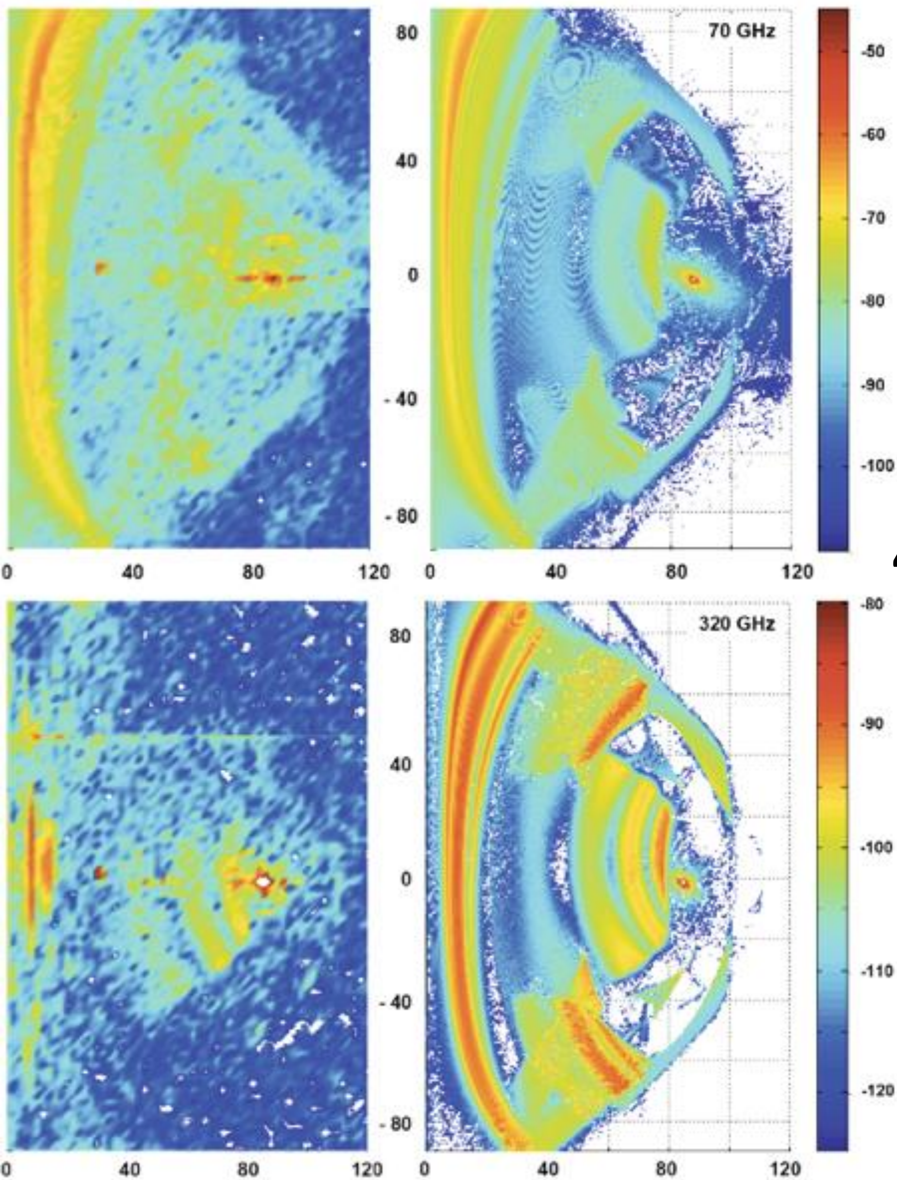
Table 1: Measured angular direction (main lobe)

Compare measured beam parameters with accurate optical model

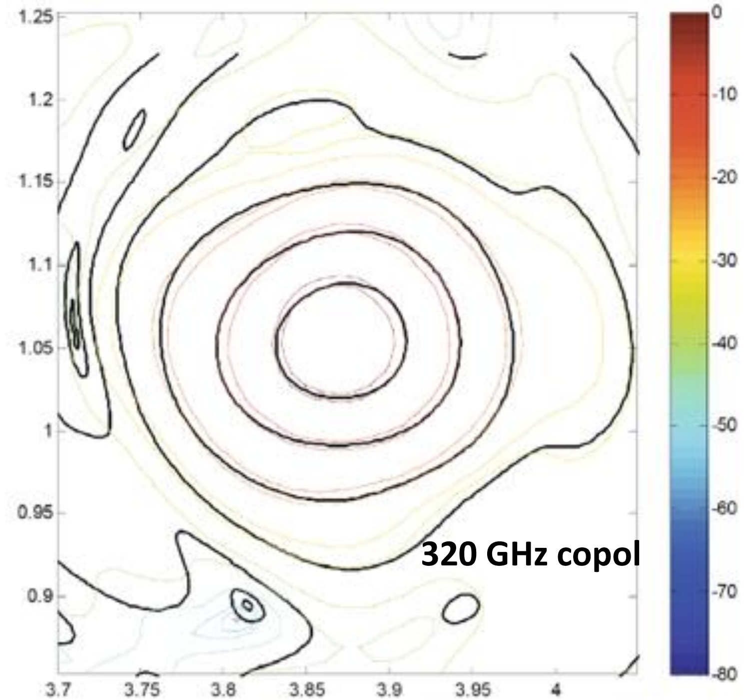
Beam verification for Planck

Comparison between simulations and measurements

Measured **Simulated**

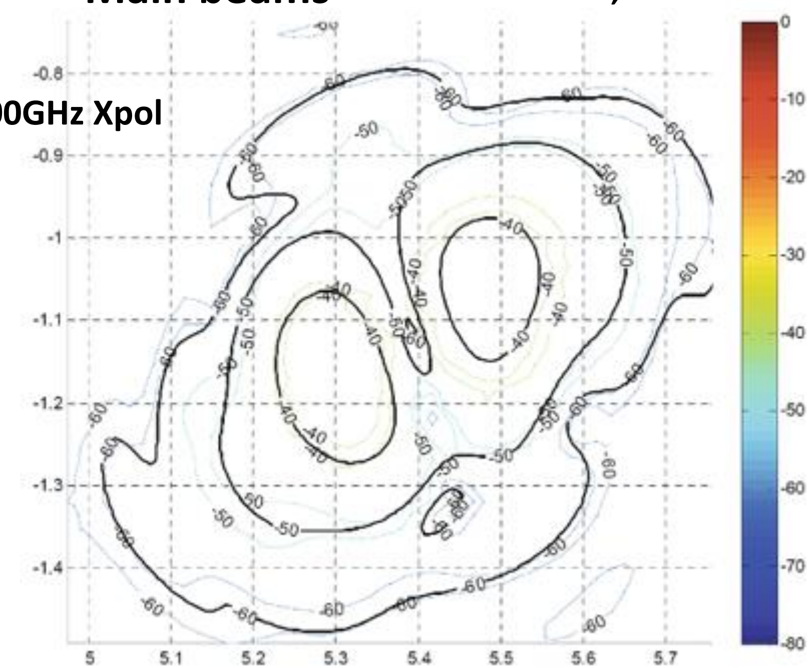


4π



Main beams **Tauber J. et al, A&A 2010**

100GHz Xpol



Optical simulations

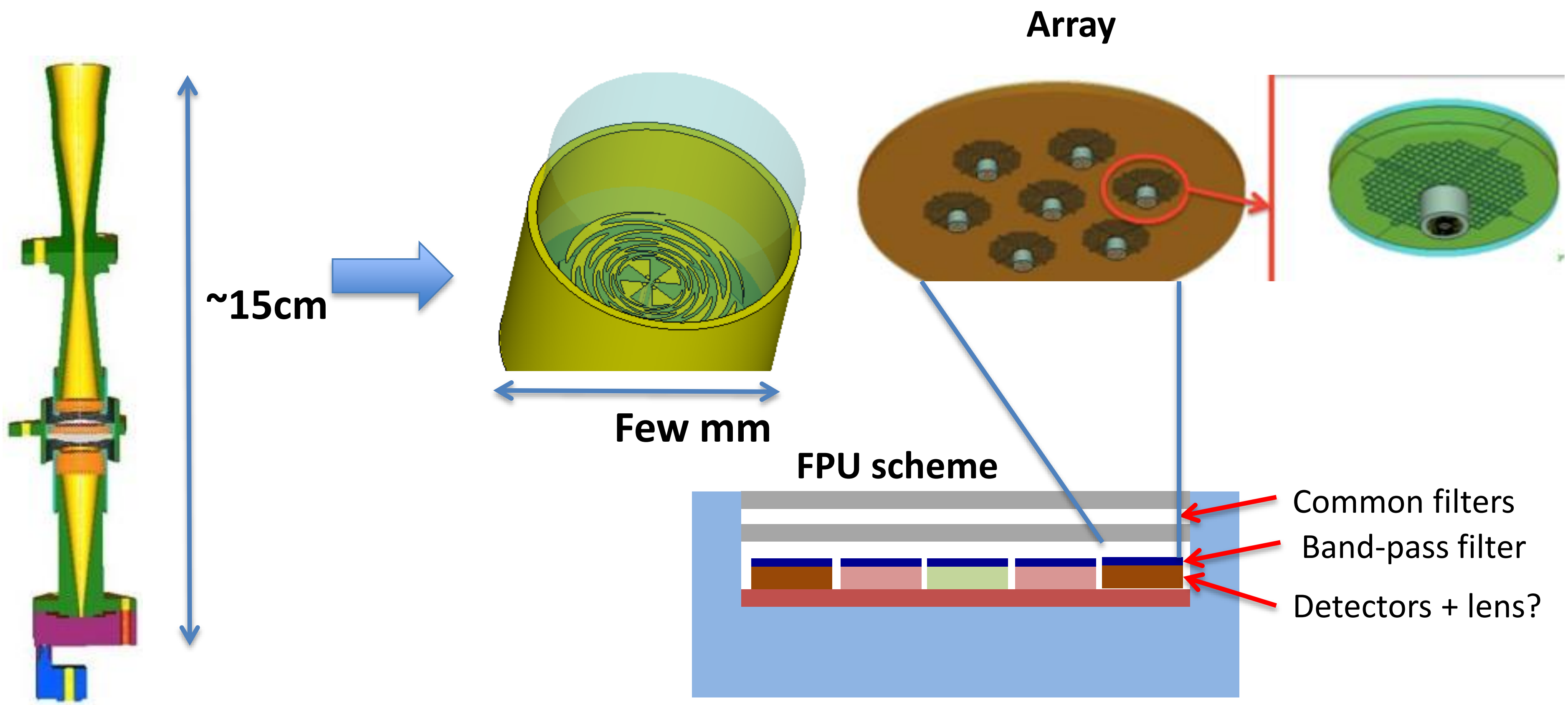
- Very good agreement between RF measurements and GRASP simulations
- Further progress in optical simulations performed since then
  - Talk from F. Villa, M. Sandri et al
  - GRASP adapted for focal surface evaluation (WaFER tool)
- Other tools will most probably need to be developed
  - We need an excellent RF model of the instrument
  - Tools developed for R&D need to be adapted
  - FEA, MoM,…..
  - Then fed back into GRASP

Optical testing and verification From Planck to COrE

- Similarities
  - Telescope: Can re-use the same technology
  - Can re-use verification / alignment procedures ?
- Differences
  - Many more pixels (10s to 1000s) + More spectral bands (9 to 15?)
    - → which testing strategy? Test on samples for components? Then rely on integrated tests on overall instrument?
  - Calibration needs more accuracy
    - due to increase sensitivity (x30) → need to have a better understanding of the instrument / reduce systematics
    - Will need to use more accurate testing equipment
  - Different technology
    - Use of planar / lens technology with possibility of cold stop and potentially higher straylight

FPU Technology

- 1000s of pixels → Is it realistic to use horns?
- If European technology used
  - Use of planar / lens technology with possibility of cold stop and potentially higher straylight



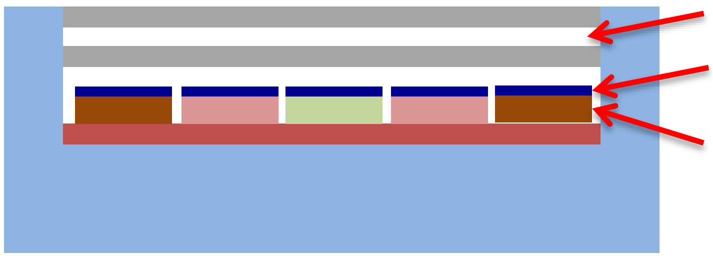
HFI bolometric detector

How to get an accurate representative measurement?

Equivalent of RFQM beam measurement

Cold stop ?

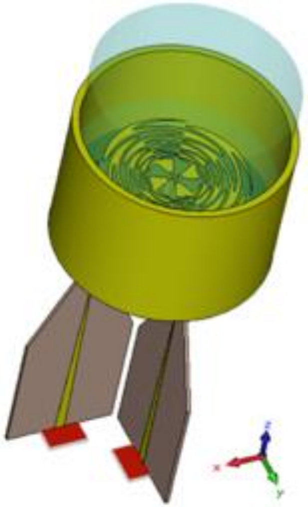
Baffles



?

- Telescope with a cold instrument in CTR?
  - Unlikely feasible by industry (Thales, Airbus space) or at a huge cost
  - Warm instrument → need to replace detector
  - Could we think of a test at Liege facility?
  - Will need combination of validation tests

Design of cavity-backed sinuous antenna with baluns. ▶



Conclusion on Calibration and Verification

- Calibration and Verification for COrE will be extremely challenging
  - More detectors, more bands, higher specs
- Strategy has to be thought well in advance
- Need to re-use what has been used for Planck as much as we can
  - But not all tests can be re-cycled
  - Will need to come up with new tests depending on technology used
- We probably need to include a calibration strategy / plan in the proposal