ESA ITT AO/1-7136

Large Radii Half-Wave Plate (HWP) Development

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COrE / PRISM workshop for a M4 ESA Mission, APC - Paris,10-11/02/2014

Task 1 - HWP requirements

Task 2 - Concept Design Selection

Task 3 - Modulator baseline Design and Analysis

- RF preliminary design
- Thermo-mechanical design

Task 4 - Critical Breadboards Definition and Analysis

- RF critical breadboards
- Thermo-mechanical critical breadboards

Task 5 - Critical Bread-boards Manufacture and Tests

- RF critical breadboards manufacture and room temperature tests
- RF critical breadboards cryogenic tests
- Thermal critical breadboards manufacture and tests
- Mechanical critical breadboards manufacture and tests

Task 6 - Modulator baseline Design Update

- Detailed RF analysis
- Detailed Thermo-Mechanical analysis

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- Rotation mechanism manufacture and cryogenic tests
- HWP system cryogenic tests

Task 8 - Conclusion and Development Plan

HWP systematics

$$\mathbf{J}_{\rm hwp}^{\rm ideal} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{J}_{\rm hwp} = \begin{pmatrix} 1+h_1 & \zeta_1 e^{i\chi_1} \\ \zeta_2 e^{i\chi_2} & -(1+h_2)e^{i\beta} \end{pmatrix}$$

O-Dea et al. 2007

- h_1 & h_2: departure from unitary transmission along HWP axes

$$h_{1,2} = \sqrt{T_{C,L}} - 1$$

- $\beta = \psi - \pi$: departure of the differential phase-shift ψ from its ideal value of π

- ζ_1 & ζ_2: cross-polarization response, leakage between axes

$$\text{x-Pol(dB)} = 20 \log_{10} \zeta$$

→ **Analysis of the HWP systematics impact on the science**

HWP Requirements

Systematic	Parameters	Requirement	Goal
HWP efficiency	η_{HWP}	>76%	>80%
Phase shift	β	$< 40^\circ$	$< 30^\circ$
	σ_β	$< 0.17^\circ / \sin\beta$	$< 0.07^\circ / \sin\beta$
Transmission	$\lvert\Delta h\rvert = \lvert h_1 - h_2\rvert$	< 0.05	< 0.05
	$\lvert h_1\rvert, \lvert h_2\rvert$	< 0.12	< 0.1
	$\sigma_{h_1}, \sigma_{h_2}$	< 0.02	< 0.02
	T_C	> 0.76	> 0.8
	T_L	> 0.76	> 0.8
	$\lvert T_C - T_L\rvert$	< 0.1	< 0.1
	σ_{T_C, T_L}	< 0.04	< 0.04
Cross polarization	ζ_1, ζ_2	< 0.02	< 0.02
	$\sigma_{\zeta_1, \zeta_2}$	< 0.002	< 0.002
	$\sigma_{\zeta_1, \zeta_2}$	< 0.002	< 0.002
	x-Pol	-34 dB	-34 dB
	$\sigma_{\text{x-Pol}}$	-50 dB	-50 dB
HWP induced ellipticity	ε_{HWP}	<2%	<1%
Flatness[a]	Δx	$< 20\ \mu\text{m}$	$< 20\ \mu\text{m}$
Modulated dis-homegeneity	h^{mod}	<0.001	<0.001
Thermal stability	NET_{HWP}	$\lesssim \frac{1\mu\text{K}/\sqrt{\text{Hz}}}{\mathcal{R}}$	$\lesssim \frac{1\mu\text{K}/\sqrt{\text{Hz}}}{\mathcal{R}}$

a. The rotating HWP shall be compatible with operation at temperatures below 50K, with a goal of 10 K.

b. Cooling of the HWP shall be achieved by conductive/radiative heat transfer only.

c. The dissipation of the HWP including mechanism shall be below 100mW at 50K with a goal of 10mW at 10K.

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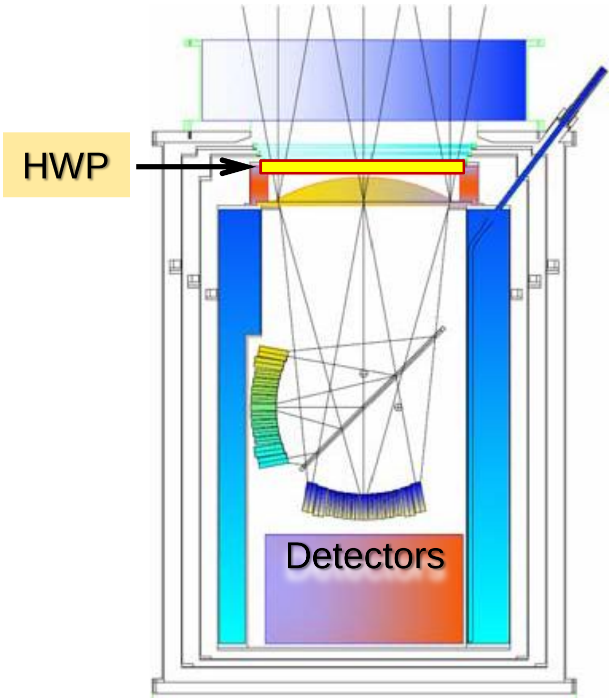
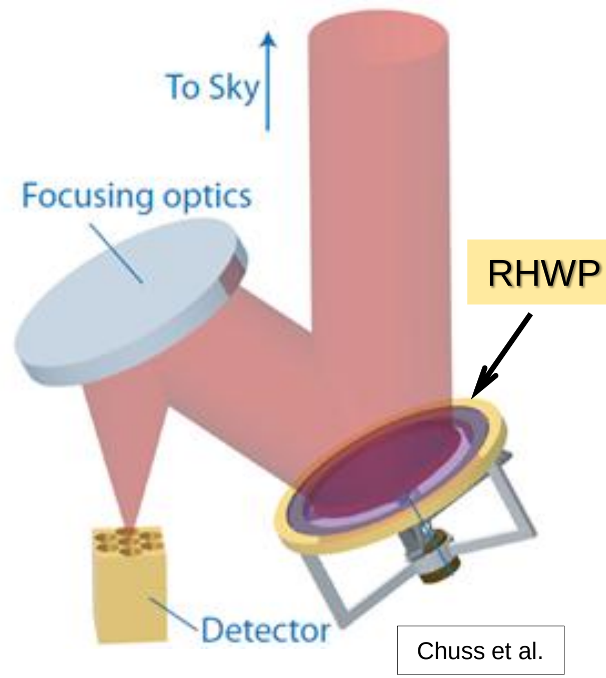
Polarisation modulator types

Refractive Modulators



B-Pol like

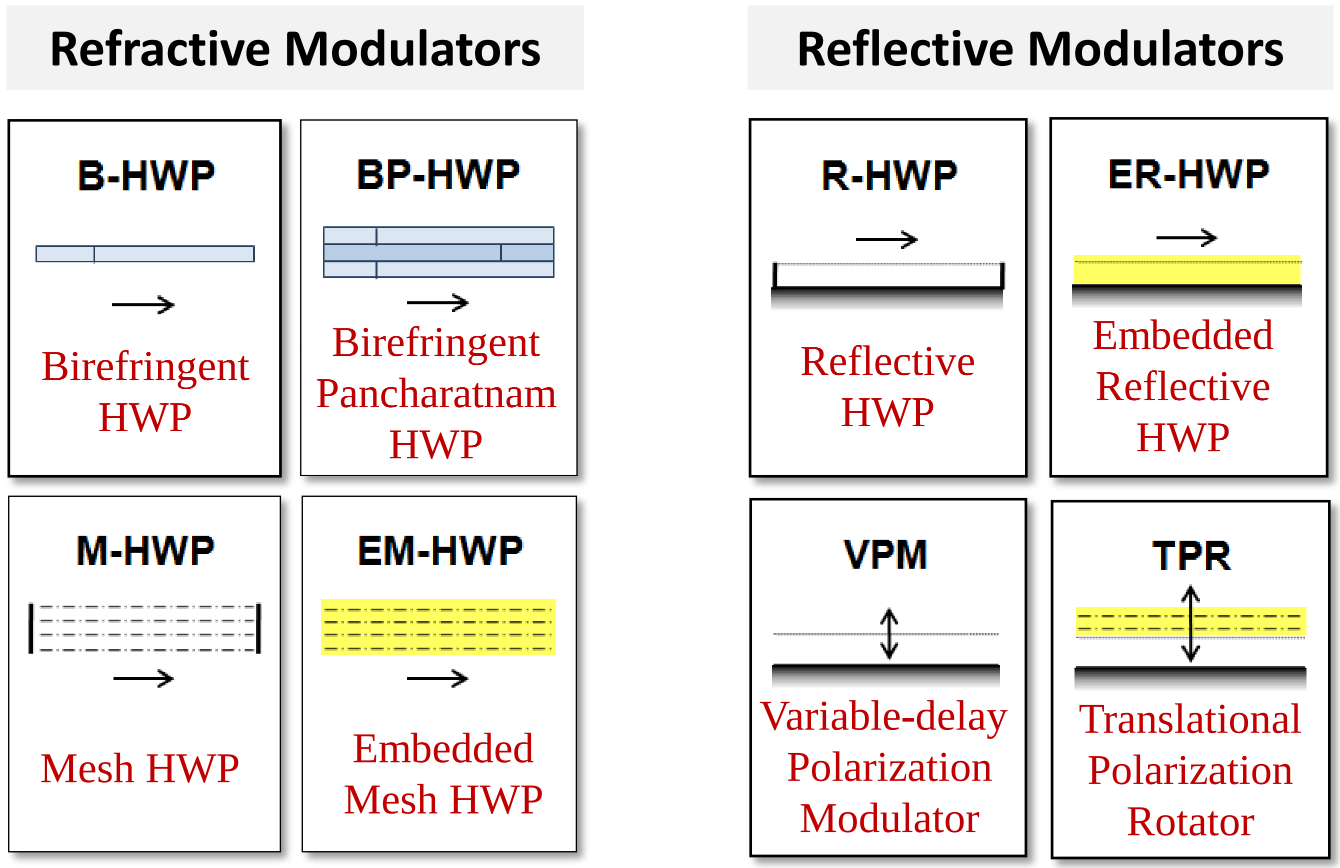
Reflective Modulators



COrE like

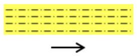
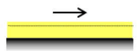
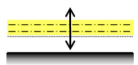
→ ITT goal to manufacture a 120 cm diameter HWP prototype

Half Wave Plate options



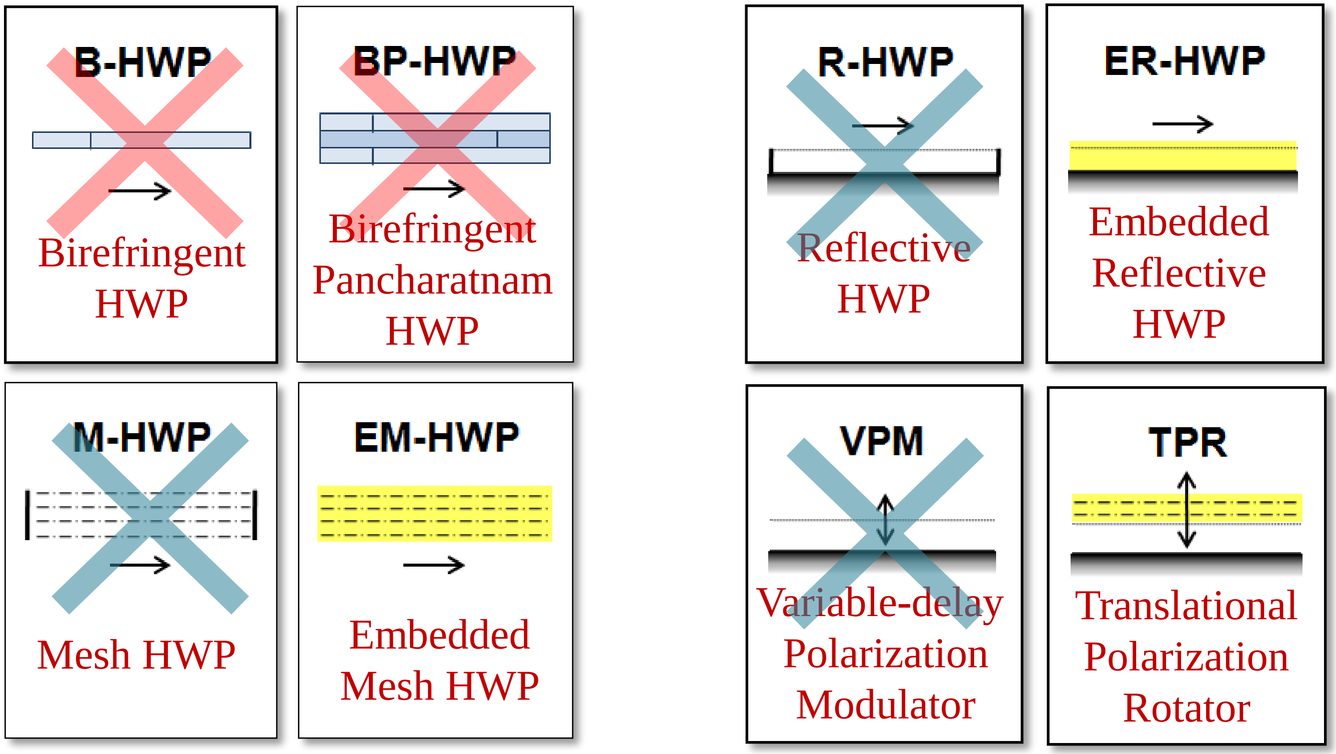
Fundamental aspects of the HWP technologies that are key for their trade-off:

- **HWP manufacturability**
- **HWP Radio Frequency (RF) performance**
- **HWP suitability for cryogenic and mechanical operation in a space environment**

Manufacture	**Transmission modulators**				**Reflection modulators**			
Mechanical modulation	**Rotation**				**Rotation**		**Translation**	
Material	**Birefringent crystal**		**Metal grids**		**Metal grids + Flat mirror**			
Modulator type	**Single Plate**	**Multi-Plate Pancharatnam**	**Air-gap Mesh-HWP**	**Embedded Mesh HWP**	**Air-gap Reflective HWP**	**Embedded Reflective HWP**	**Variab. delay Polarization Modulator (VPM)**	**Translational Polarization Rotator (TPR)**
Modulator sketch	B-HWP 	BP-HWP 	M-HWP 	EM-HWP 	R-HWP 	ER-HWP 	VPM 	TPR 
Material availability	Limited to ~30 cm ∅ (Sapphire)	Limited to ~30 cm ∅ (Sapphire)	> 120 cm ∅ (Cu on PP)	> 120 cm ∅ (Cu on PP)	> 120 cm ∅ (Cu on PP)	> 120 cm ∅ (Cu on PP)	> 120 cm ∅ (Cu on PP)	> 120 cm ∅ (Cu on PP)
Mechanical robustness	High	High	Very Low	Medium	Very Low	High	Very Low	Medium
Relative Mass (without mechanism)	High (crystal)	High (crystal)	Very low (thin plastic)	Low (bulk plastic)	High (mirror)	High (mirror)	High (mirror)	High (mirror)
Maximum achievable diameter at JBCA	~30 cm	~30 cm	52 cm	33 (52 cm) 120 cm	52 cm	33 (52 cm) 120 cm	52 cm	33 (52 cm) 120 cm
Group expertise	Yes	Yes	Yes	Yes	Yes	Yes	NASA coll.	Yes

Advantage		**Disadvantage**		**Not usable**		**Grant goal**	

Manufacture issues



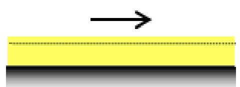
- Birefringent crystals limited dimensions (~30cm∅)
- Free standing grids and substrates fragility for large diameters
- ER-HWP, EM-HWP and TPR all share same photolithographic technology

RF performance	Transmission modulators				Reflection modulators			
Mechanical modulation	Rotation				Rotation		Translation	
Material	Birefringent crystal		Metal grids		Metal grids + Flat mirror			
Modulator type	Single Plate	Multi-Plate Pancharatnam	Air-gap Mesh-HWP	Embedded Mesh-HWP	Air-gap Reflective HWP	Embedded Reflective HWP	Variab. delay Polarization Modulator (VPM)	Translational Polarization Rotator (TPR)
Modulator sketch	B-HWP	BP-HWP	M-HWP	EM-HWP	R-HWP	ER-HWP	VPM	TPR
Modulated Stokes parameters	Q & U	Q & U	Q & U	Q & U	Q & U	Q & U	Q or U	Q & U
Maximum bandwidth	Narrow	Very Broad ~110%	Broad ~80%	Broad ~100% **T3.1**	Narrow	Narrow **T3.1**	Narrow	Narrow
Multiple sub-bands	Need periodic ARC	Limited to max BW	Limited to max BW	Lim. to max BW **T3.1**	Periodic	Periodic **T3.1**	Periodic	Limited by QWP BW
Modulation efficiency	> 99%	> 99%	> 99%	> 99% **T4.1a,b, 5.1,2**	> 90%	> 90% **T4.1a,b, 5.1,2**	> 90%	> 90%
Transmission / Differential transmission	> 90 % < 1 %	> 90 % < 1 %	> 90 % < 1 %	> 90 % / < 1 % **T4.1a,b, 5.1,2**	Not applicable	Not applicable	Not applicable	Not applicable
Reflection/ Differential Reflection	3% 0.1%	3% 0.1%	4% 2%	< 4% / 2% **T4.1a,b, 5.1,2**	> 98 % < 1 %	> 98% / < 2% **T4.1a,b & 5.1**	> 98 % < 1 %	> 98% / < 2%
On-axis Average Cross-Polarisation	< -20 dB (6% BW)	< -20 dB (110% BW)	< -20dB (80%BW)	-35dB (25% BW) **T4.1a,b, 5.1,2**	< -30dB	Not available **T4.1a,b & 5.1**	Not Available	Not available
Co-Polar beam impact Ellipticity	Not available	Not available	Not available	~1% (25% BW) **T4.1c & 5.1**	<1%	Not available **T4.1c & 5.1**	Not available	Not available
Cross-Polar beams	Not available	~ -30dB	Not available	<-35dB (25%) **T4.1c & 5.1**	< -30dB	Not available **T4.1c & 5.1**	Not available	Not available
Flatness / Homogeneity	Very high	High	High	High **T4.1d & 5.1**	High	High **T4.1d & 5.1**	High	High

Advantage		Disadvantage		Not usable		Will be verified	by Task #

RF performance issues

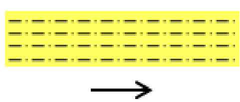
ER-HWP



Embedded Reflective HWP

- Periodic narrow bands across all COrE channels
- Ellipticity & Cross-pol at low levels in air-gap version

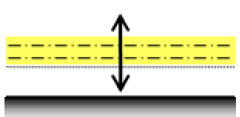
EM-HWP



Embedded Mesh HWP

- Bandwidth presently limited to ~100% (180% required)
- Low Ellipticity & Cross-pol

TPR



Translational Polarization Rotator

- Limited bandwidth, similar to EM-HWP

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Large radii HWP development

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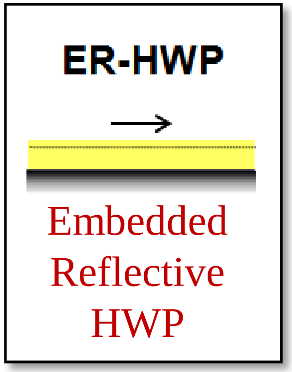
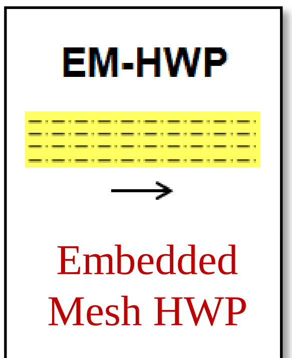
Cryo-mechanical	**Transmission modulators**				**Reflection modulators**			
Mechanical modulation	**Rotation**				**Rotation**		**Translation**	
Material	**Birefringent crystal**		**Metal grids**		**Metal grids + Flat mirror**			
Modulator type	**Single Plate**	**Multi-Plate Pancharatnam**	**Air-gap Mesh-HWP**	**Embedded Mesh HWP**	**Air-gap Reflective HWP**	**Embedded Reflective HWP**	**Variab. delay Polarization Modulator (VPM)**	**Translational Polarization Rotator (TPR)**
Modulator sketch	B-HWP	BP-HWP	M-HWP	EM-HWP	R-HWP	ER-HWP	VPM	TPR
Modulation mechanism	Cryogenic mechanical rotator						Cryogenic mechanical translator	
Mechanism cryogenic heat dissipation	Low **Task 4.2d & 5.3**						Not Available	
Waveplate robustness to cooling cycles	Low (ARC problems	Low (ARC problems)	High	High **T4.2a & 5.3**	High	High **T4.2a & 5.3**	High	High
Waveplate gradient Temperature	Low	Low	Not Available	Not available **T4.2b & 5.3**	Not Available	Not available **T4.2b & 5.3**	Not Available	Not Available
Waveplate low temperature emissivity	Sapphire < 1%	Sapphire < 1%	Low	Low **T4.2c & 5.3**	Low	Low **T4.2a & 5.3**	Low	Low
Waveplate low T differential emissivity	Low	Low	Low	Low **T4.2c & 5.3**	Low	Low **T4.2c & 5.3**	Low	Low

Advantage		**Disadvantage**		**Not usable**		**Will be verified**	**by Task #**

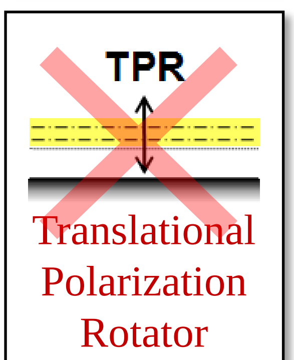
Cryo-mechanical issues



- Requires a relatively compact cryogenic rotation mechanism that can be tested in a small cryostat. It can be compatible with room temperature motor, via a simple shaft.
- Expertise with these systems.
- Thermal gradients across plate strongly reduced by mirror.



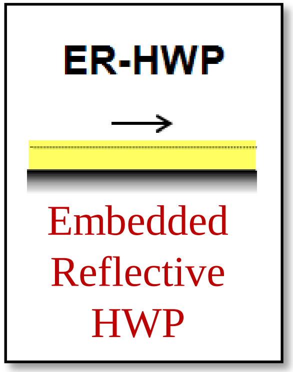
- Requires large cryogenic rotation mechanism and associated large dewar for testing
- Thermal gradients across plate to be investigated



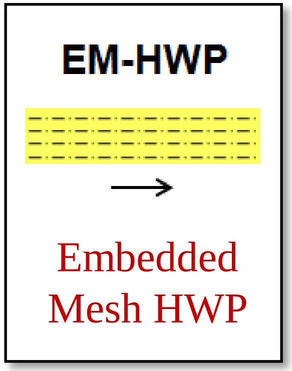
- Requires translation mechanism (no expertise within collab.)
- Thermal gradients across plate to be investigated

Task 2 Conclusions

Based on the previous considerations, we defined:



1) Baseline option



2) Backup solution

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Now

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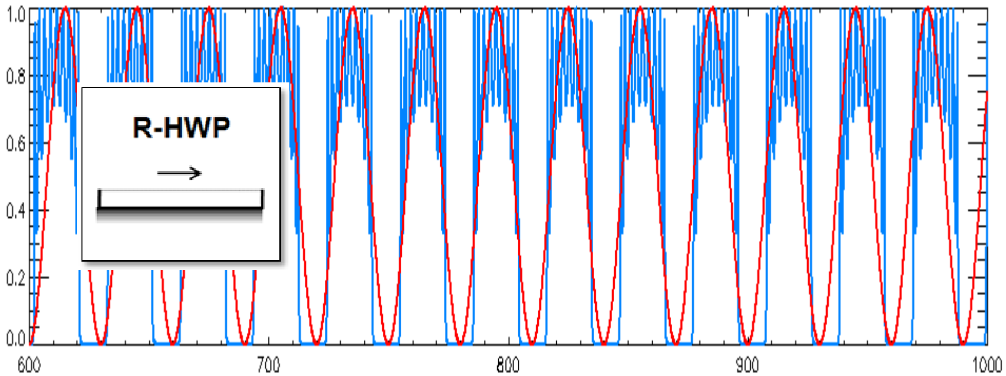
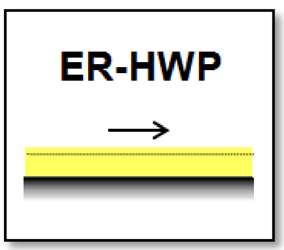
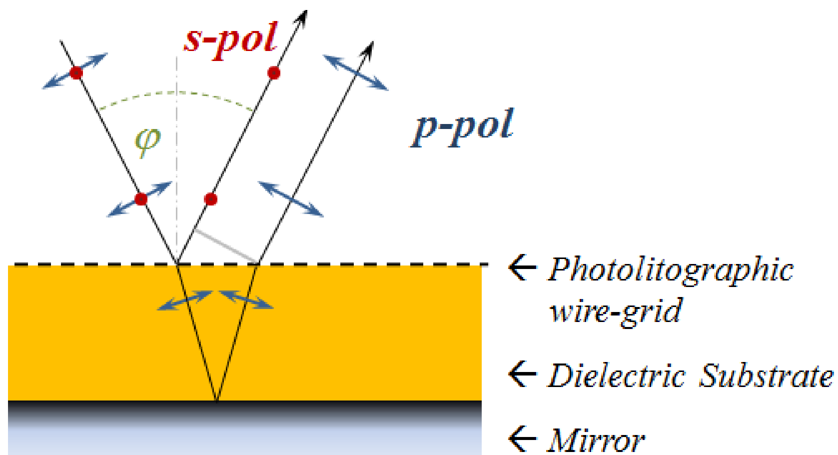
RF preliminary design



Air-gap R-HWP polarisation modulation efficiency (red) and possible sub-filtering transmission (blue) for a channel around 795 GHz **(COrE proposal)**





Under study:

- **Substrate impact on bandwidth (compared to air-gap version)**
- **Anti-reflection coatings, multiple dielectric layers, modified grids**
- **Impact on ellipticity and cross-polar beam**
- **Filtering for polarisation efficiency improvement**

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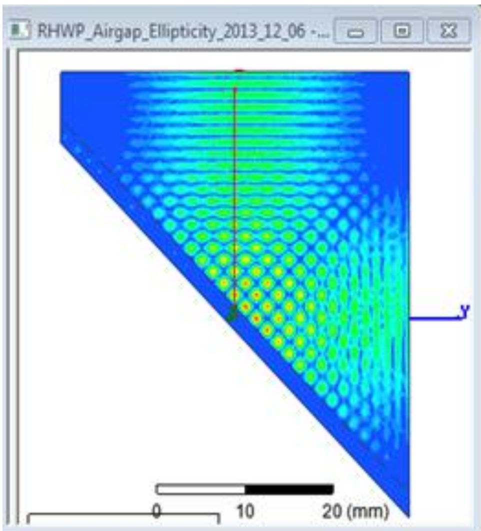
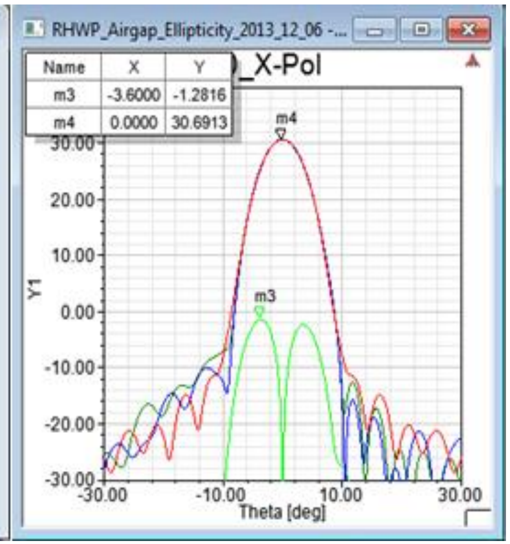
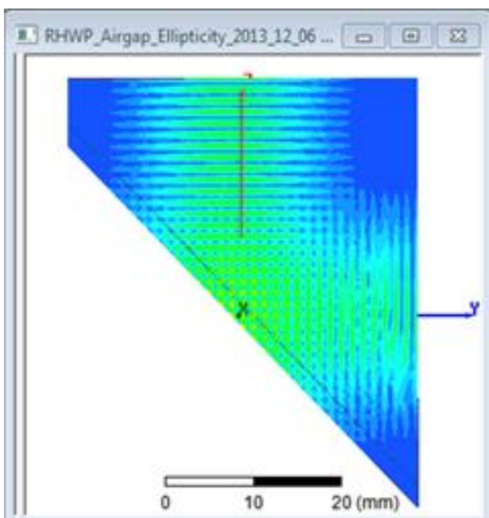
Ellipticity and Cross-polar beam simulations

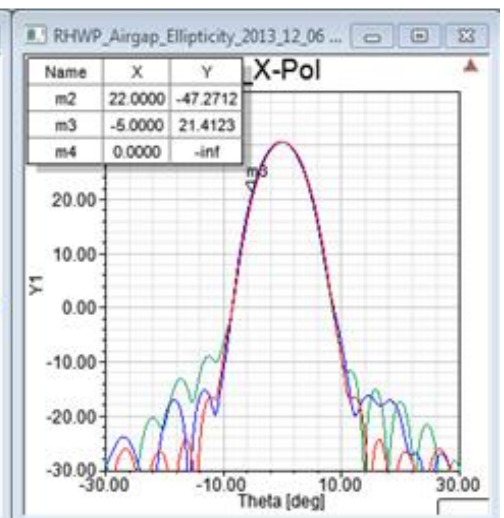
S - Pol





P - Pol



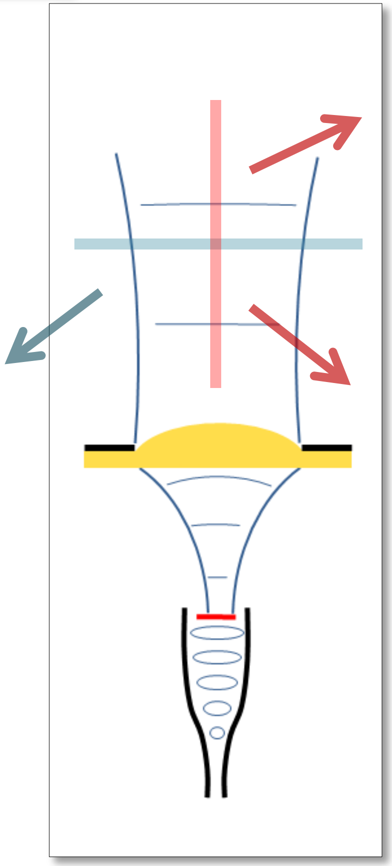


Preliminary results
Air-gap RHWP
ν = 120 GHz

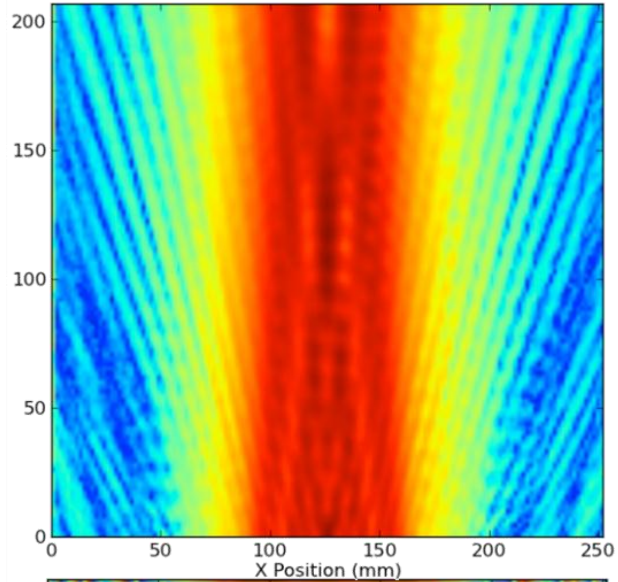
Ellipticity < 1%
Cross-pol < -30dB

Accurate RF Testing Example (100 GHz)

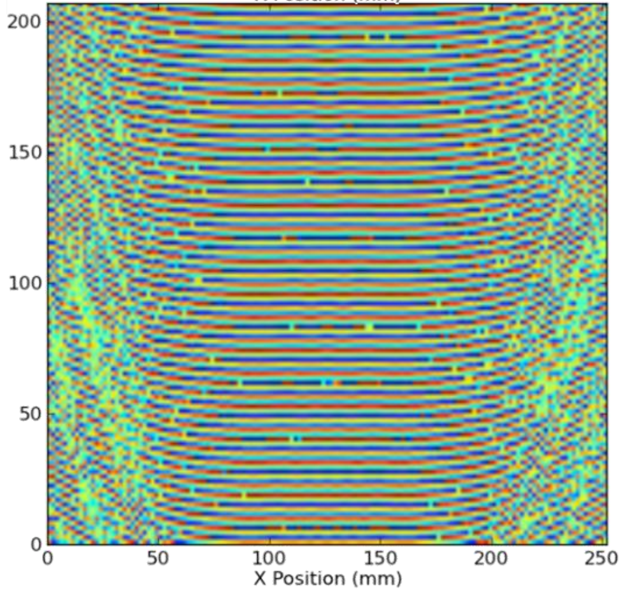
Plano convex lens



Longitudinal cut

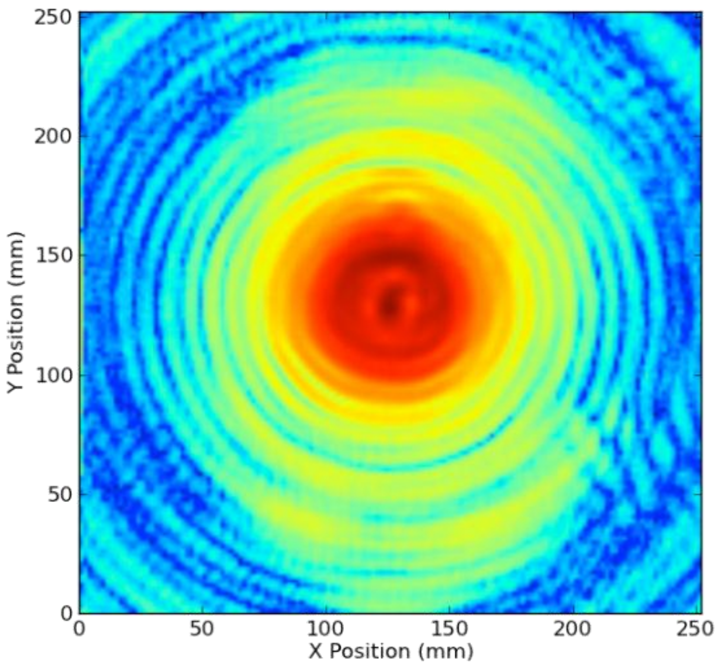


Intensity



Phase

Transversal cut - Intensity

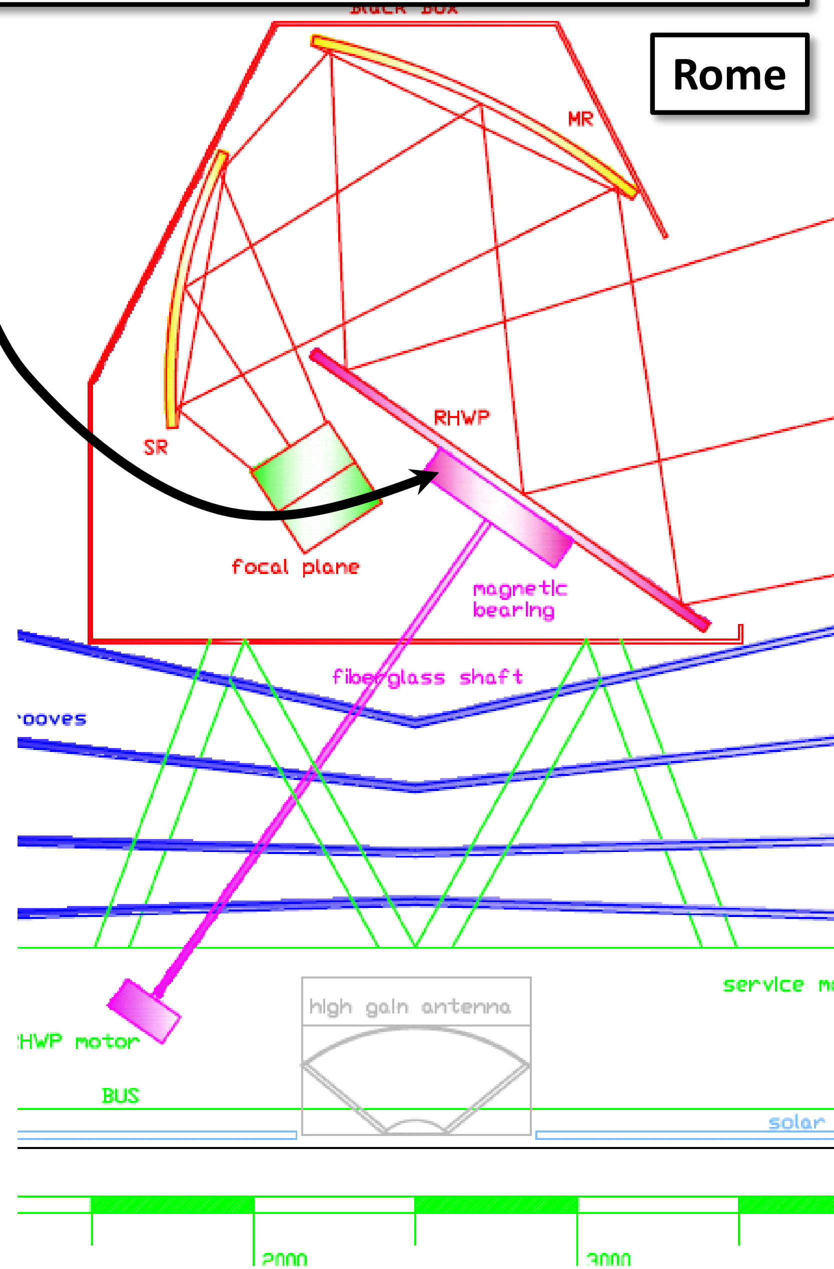


Ozturk,
Maffei, Schemmel
ESA Antenna
Workshop 2013

Rotator design concept

Rome

- Al honeycomb plate (for flatness, mass & inertia) with deposited ER-HWP: < 20 kg, < 5 kg m^2 rotating assembly. Lower mass & I with CFRP, also possible.
- Flexible Cu straps for temperature uniformity
- Latched at launch
- Low conductivity shaft connecting HWP assembly to motor in service module (conductivity of shaft << conductivity of supports: (8 mW with no intermediate heat sinks, less with intermediate straps to V-grooves))
- At the moment, ϕ1.5m RHWP looks feasible



Facilities Upgrade at JBCA

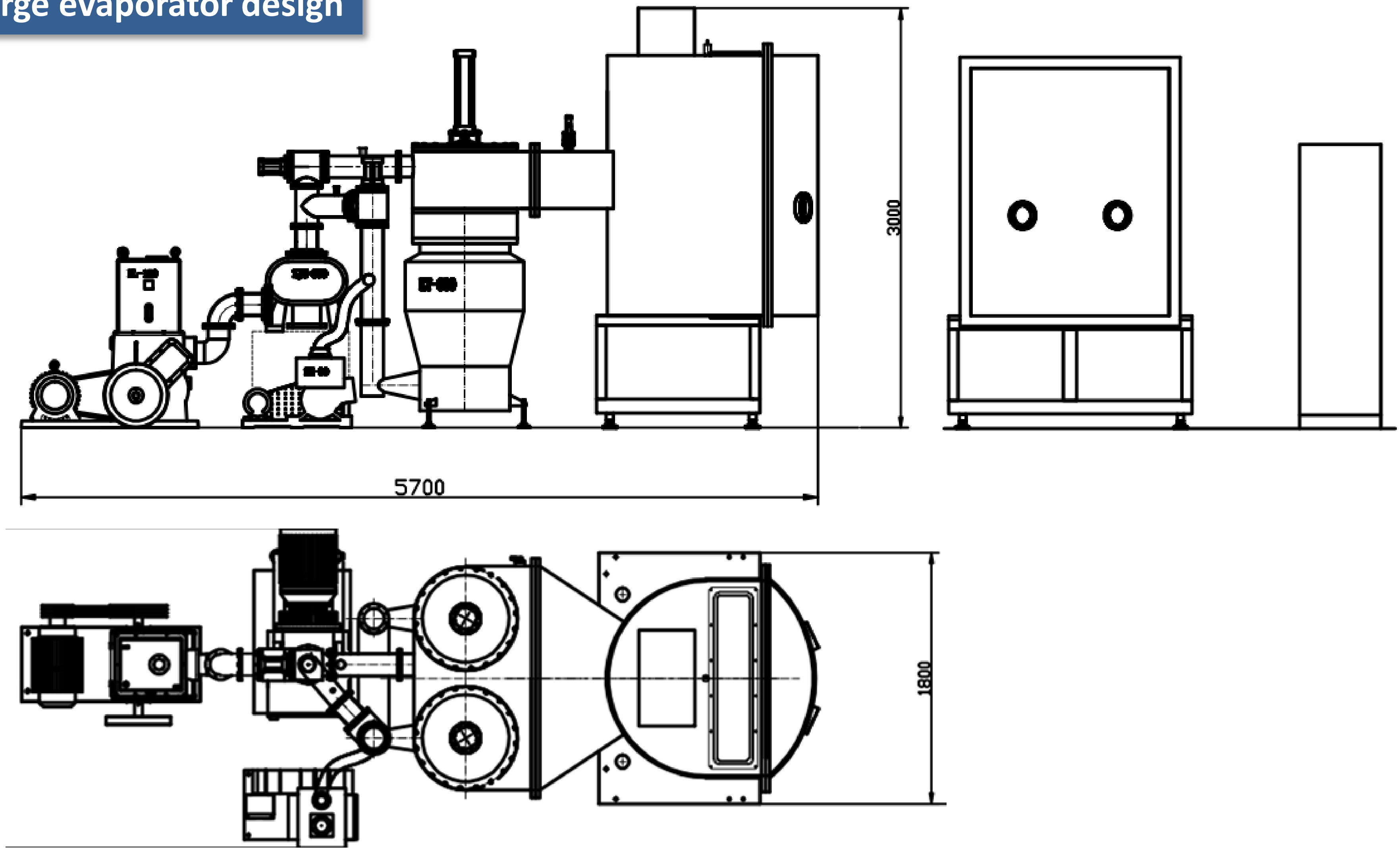
- New enlarged cleanroom (ready)
- Large evaporator (ordered, under manufacture)
- Etching tanks for photolithography (assembling)
- Large exposure box (assembling)
- Large vacuum press oven (designed)
- Photoresist spray XY table (ongoing tests)

Clean room enlargement

JBCA Manchester

Manchester University investment

Large evaporator design



Custom made evaporator for metal coating (1.4m diameter)

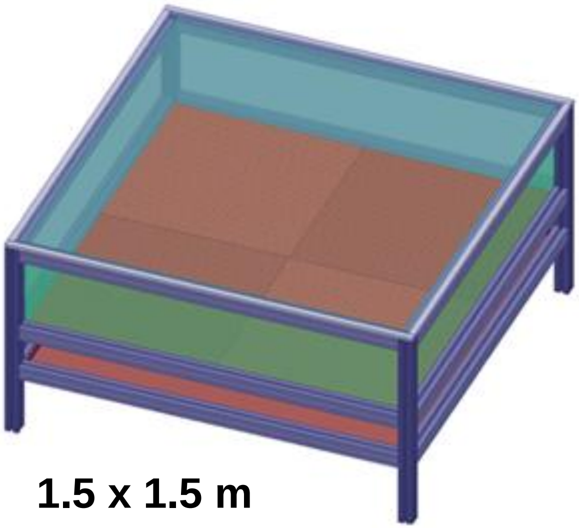
Large evaporator example

Shanghai Vakia Coating Technology Co. Ltd.

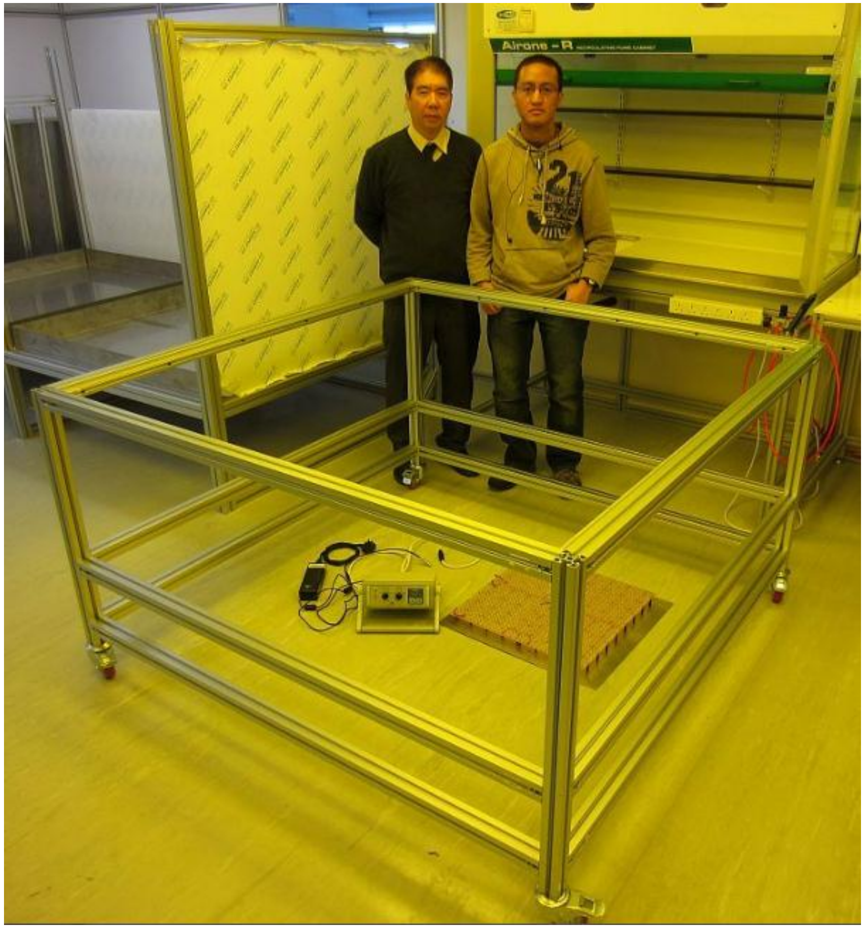
Vacuum chamber

Rotary and diffusion pumps

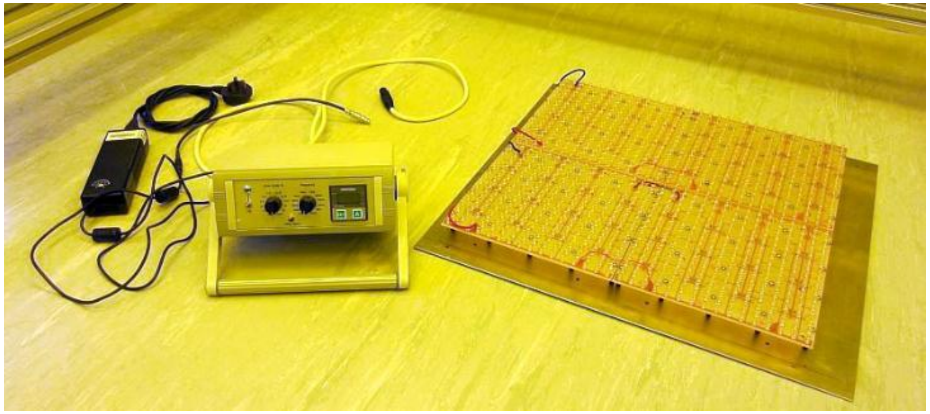
UV exposure box



1.5 x 1.5 m

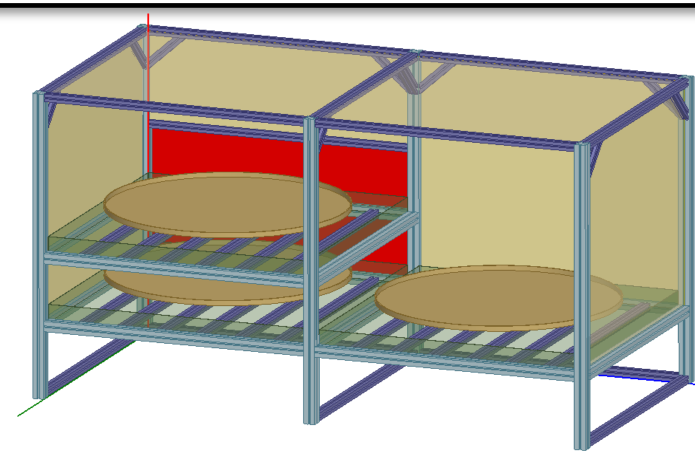


UV exposure table for 1.2m samples



UV LED power supply and controller

Photolithography etching



Processing tanks and support frame for 1.2m samples

Uniform flow liquid circulation system

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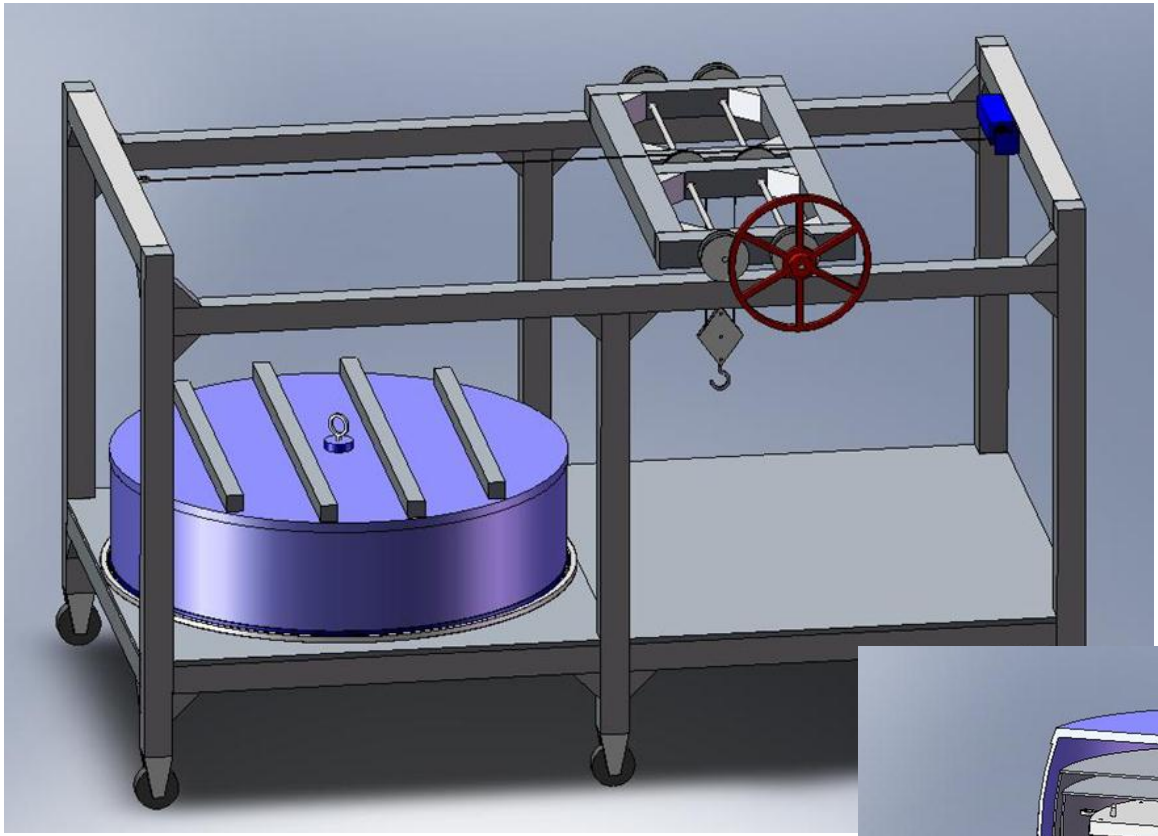
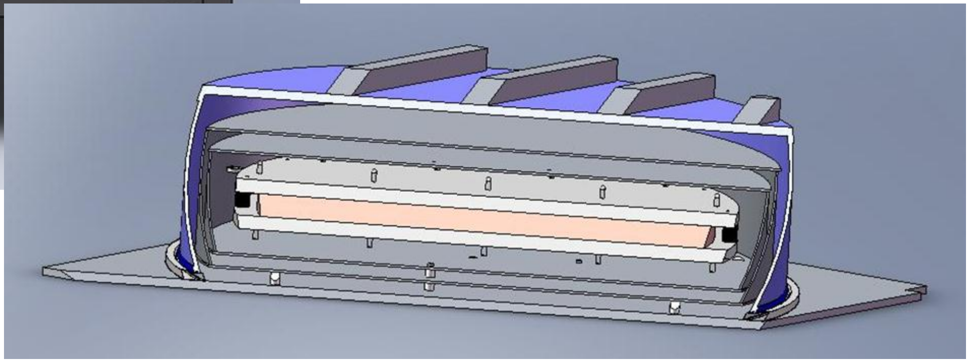
Large radii HWP development

Very Large Press Oven

Vic Haynes



Structure for oven operations



Internal shields structure

Conclusions

- **Project officially started in October 2013→ ~ 1 yr left**
- **On-going development of facilities for unprecedented large diameter devices**

  → From 30cm to 120cm ∅
- **Embedded Reflective HWP design selected as baseline option**
  - Channels bandwidth might be improved adding grids, modifying geometries

    → Non-periodic wider sub-bands
- **ER-HWP systematics experimental characterisation**
  - Very accurate lab measurements will be performed to validate our models
- **Development of the rotation mechanism**
  - Cryogenic lab measurements will be carried out
  - Rotator for a ~1.5m ∅ waveplate looks feasible
- **Waveplate dimensions**
  - In principle, same type of instrumentation to manufacture >1.5m ∅