Space-EPS* – a space suitable engineering model of an entangled photon source

* funded by the European Space Agency under contract No. 4000112591/14/NL/US

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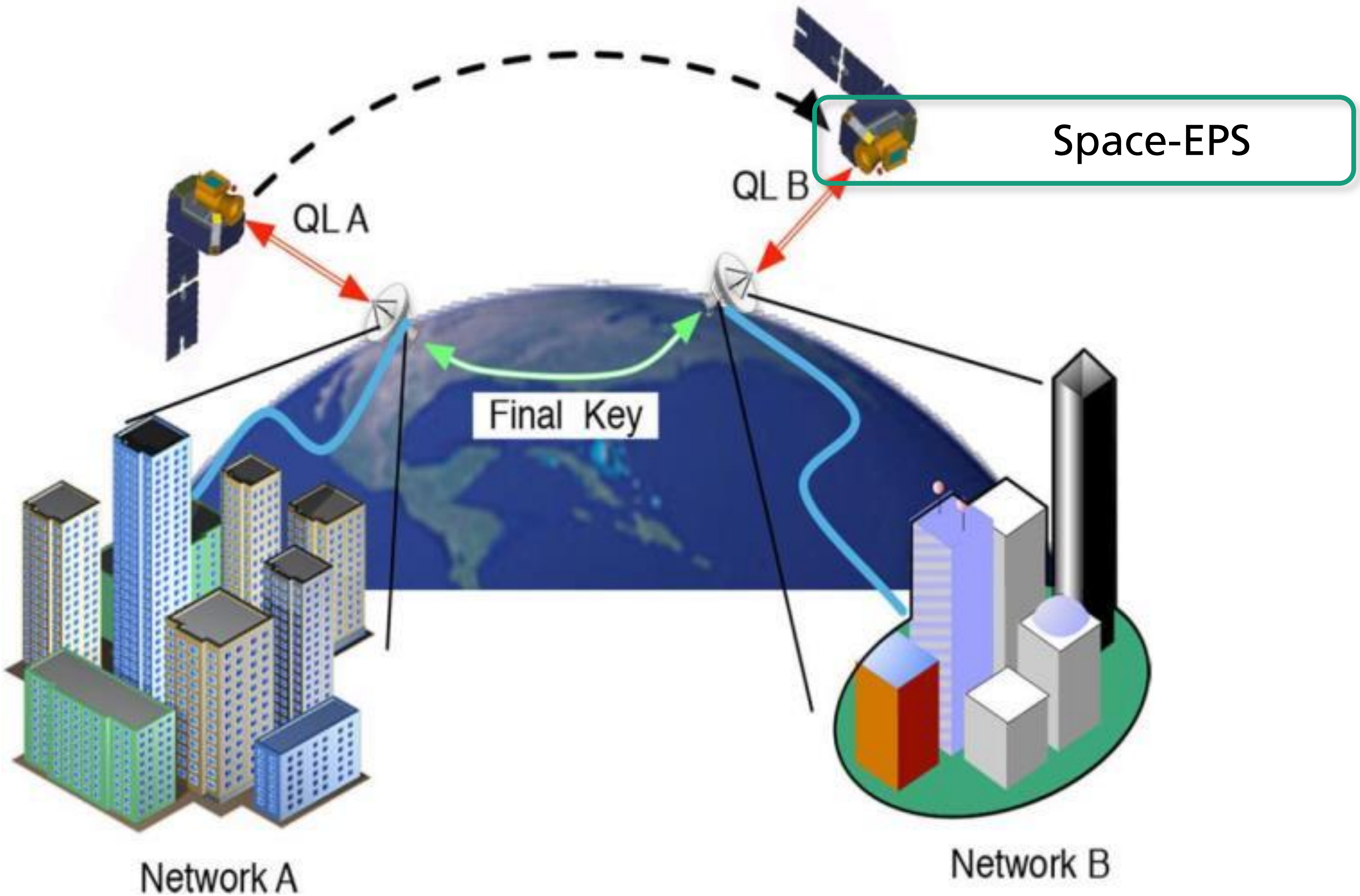
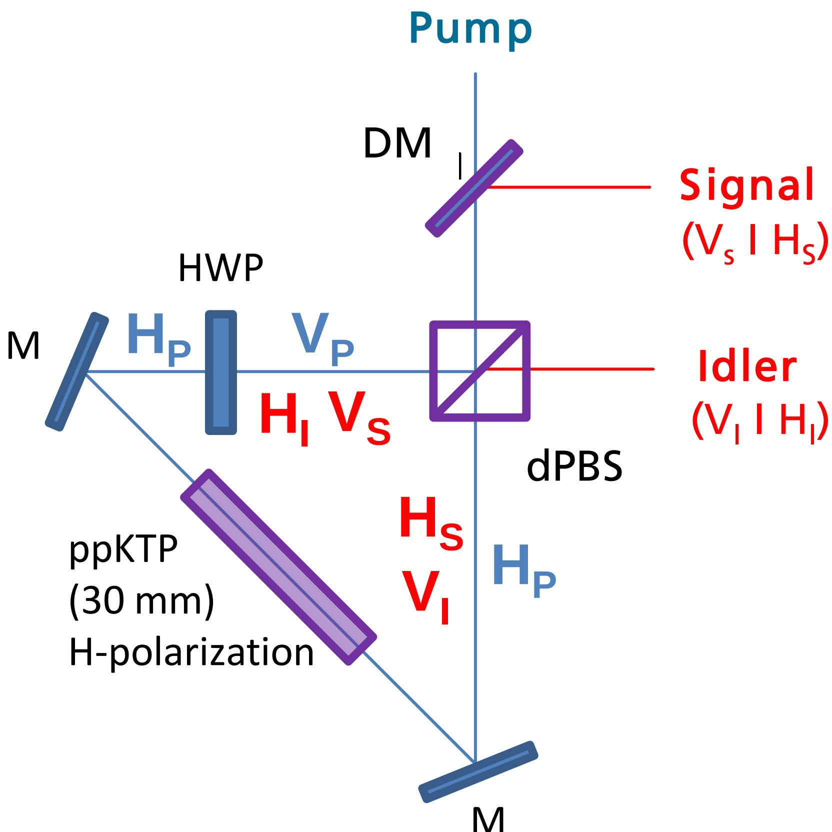
Project Goal

Space-suitable Single-Photon Source for QKD (Space-EPS)



Th. Jennewein, B. Higgins and E. Choi: A proposed micro-satellite mission would demonstrate technology for satellite-based global-scale quantum key distribution. 1 May 2014, SPIE Newsroom. DOI: 10.1117/2.1201404.005453

Engineering Approach
Requirements



S. Ramelow, A. Mech, M. Giustina, S. Gröblacher, W. Wieczorek, J. Beyer, A. Lita, B. Calkins, T. Gerrits, S. Nam, A. Zeilinger, and R. Ursin, "Highly efficient heralding of entangled single photons," Opt. Express 21, 6707-6717 (2013).

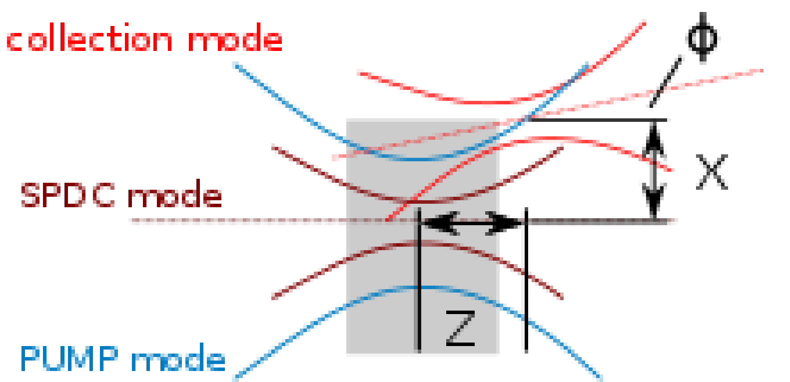
- Hybrid setup for polarization entanglement
  - Sagnac Interferometer
  - Spontaneous parametric down-conversion (SPDC) in bulk periodically poled ppKTP
  - Pumped at 405 nm
- Space suitable for down- (up-)link configuration

Specification	**Goal**
Total Mass	≤3 kg
Total Size	≤ 150 x 150 x 100 mm³
Total Power Consumption	≤ 10 W (peak)
Visibility	**> 98 % in 0º/90º and +45º/-45º basis**
Detection rate*	0.64e6 photon pair events/s

* estimated for 25 mW pumping power

Engineering Approach

Optical Design – Mechanical Tolerances

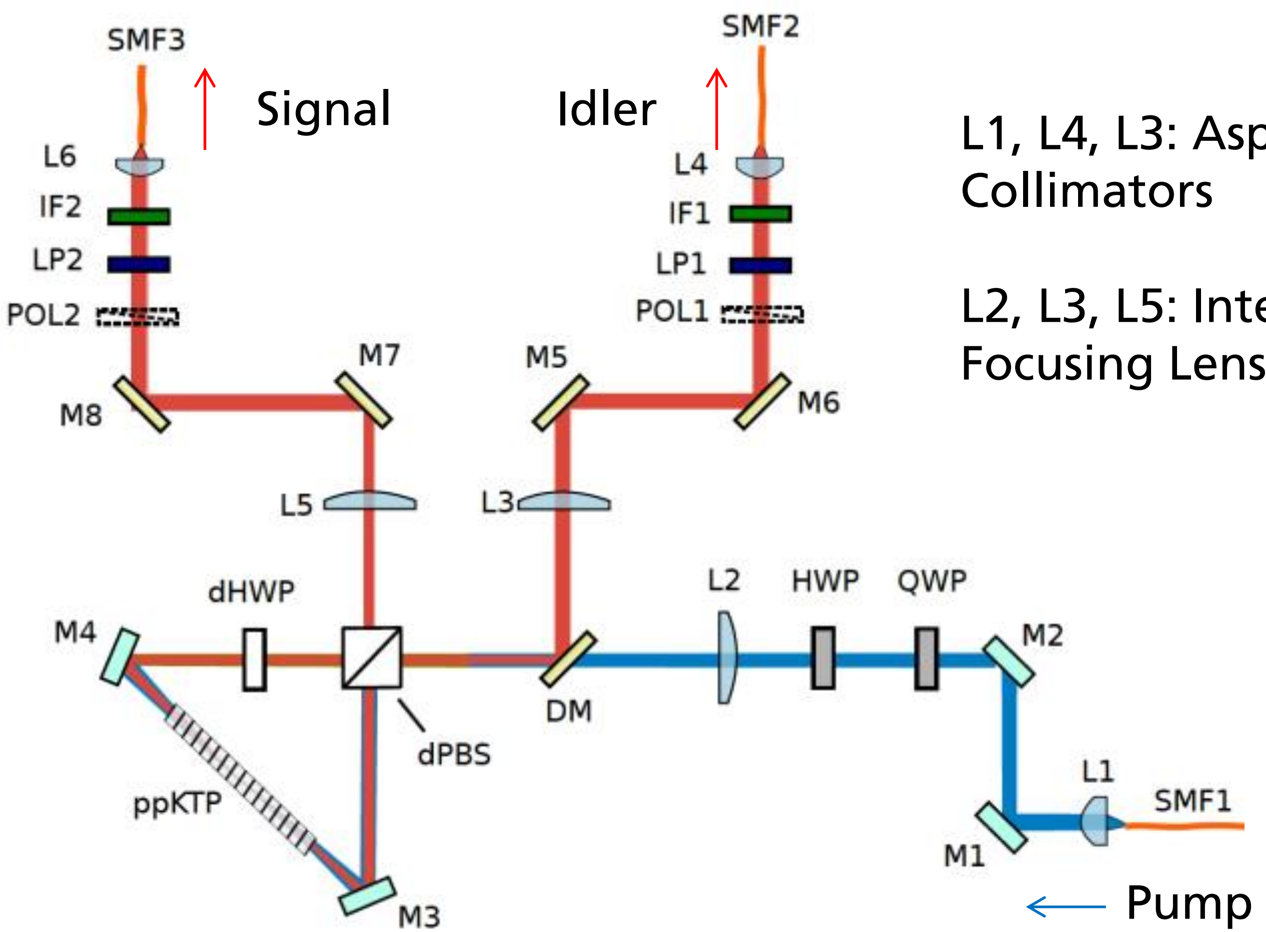


Definition of angular dealignement (φ), transverse dealignement (X), and axial dealignment (Z) of the collection mode with respect to the SPDC emission.

	Beam Parameters				Calc. efficiency		Est. Exp. Rates		99% TOLERANCE			95% TOLERANCE		
	ζp	ζs	wp/µm	ws/µm	η	pairs/nm	rate	@ 20mW	X/µm	Z/mm	ϕ/µrad	X/µm	Z/mm	ϕ/µrad
Optimal Brig	2,84	2,84	18	26	0,75	1,00	1,86	Mcps	2,6	1,0	490,0	5,9	2,5	1100,0
Trade-off 1	1,00	1,60	31	35	0,79	0,86	1,60	Mcps [1]	3,5	1,9	364,0	7,9	4,4	823,0
Trade-off 2	0,55	1,20	42	40	0,85	0,70	1,30	Mcps	4,4	3,2	302,0	10,0	7,3	683,5
Trade-off 4	0,10	0,68	98	53	0,90	0,24	0,45	Mcps	5,3	4,4	240,0	12,0	10,1	544,0
Optimal Her	0,03	0,20	178	98	0,97	0,09	0,14	Mcps [2]	10,0	15,8	127,0	22,6	36,0	288,0

- Trade-off 2:most sensible between heralding efficiency, pair-generation rate and transverse misalignment tolerance
- Expected: 1 million coincidences per mW for <15mW of pump power

Engineering Approach
Optical Design - Layout



L1, L4, L3: Aspheric Fiber Collimators

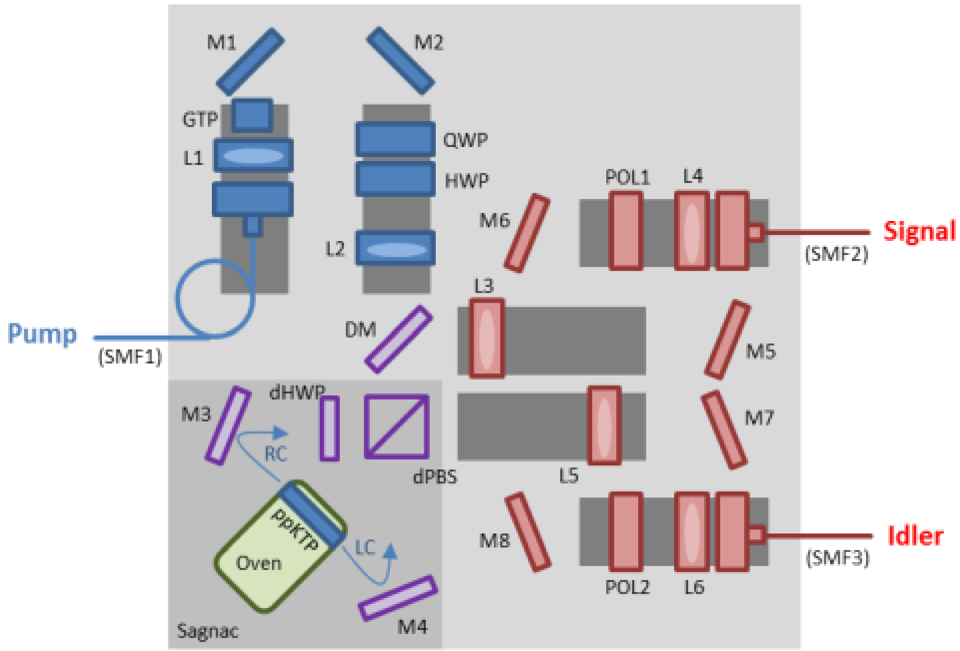
L2, L3, L5: Interferometer Focusing Lenses, f = 200mm

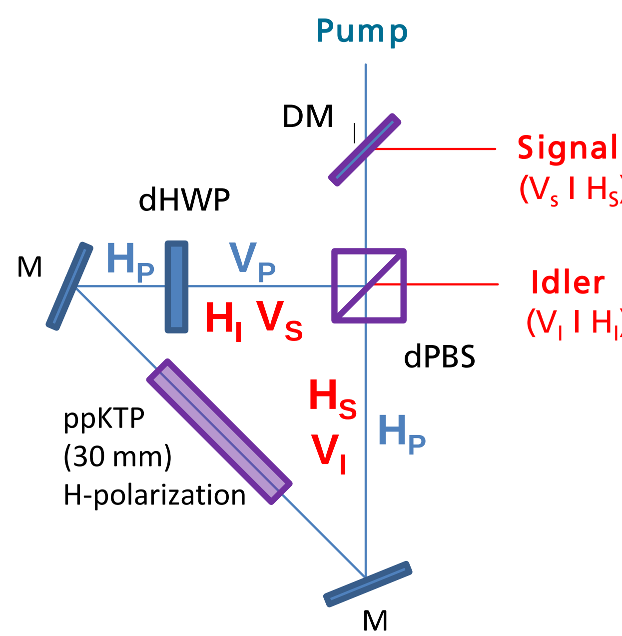
Engineering Approach
Lab Model

The Lab-Model of the EPS provides basic Parameters for the Design (Pathlengths, Distances, Alignment Tolerances) and thus is the major basis for the EQM Design!

Engineering Approach
Lab Model – Setup Space-EPS

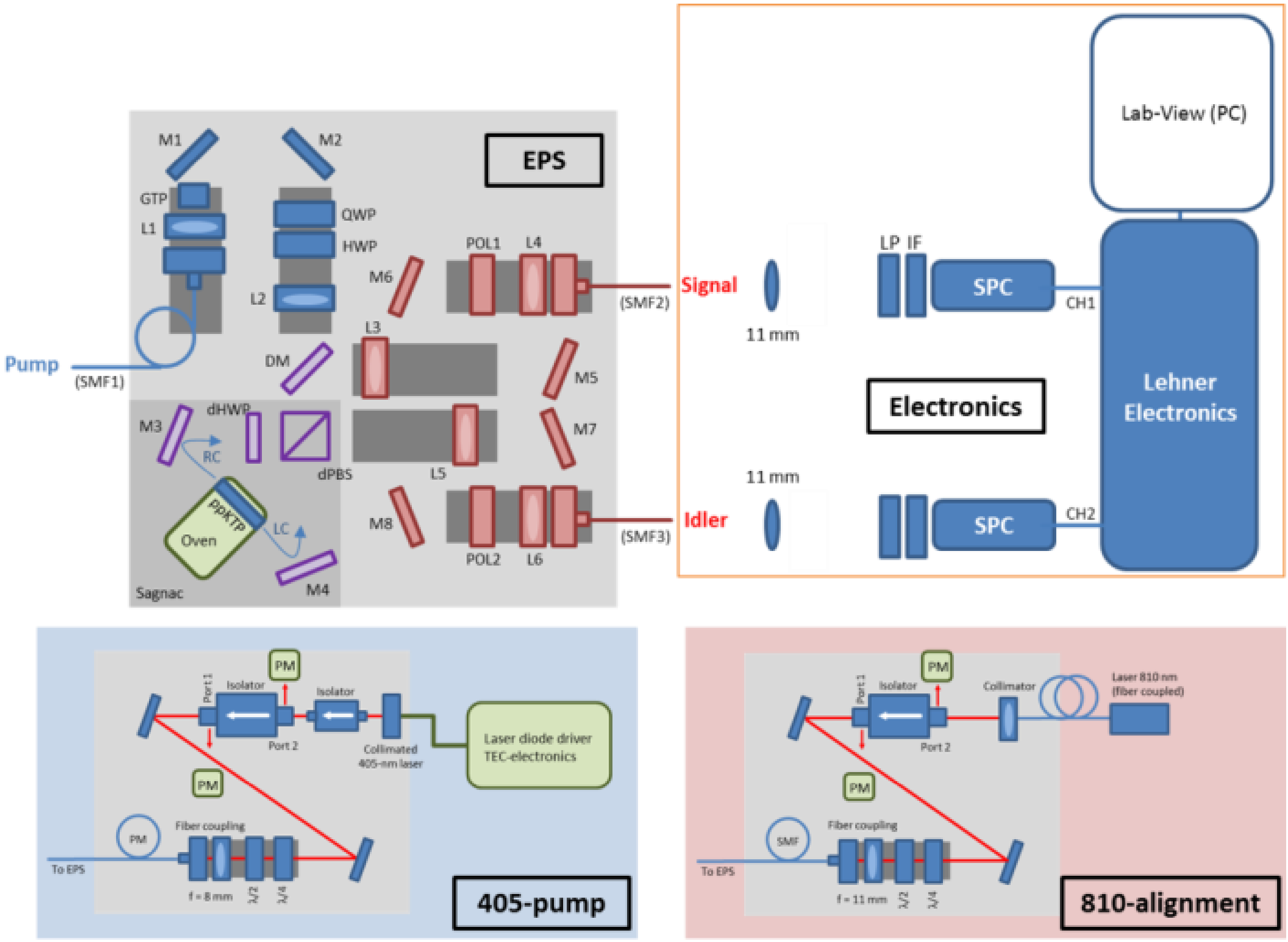
- Setup of the Space-EPS Lab-Model



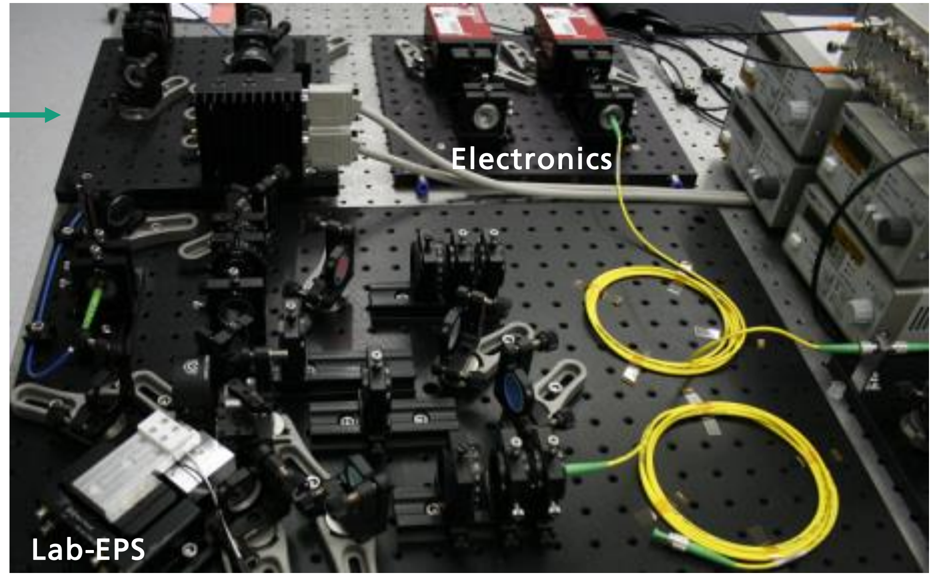


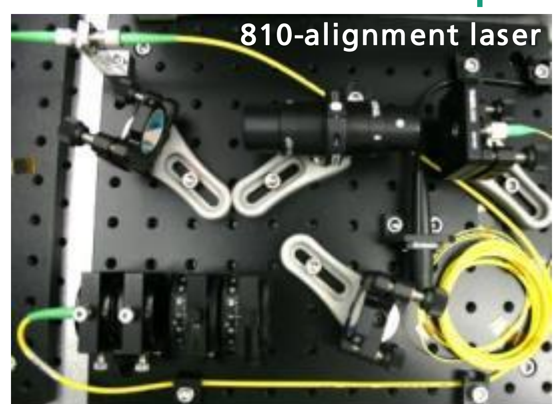
Engineering Approach

Lab Model – Setup Space-EPS & External Devices



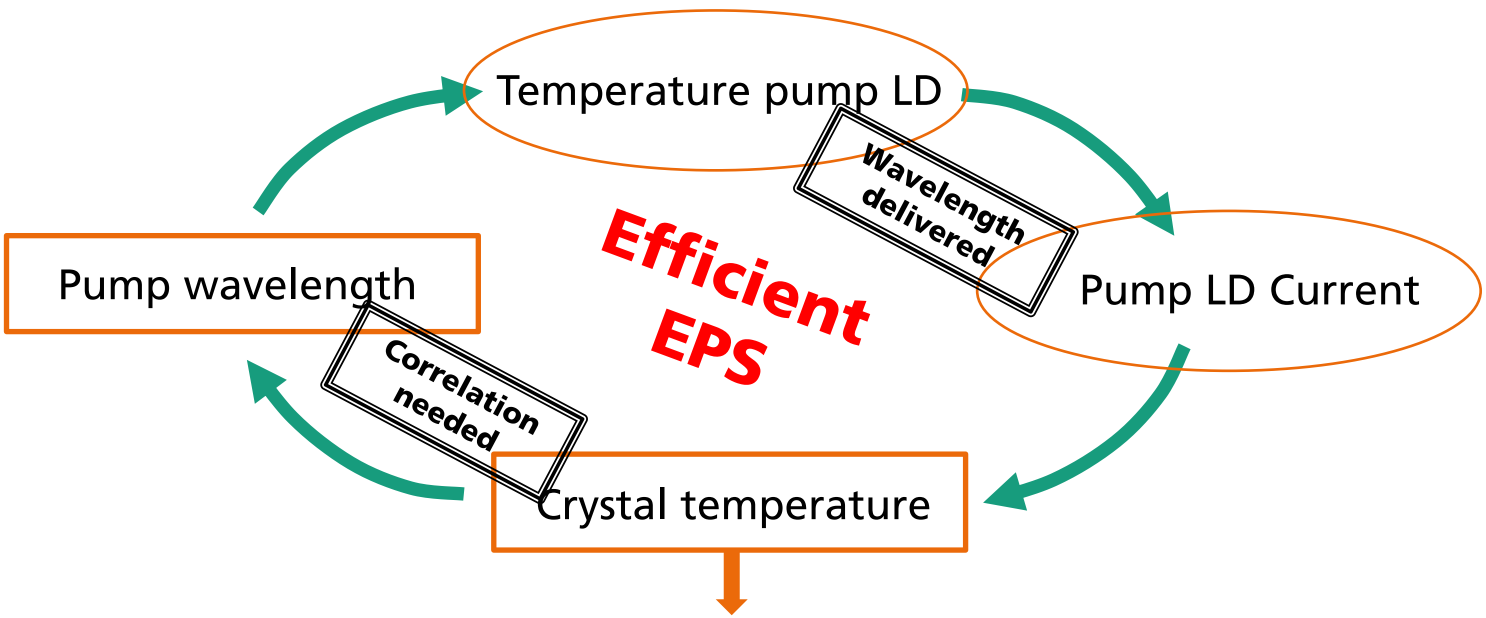
Engineering Approach
Lab Model – Realized Setup





Engineering Approach
Lab Model – Crystal Temperature vs. Pump Wavelength

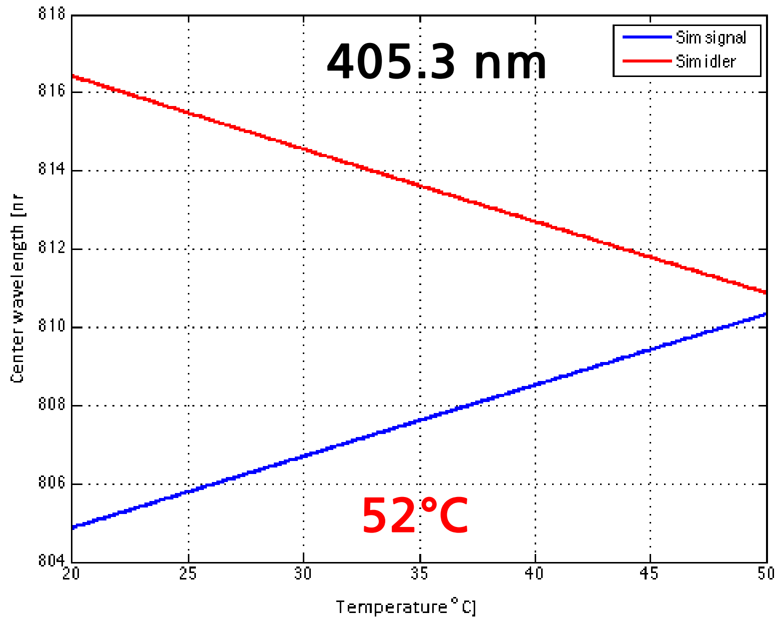
- Catch-22 situation:

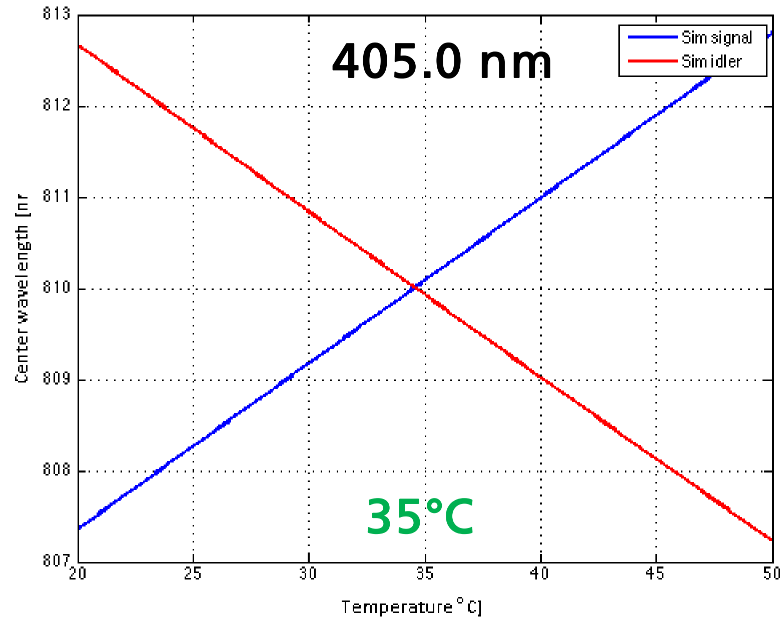


Influence on design TEC (oven)

Engineering Approach
Lab Model – Crystal Temperature vs. Pump Wavelength

- Correlation pump wavelength / crystal temperature:

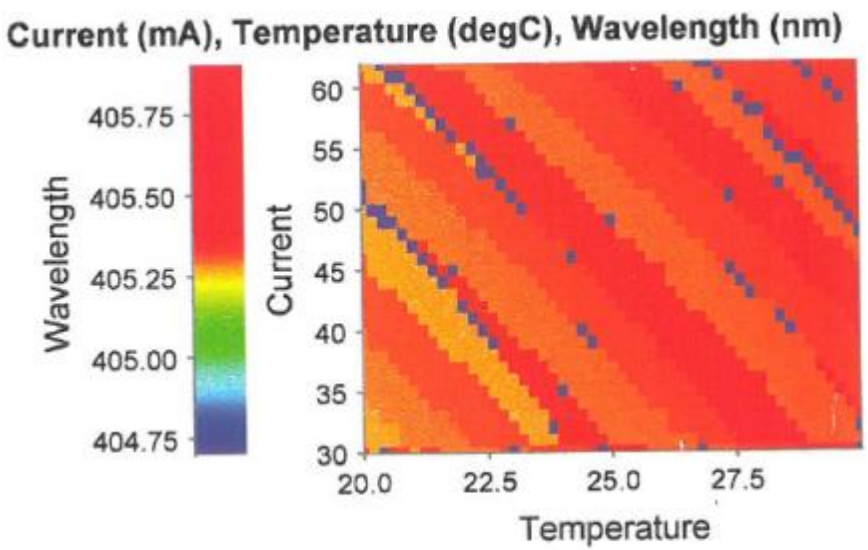




→ **Small changes on pump wavelength have huge impact !**

Engineering Approach
Lab Model – Crystal Temperature vs. Pump Wavelength

- Wavelength delivered by ONDAX-LDs used:



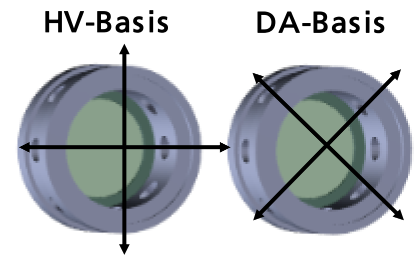
→ Only one of three ordered diodes provide 405.0 nm at all
→ Usable power only P = 4.6 mW (due to: non-polarized, not fiber coupled LD)
→ <u>Desired Pump-LD</u>: locked wavelength @ locked current / temperature

Engineering Approach
Lab Model – Results

- Results from Lab-EPS @ full available pump power (4.6 mW, T_{oven}=36°C):

  - HV-visibility: $V_{H/V} = \frac{n_{H/V}+n_{V/H}-n_{H/H}-n_{V/V}}{\sum n_{ij}}$
  - DA-visibility: $V_{D/A} = \frac{n_{D/A}+n_{A/D}-n_{D/D}-n_{A/A}}{\sum n_{ij}}$

  } Settings Pol1/2:



V_DA [%] =	96,9837	Error V_DA [%] =	0,0155
V_HV [%] =	99,0565	Error V_HV [%] =	0,0084
Power (in EPS) /mW:		4,60	
Pair-Counts (over 60s):		18992277	
Pair-Counts (per second) =		316538	
Laser diode current /mA:		55,000	
Laser diode NTC /kOhm:		11,000	
Crystal oven NTC /kOhm:		6,265	

Goal parameters:

→ Count-Rate >100.000 s^{-1}

→ Visibility HV-Basis ≥ 98 %

→ Visibility DA-Basis ≥ 98 %

Engineering Approach
Lab Model – Results

- But with "special excited" pump mode and without realigning EPS …

V_DA [%] =	98,1971	Error V_DA [%] =	0,0304
V_HV [%] =	98,9941	Error V_HV [%] =	0,0224
Pair-Counts (over 60s @1mW):		2804996	
Pair-Counts (@ 1mW/s) =		46750	

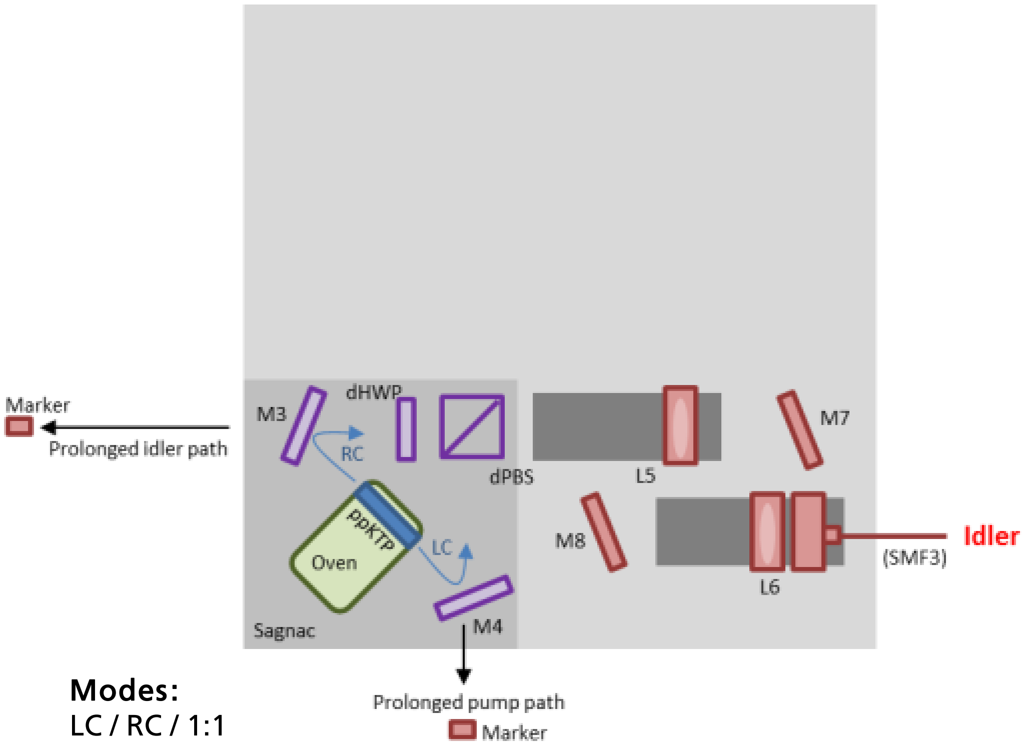
Goal parameters:
→ Visibility DA > 98 %

- … also >98% DA-visibility can be reached (but is difficult to control) !

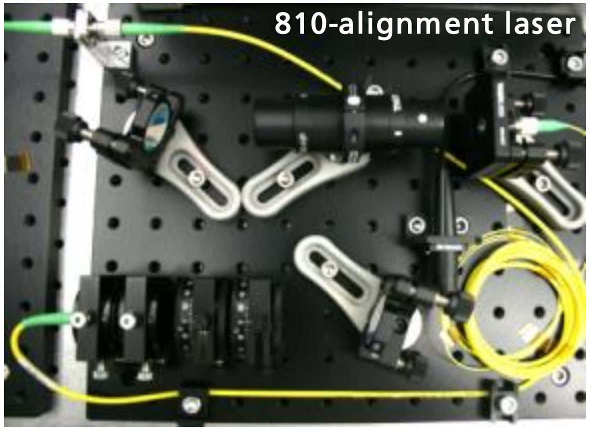
→ **Current results prove a predominant influence of the (external) pump laser diode over alignment issues**
→ **No "better" pump diode available at the moment**
→ **But: DA-visibility may improve using Glan-Thompson polarizer in the pump path (PER 100.000:1) !**

Engineering Approach
Lab Model - Assembly Algorithm Derivation

- Alignment algorithm: Step 1 („Reference path“)

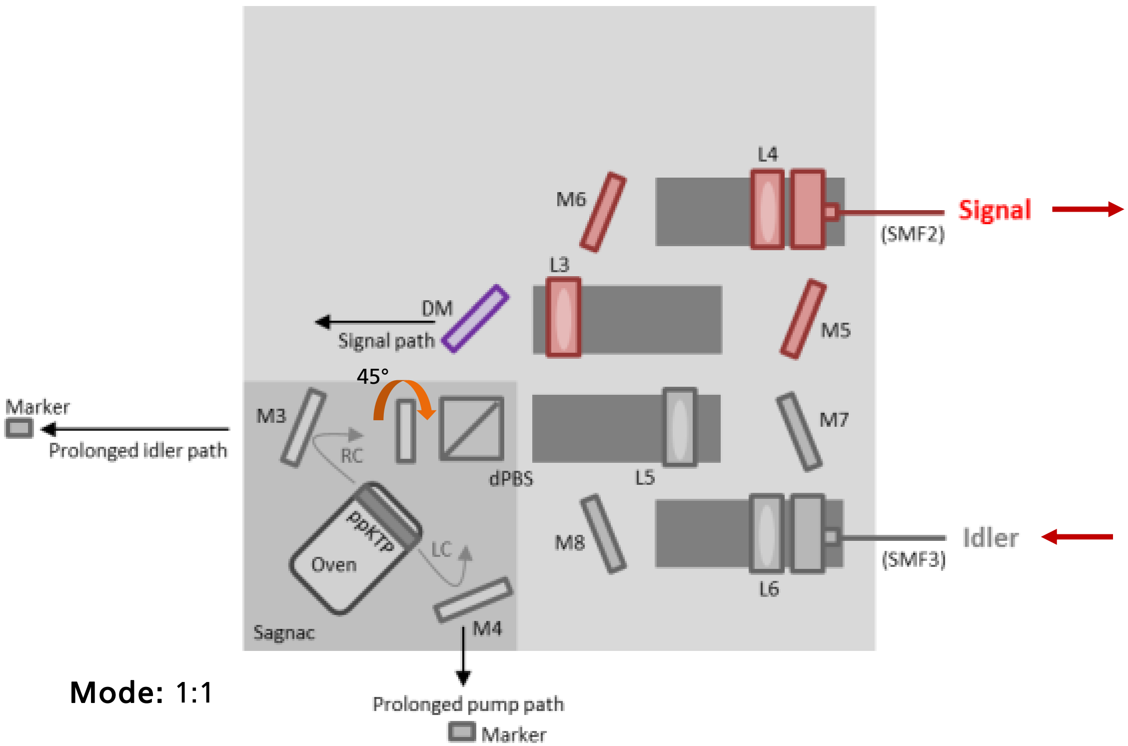


Modes:
LC / RC / 1:1



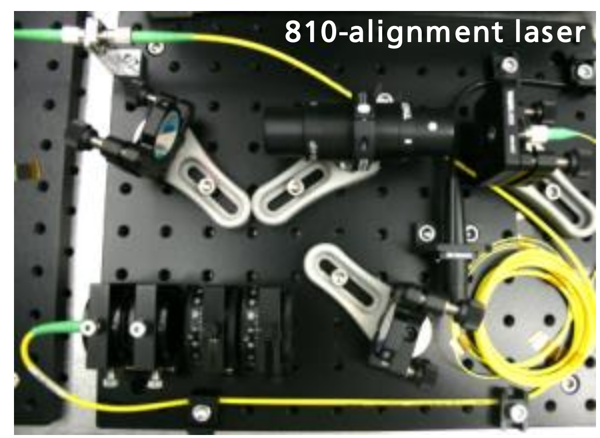
Engineering Approach
Lab Model - Assembly Algorithm Derivation

- Alignment algorithm: Step 2 („Signal path“)



Mode: 1:1

Power meter



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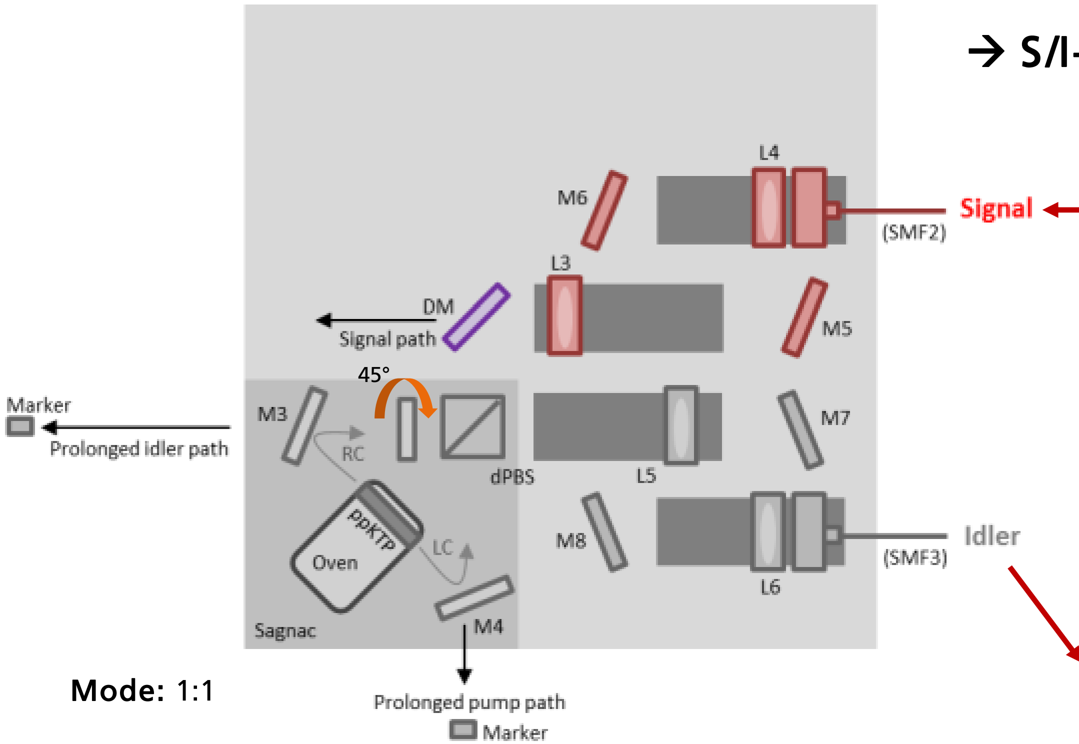
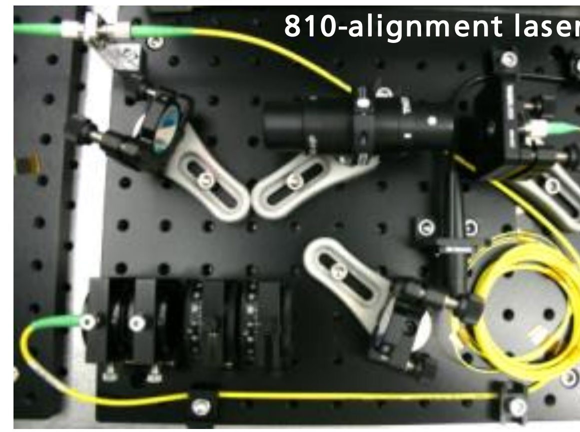
Engineering Approach

Lab Model - Assembly Algorithm Derivation

- Alignment algorithm: Step 3 („Check symmetry“)

→ S/I-paths matched to Sagnac!





Mode: 1:1

Power meter

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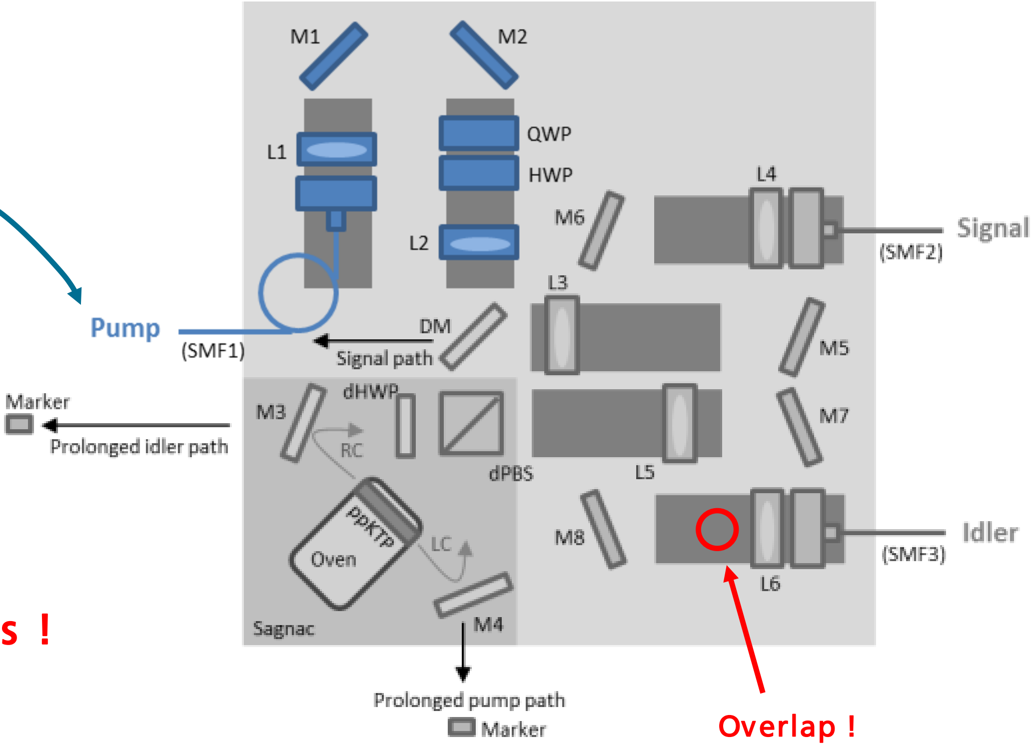
Engineering Approach
Lab Model - Assembly Algorithm Derivation

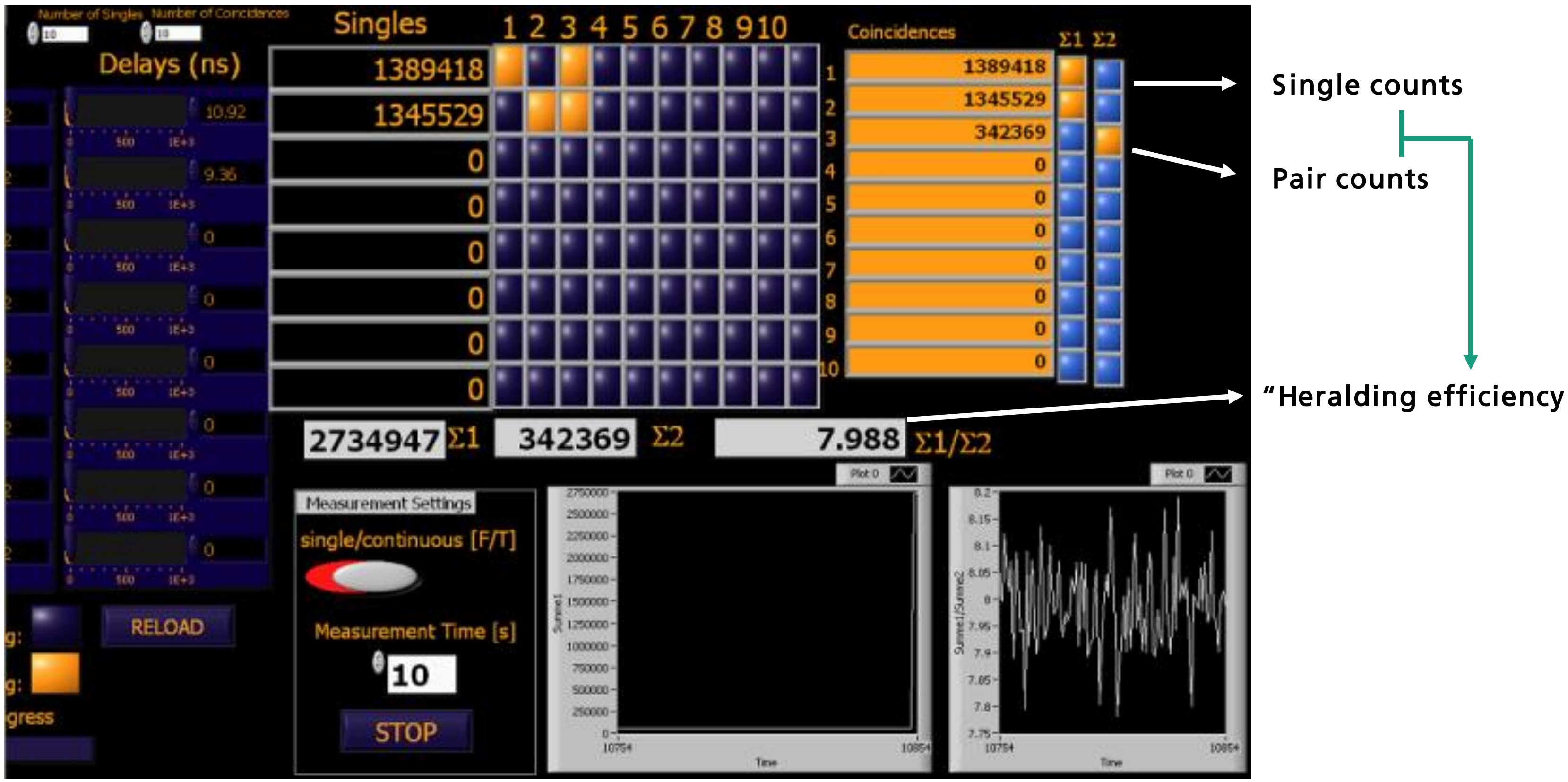
- Alignment algorithm: Step 4 („Pump path“)



→ P-path matched to S/I-paths !

Engineering Approach
Lab Model - Assembly Algorithm Derivation

- Start Quantum-level alignment via LabView:



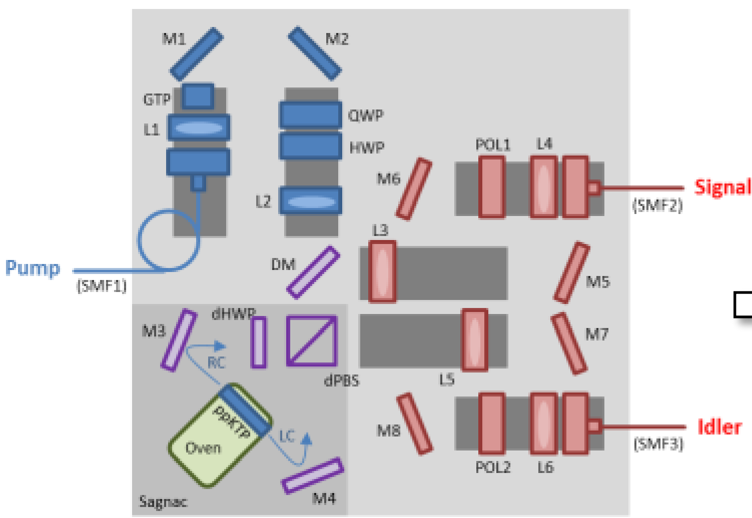
Engineering Approach

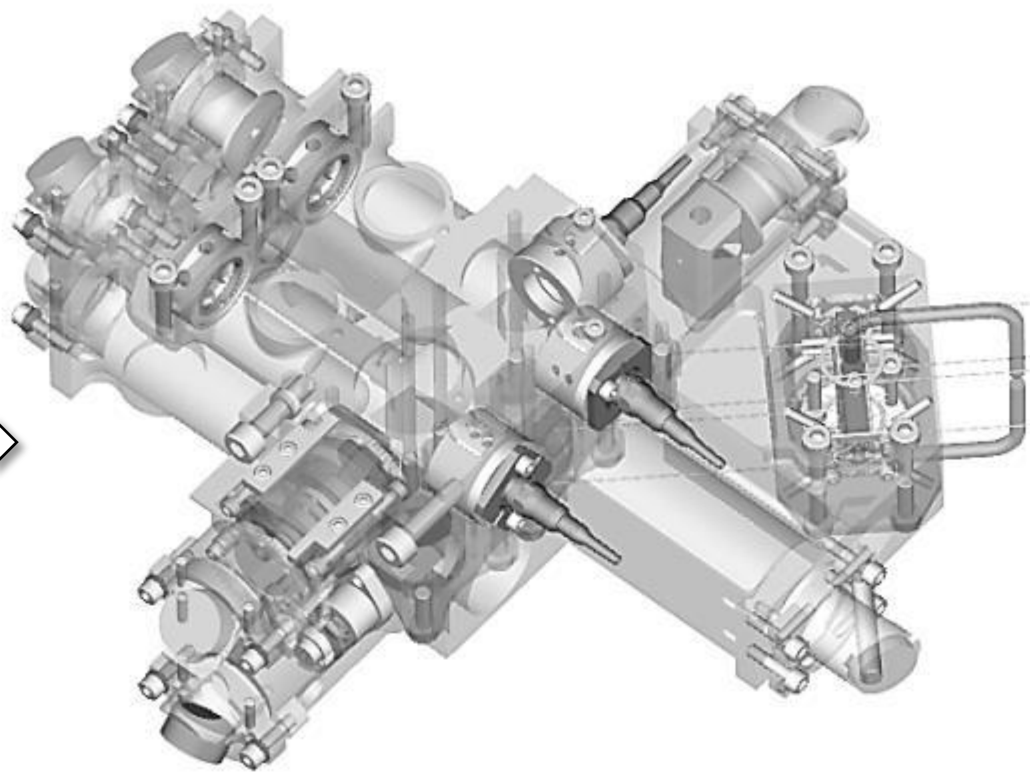
Lab Model – Derivation of Assembly DOF, Precision

Component	Material	Aperture	DOF (initial positioning)	DOF (SPDC/LD alignment)	DOF (operation)	Resolution	T dependence
Optical EPS components							
SMF1	silica	NA=0.12	Dv,Dh,Dz	-	-	high	low
SMF2	silica	NA=0.12	Dv,Dh,Dz	-	-	high	high
SMF3	silica	NA=0.12	Dv,Dh,Dz	-	-	high	high
M1,M2	fused silica	12.5mm	Rv,Rh	Rv,Rh	-	high	?
M3,M4	fs substrate	12.5mm	Rv,Rh	Rv,Rh	-	high	?
M5-M8	?	12.5mm	Rv,Rh	Rv,Rh	-	high	?
L1	model-depende	9mm	Dv,Dh,Dz	-	-	med	?
L2	fused silica	12.5mm	Dv,Dh,Dz	Dz	-	low	?
L3	BK7	12.5mm	Dv,Dh,Dz	Dz	-	low	?
L5	BK7	12.5mm	Dv,Dh,Dz	Dz	-	low	?
L6,L4	model-depende	9mm	Dv,Dh,Dz	Dz	-	med	?
dHWP	quartz	12.5mm	Rv,Rh,Rz	Rz	-	low	high
dPBS	BK7/FS	10mm	Rv,Rh	-	-	low	?
DM	FS	custom	Rv,Rh	Rv,Rh	-	med	?
HWP	quartz	10mm	Rv,Rh	Rz	Rz	0.5°	low
QWP	quartz	10mm	Rv,Rh	Rz	Rz	0.5°	low
PPKTP	KTP	1x2mm2	Rv,Rh,Dv,Dh,Dz	Rv,Rh,Dz	-	med	high
IF1,IF2	?	12.5mm	Rv,Rh,Dv,Dh,Dz	-	-	low	?
LP1,LP2	?	12.5mm	Rv,Rh,Dv,Dh,Dz	-	-	low	?
POL1,POL2	?	12.5mm	Rv,Rh,Dv,Dh,Dz	Rz	Rz	0.5°	low

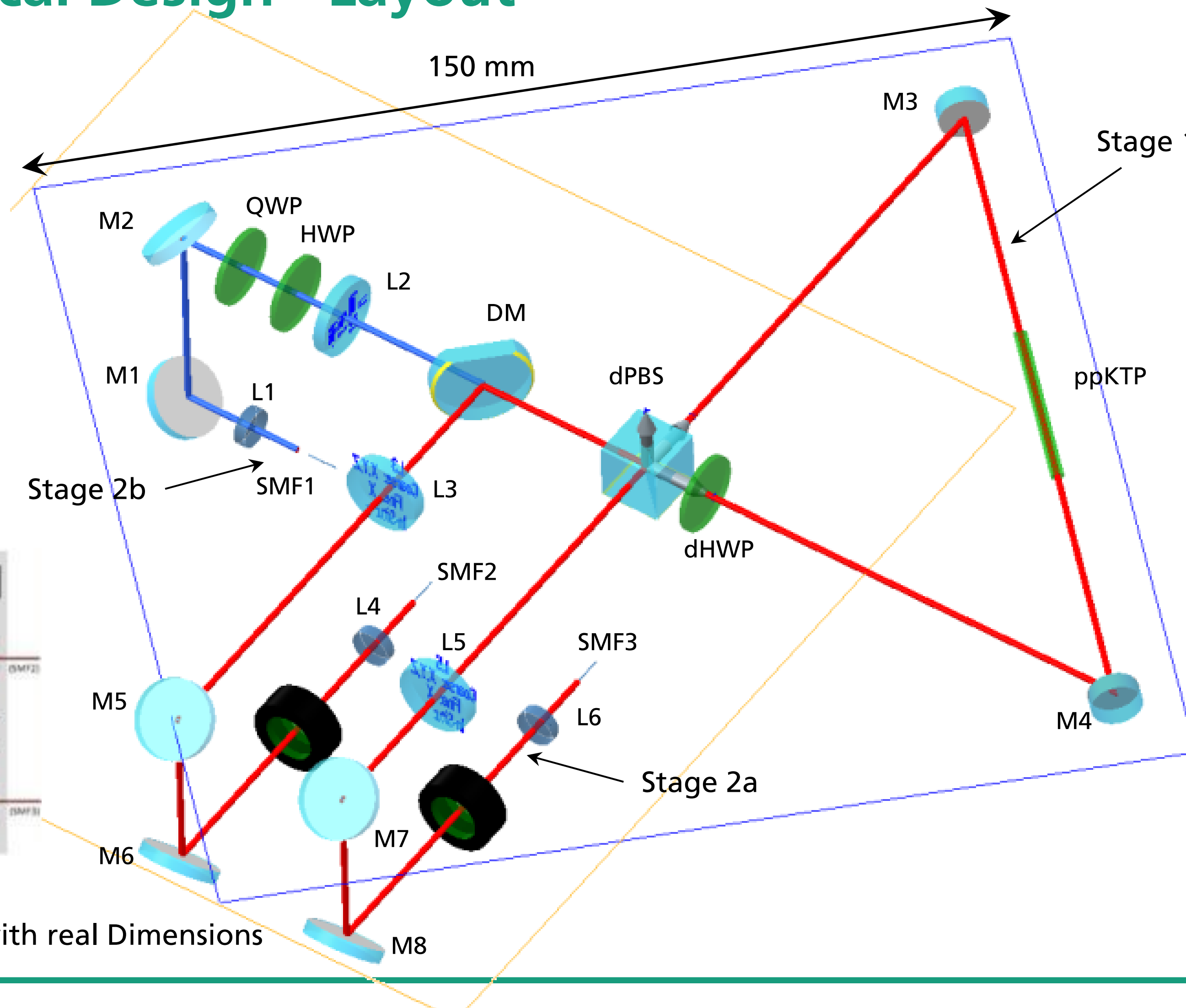
Engineering Approach

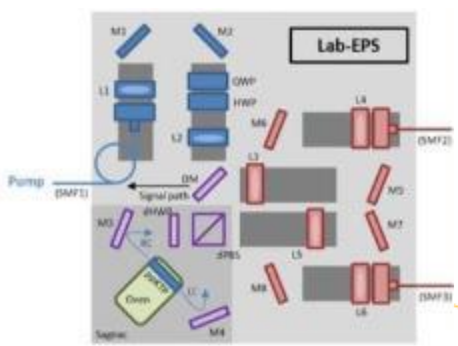
From the Lab Model to the EQM





Engineering Approach
Optomechanical Design - Layout





Optomechanical Design with real Dimensions

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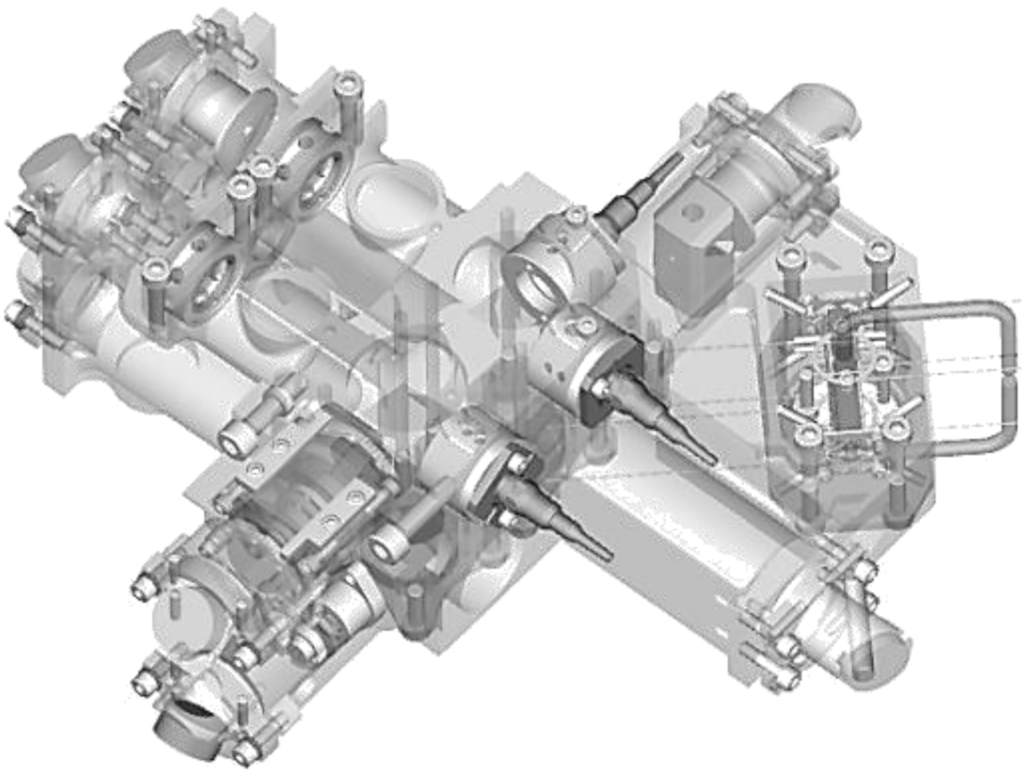
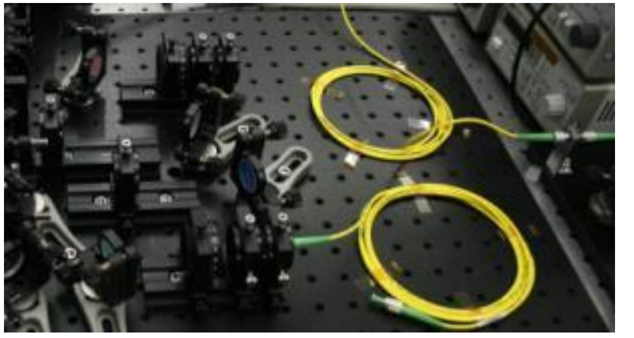
Engineering Approach
Optomechanical Design - Principles

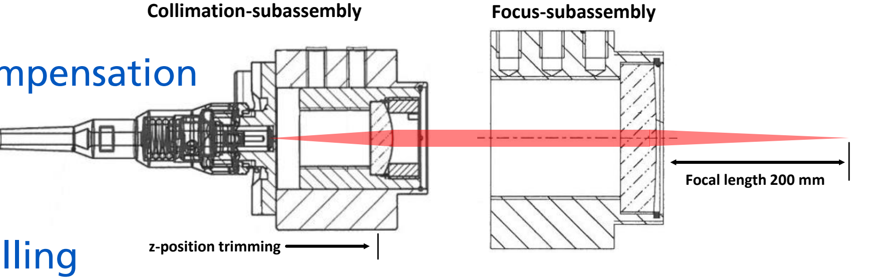


- INVAR „lightweight“ base structure
- Precision stops and guidings for alignment, e.g. alignment turned lenses
- Anorganic, robust bonding of components - soldering

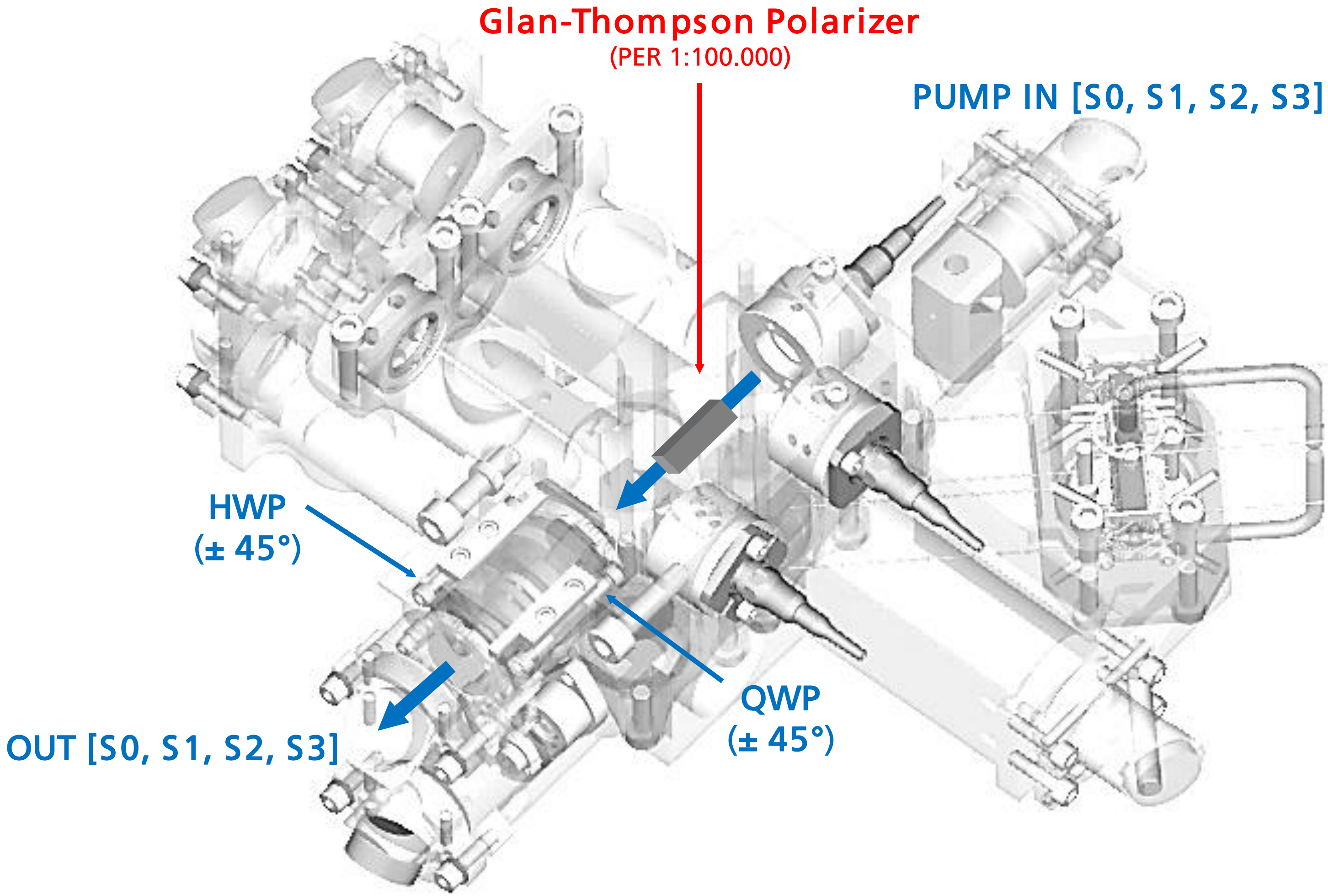
Engineering Approach
EQM Design Details



- Lab-Model
- The transition into Engineering Model
  - Glan-Thompson integration
  - Pump beam displacement compensation
  - Trimming procedure
    lens combinations
  - ppKTP temperature levelling
  - Component manufacturing
  - Sub-assembly preparation
  -
- GOAL: EQM-prototype for testing

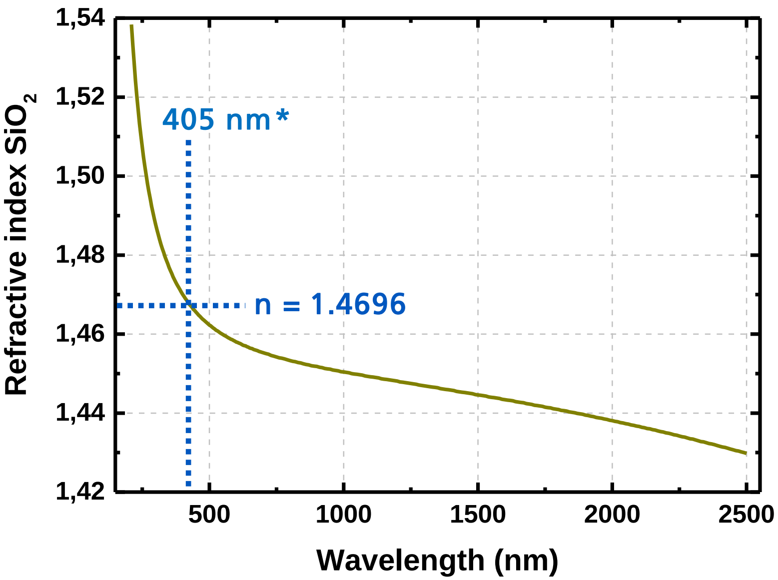


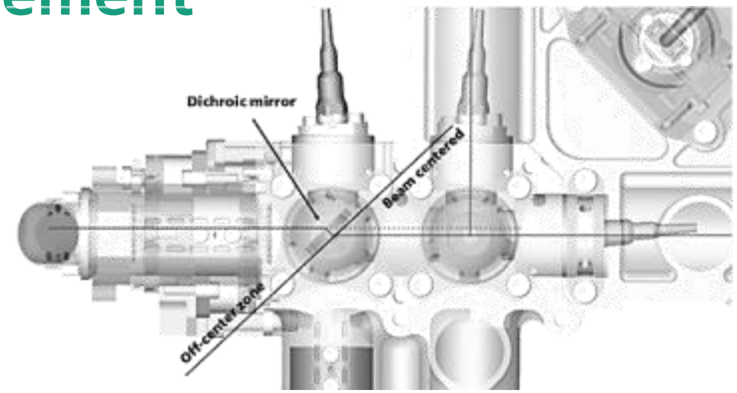
Engineering Approach
Design Details – Pump Polarization

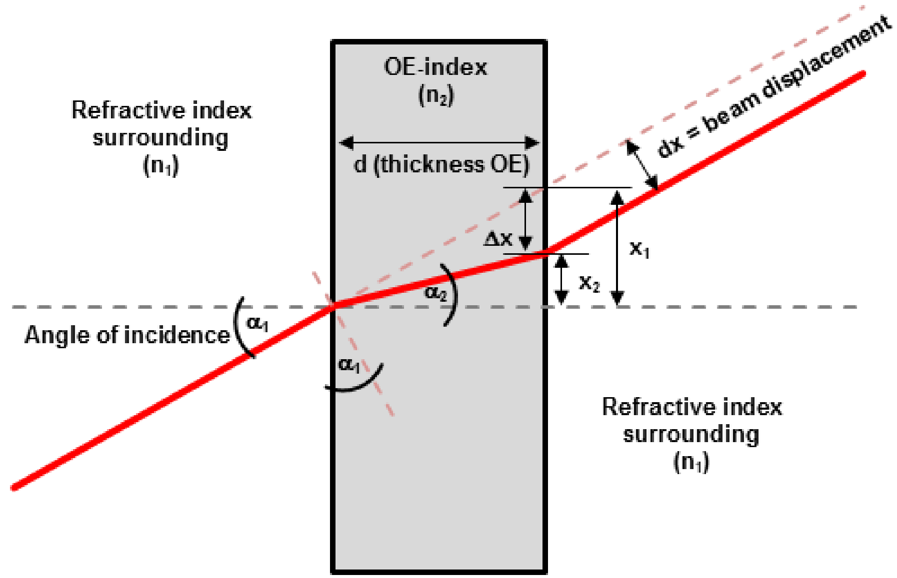


Engineering Approach
Design Details – Beam Displacement

- Compensating beam displacement



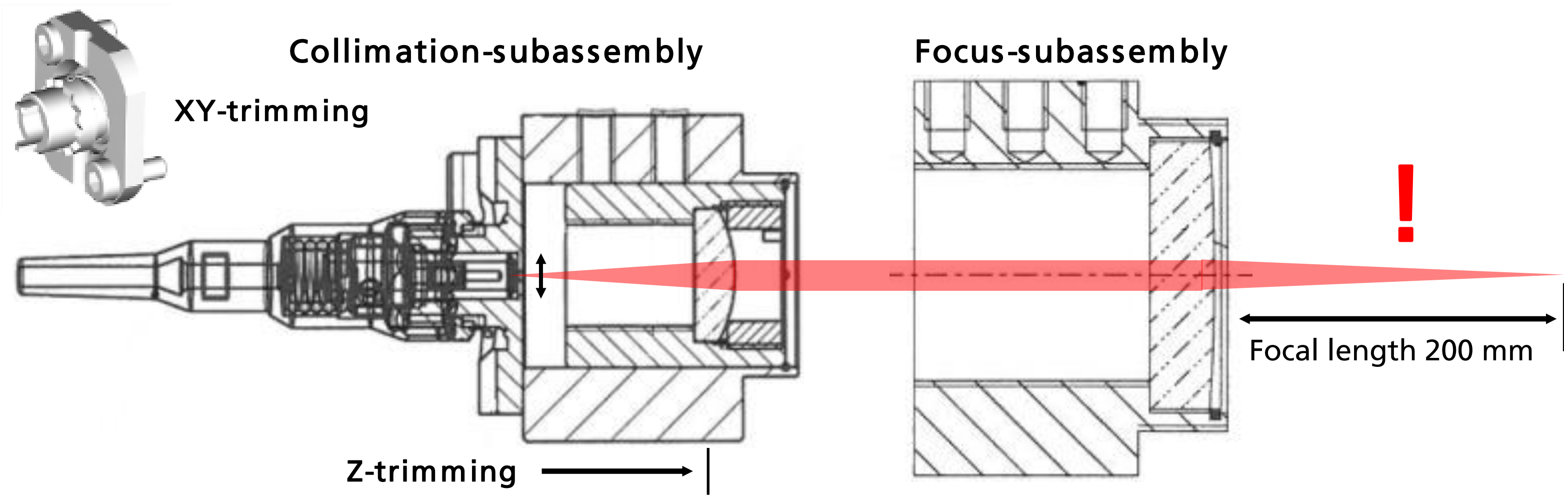




→ **Beam displacement 638 µm (off-center propagation pump-path)**

Engineering Approach
Design Details – Collimator / Focus Trimming

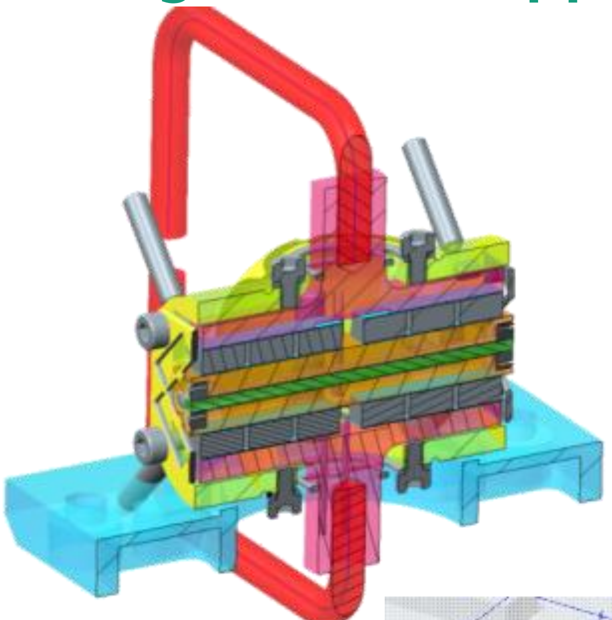
- Trimming procedure of collimating / focussing lens pair
  - Basic scheme for matching lens pair:



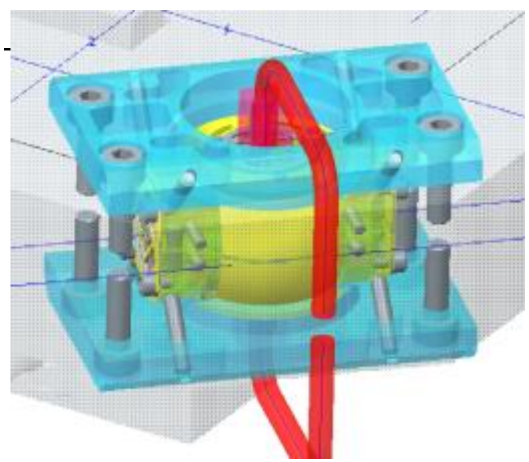
→ **Centering of fiber-tip (XY-adjustment mounting plate)**
→ **Trimming of z-position of collimating lens**
→ **Once trimmed and assigned, no later adjustment needed !**

Engineering Approach

Design Details – ppKTP Temperature Levelling



Calotte Clamping, M1-

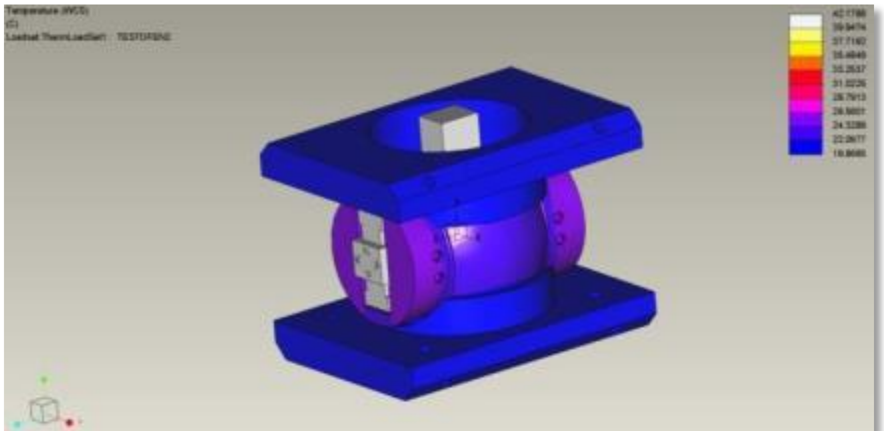


„Oven“ Integrated in Platform

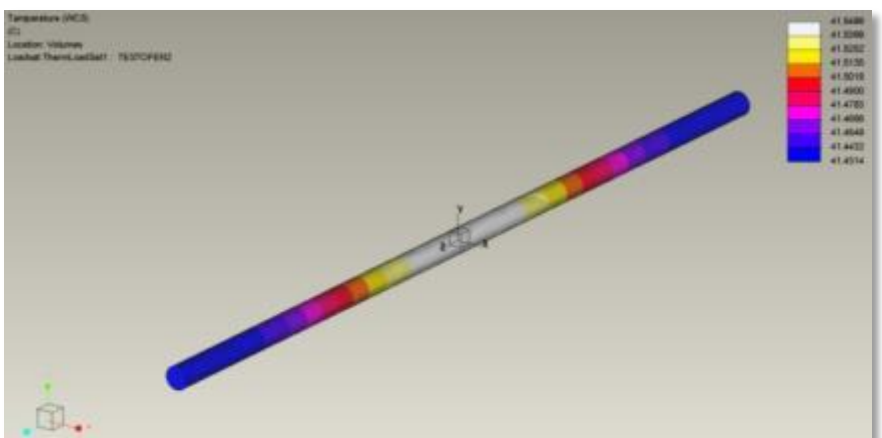
- Fully symmetric, temperature Distribution optimized Assembly
- Cu-Mount and DC93-500 heat conducting Silicone for ppKTP; Peltier Elements for Heat Pumping
- TiAl6V4 Flexures for mechanical decoupling
- INVAR Calotte for Tip/Tilt Alignment of Crystal

Engineering Approach

Design Details – ppKTP Temperature Levelling



Calotte Model



Temperature-Distribution within central Region of Crystal

- Goal: Even Temperature Distribution with ca. 0.1K in Pump Region of ppKTP
- Set Temperature within Crystal: ca. 41°C
- Environment: 20°C
- Heat Load within Crystal: ca. 10mW (worst case)
- Result of Optimization: ΔT within Crystal ca. 0.11K

Engineering Approach
Design Verification Matrix

Level	Description	Goal	Condition	Status CDR
Mechanical System Parameters				
System	Overall weight	≤1.5 kg	Calculated by design	3 kg without lightweigt structured platform
System	Overall dimensions	≤100 x 100 x 80 mm^3	Calculated by design	150x150 mm^2 <80 mm height
System	Mechanical stability	Tbd: load vs. optical tolerances	Calculated by FEA	n.a.
Electrical System Parameters				
System	Overall power consumption	<8 W	Estimated by analysis	Crystal Temperature: max. 0.2 W (@ ΔT 20K)
Thermal System Parameters				
System	ppKTP temperature stability	<0.5 K	Calculated by FEA	0.11 K

Current Status
EQM Components – ppKTP Temperature Leveller

Electroplated Calotte half Spheres

- INVAR Calotte
- Electroplated Ni/Pd/Au
- Defined Thickness 5..10 µm
  - NiP 7,5µm±20%
  - Pd 0,3µm±30%
  - Au 0,01µm - 0,06µm

PacTech
member of nagase group

Heat Sink / Peltiers / Heatsink Sub-Assembly

- Cu Heatsink
- Sputtered Ti/Pt/Au (0,5µm)
- Oven Soldering Crystal Heatsink/ Peltiers / Outer Heatsink

MICRO-HYBRID

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Current Status
EQM Components – ppKTP Temperature Leveller

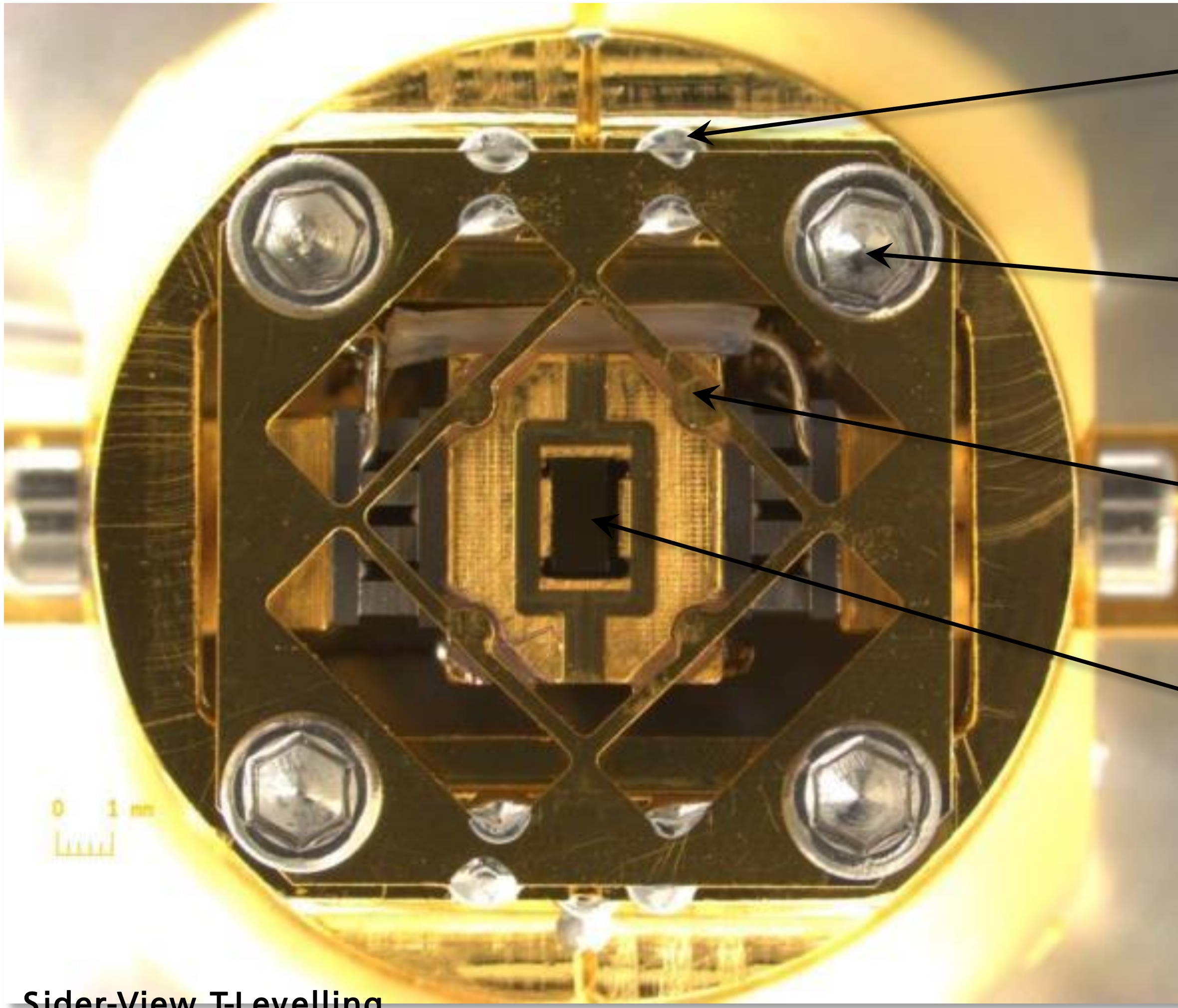
Integrated Heatsinks and Peltiers and Springs

Integrated Calotte

- ppKTP Crystal glueing in Heatsink
- Spring Assembly by combining Clamping, Glueing and Soldering
- Calotte Assembly by Clamping and Soldering

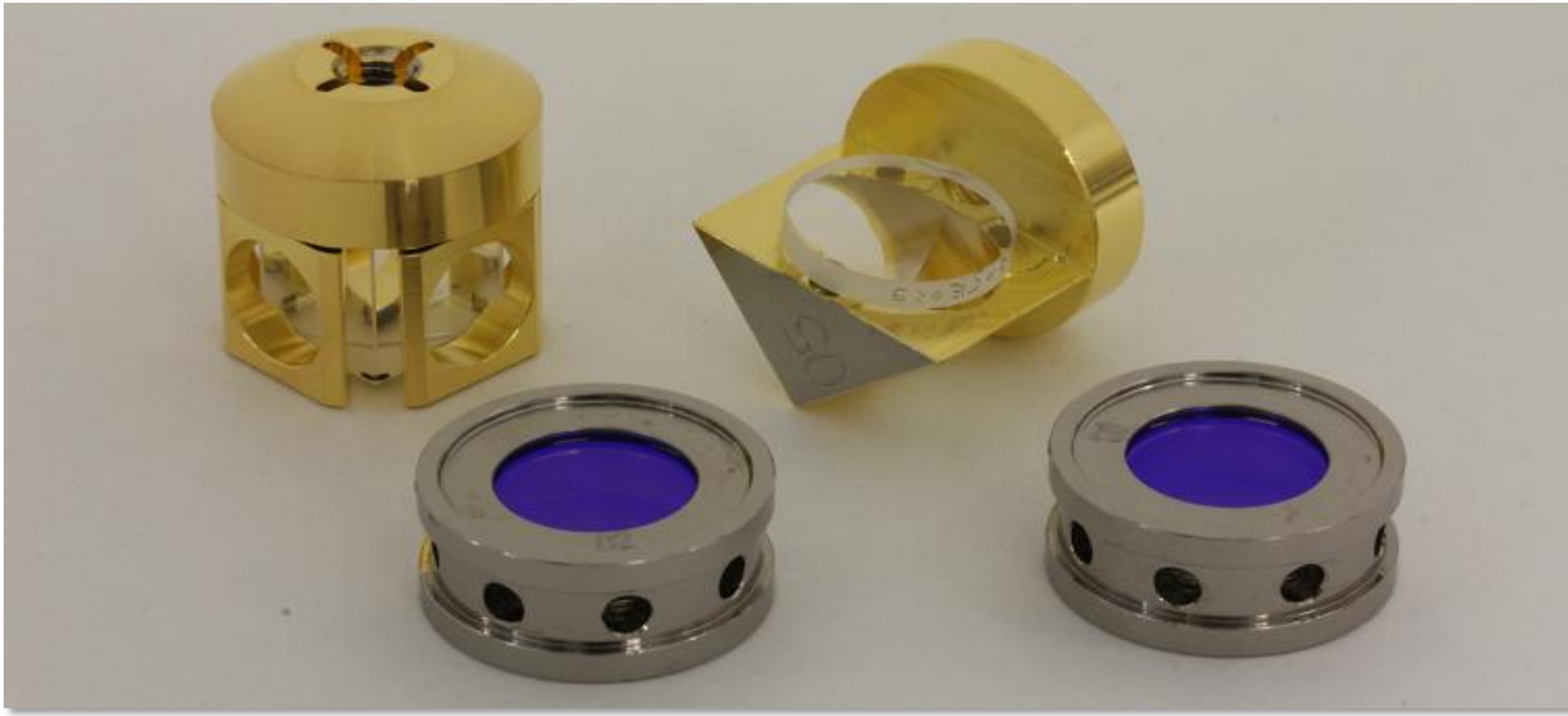
Current Status

EQM Components – ppKTP Temperature Leveller



Sider-View T-Levelling

Current Status
EQM Components – passive Components



dPBS (upper left), DM (upper right), Analyzer and Polarizer (lower)

Current Status
EQM Components – Trimmed Fiber Collimators

Fully integrated Collimator Assembly

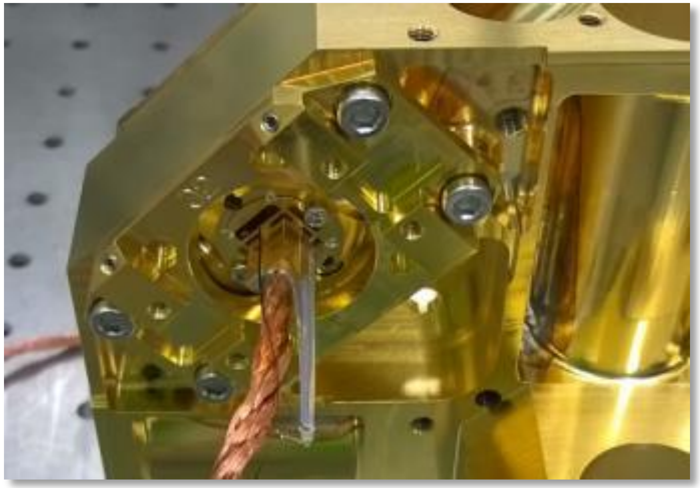
Backside View – Diamond Mini-AVIM Plug, soldered

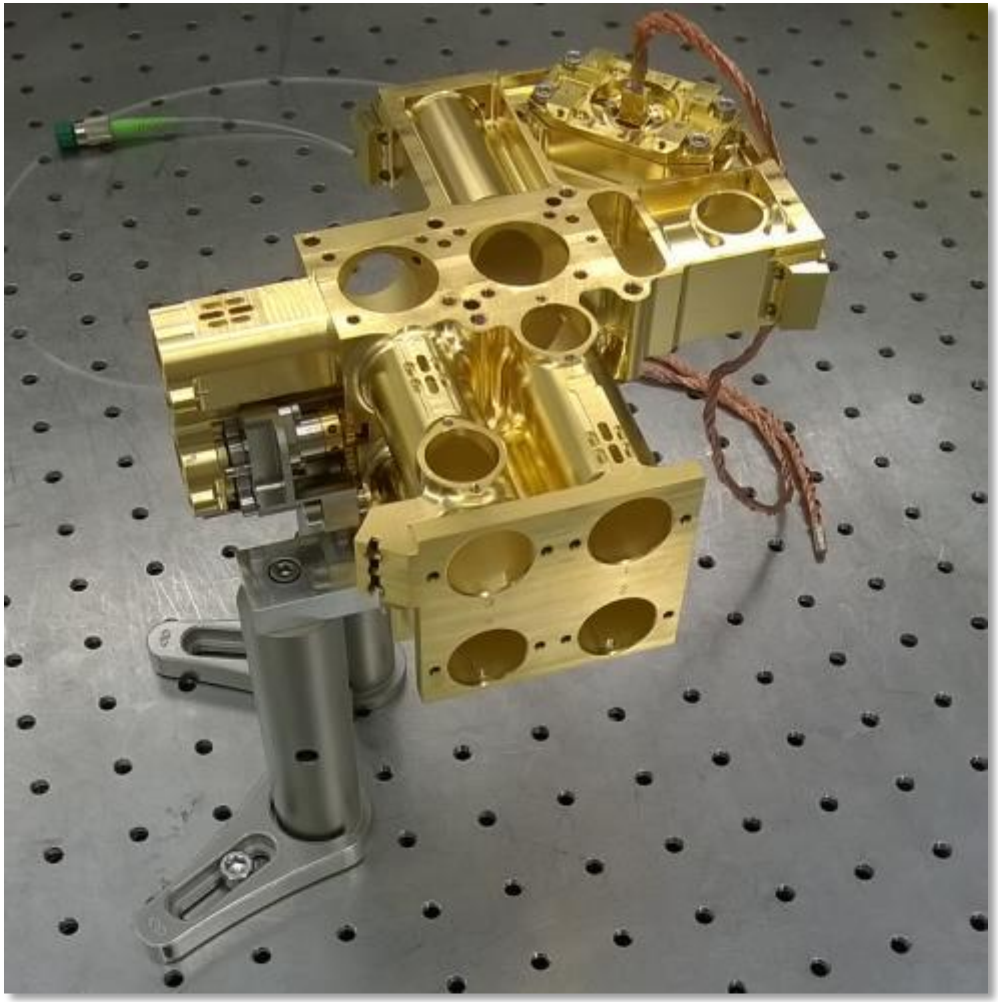
Current Status
EQM Components – INVAR Base

- INVAR Housing
- Electroplated Ni/Pd/Au
- Defined Thickness 5..10 µm
  - NiP 7,5µm±20%
  - Pd 0,3µm±30%
  - Au 0,01µm - 0,06µm

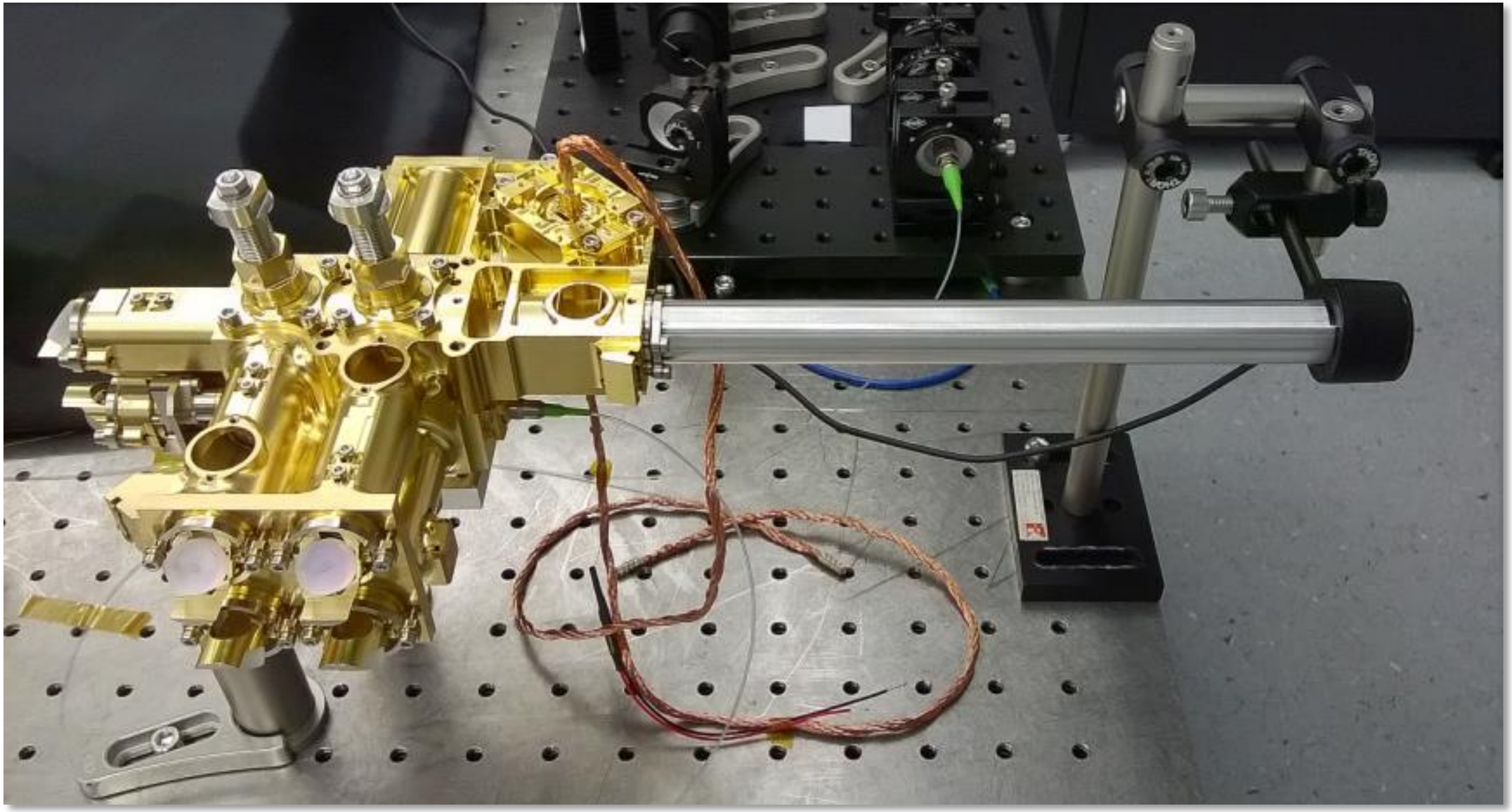
PacTech member of nagase group

Current Status
EQM Assembly – 8th of December 2016





Current Status
EQM Assembly – 21st of March 2017

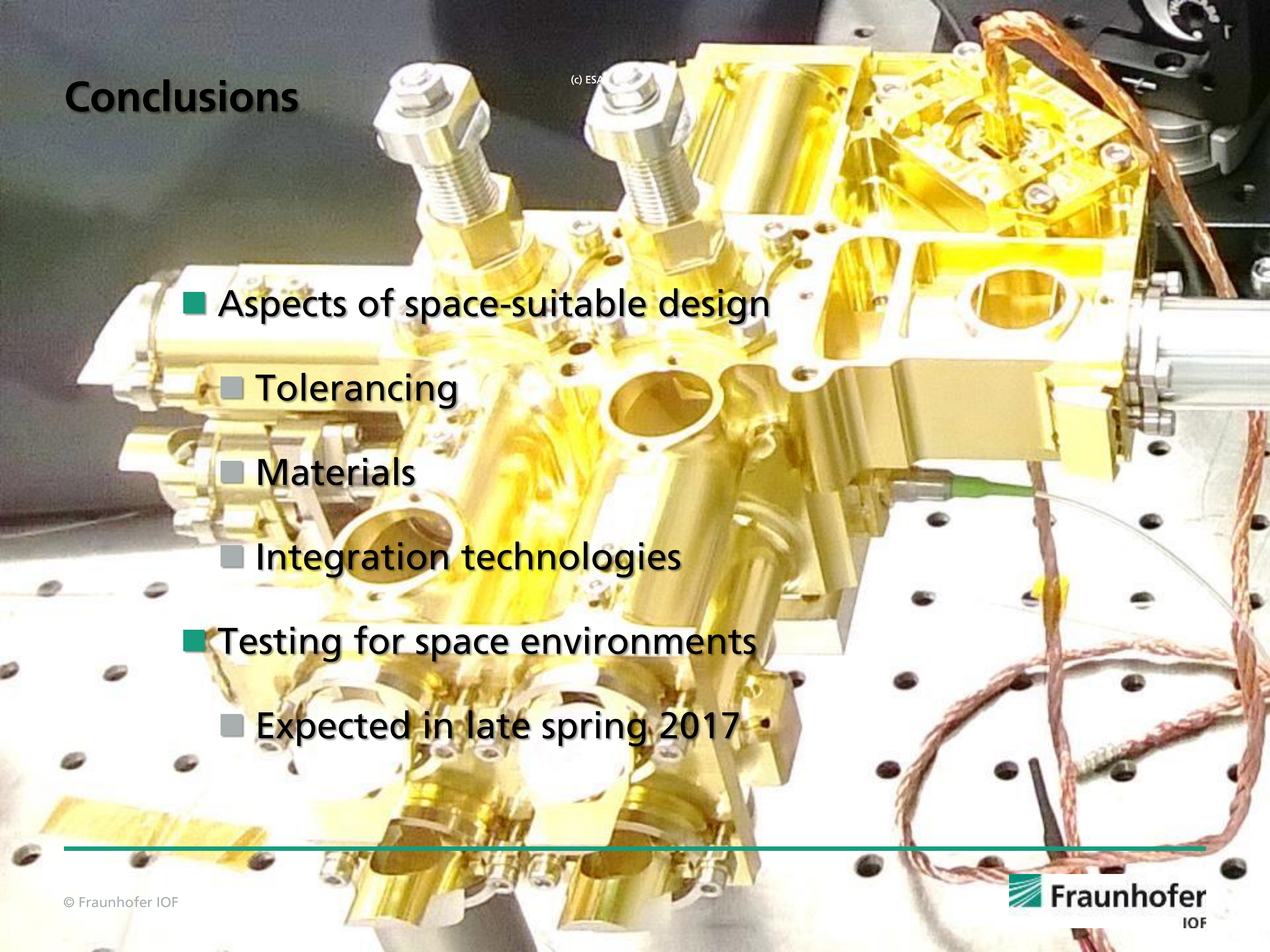


Outlook

EQM Evaluation – Test Plan

Task	Description	Measure
1	Initial Entanglement Quality	Visibility HV-Basis: n.n. % Visibility DA-Basis: n.n. % Pair Counts: n.n. / 60 s @ n.n. mW (measured) Pair Counts: n.n. / s @ 20 mW (calculated)
2	Non-Operational Temperature Cycling Test at normal Pressure	-40/+60 °C for 10 cycles, 2 °/min ramps
3	Post 1st Test Entanglement Quality	See Task 1
4	Non-Operational Temperature Cycling Test at Vacuum	-40/+60 °C for 4 cycles, 2 °/min ramps, at 10^{-4} mbar
5	Post 2nd Test Entanglement Quality	See Task 1
6	Mechanical Load Test	**Acceleration** 7.5 g, duration 3 min **Sinusoidal vibration** (resonance search range 5-2000 Hz at 0.5 g and 2 octaves/min, then sweep in in a range 5-21 Hz @ 11 g / 21-60 Hz @ 20 g / 60-100 Hz @ 6 g, each with 2 octaves/min and **Random Vibration** (resonance search range 5-2000 Hz at 0.5 g and 2 octaves/min), then all axes at 2.5 min/axis: 20-100 Hz (+3 dB/octave), 100-300 Hz (PSD(M)c = 0.05 g2/Hz × (mass + 20 kg)/(mass + 1 kg), 300-2000 Hz (-5 dB/octave)
7	Final Entanglement Quality	See Task 1

Conclusions



(c) ESA

- Aspects of space-suitable design
  - Tolerancing
  - Materials
  - Integration technologies
- Testing for space environments
  - Expected in late spring 2017


Fraunhofer IOF –
Research for the Future