Solar Pumped Optical Cryocooling (SPOC) with electrical power recuperation

a system and feasibility analysis

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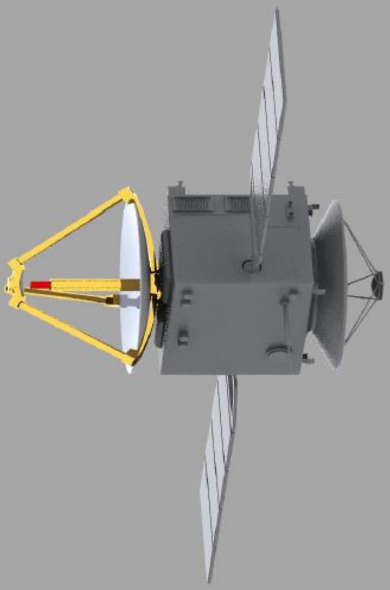

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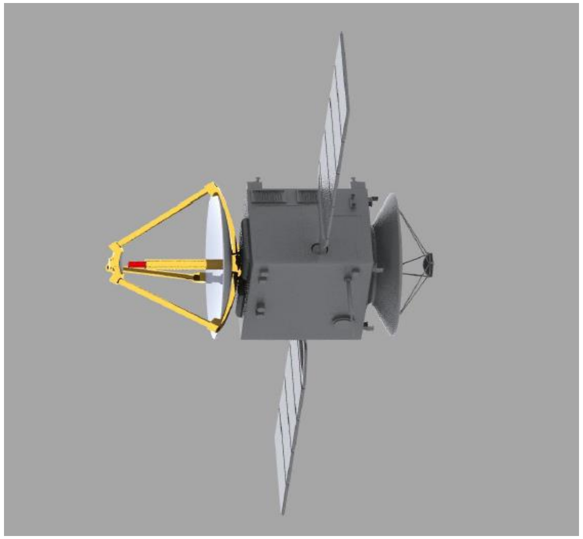
Lumium
optical systems

Solar Pumped Optical Cryocooling (SPOC) with electrical power recuperation

project details

Start date	June 1^{st} 2020
Original end date	June 1^{st} 2021
Work completion date	September 21^{st} 2021
Budget	65 k€ (Lumium original budget request) +10 k€ additional purchase order to Vexlum (Finland)
Work carried out by	B. Heeg (Lumium, sole-proprietor business)
Other involvement	Walker V.O.F., Delft – Solidworks drawings and thermal analysis



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(under construction)

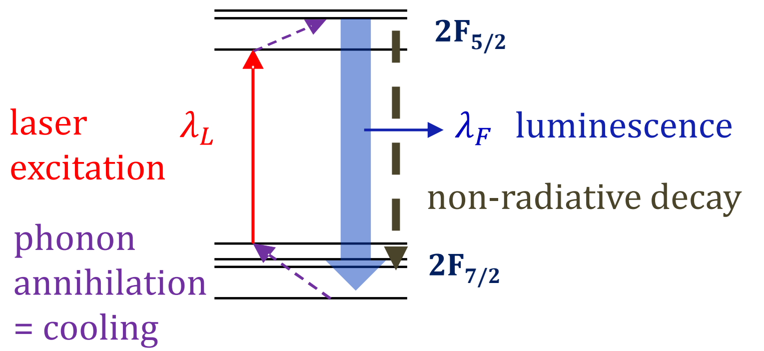
Background of optical cryocooling

The anti-Stokes luminescence cooling process:

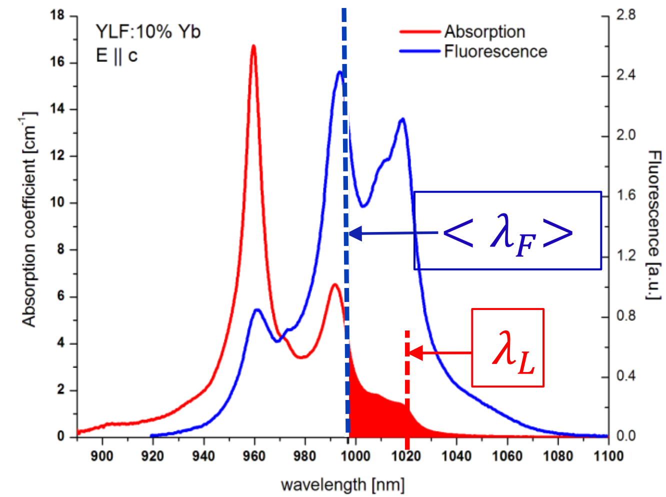
1. Cooling medium absorbs laser photons at single wavelength λ_L
2. Re-emits spectrum of photons λ_F with on average higher energy
3. Equilibrium is restored by annihilation of lattice vibrations (phonons)

→ Leading to cooling *if* non-radiative processes are at a minimum

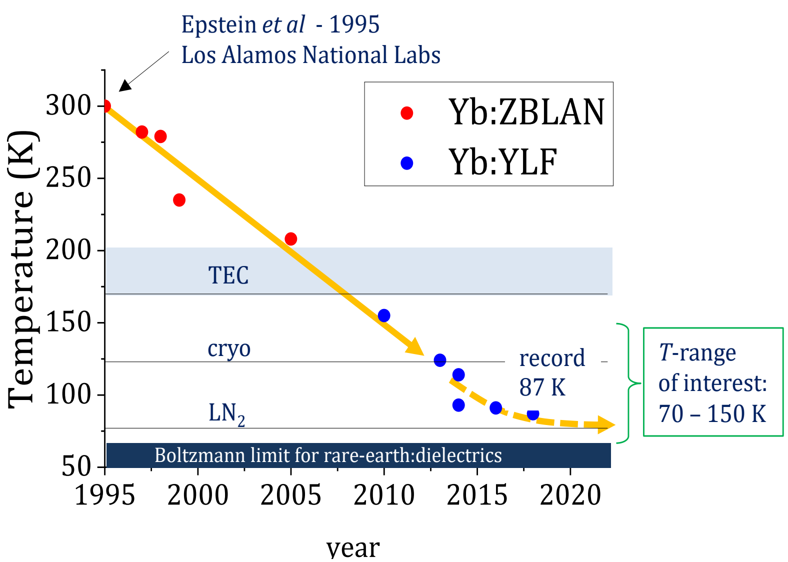
Example: energy diagram of Yb^{3+} ion



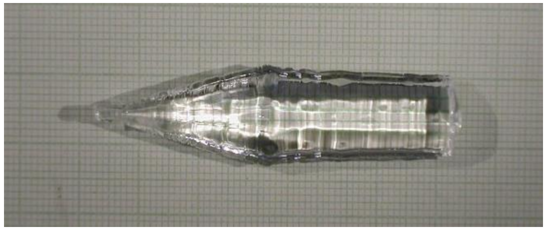
Absorption and luminescence spectra of Yb:YLF



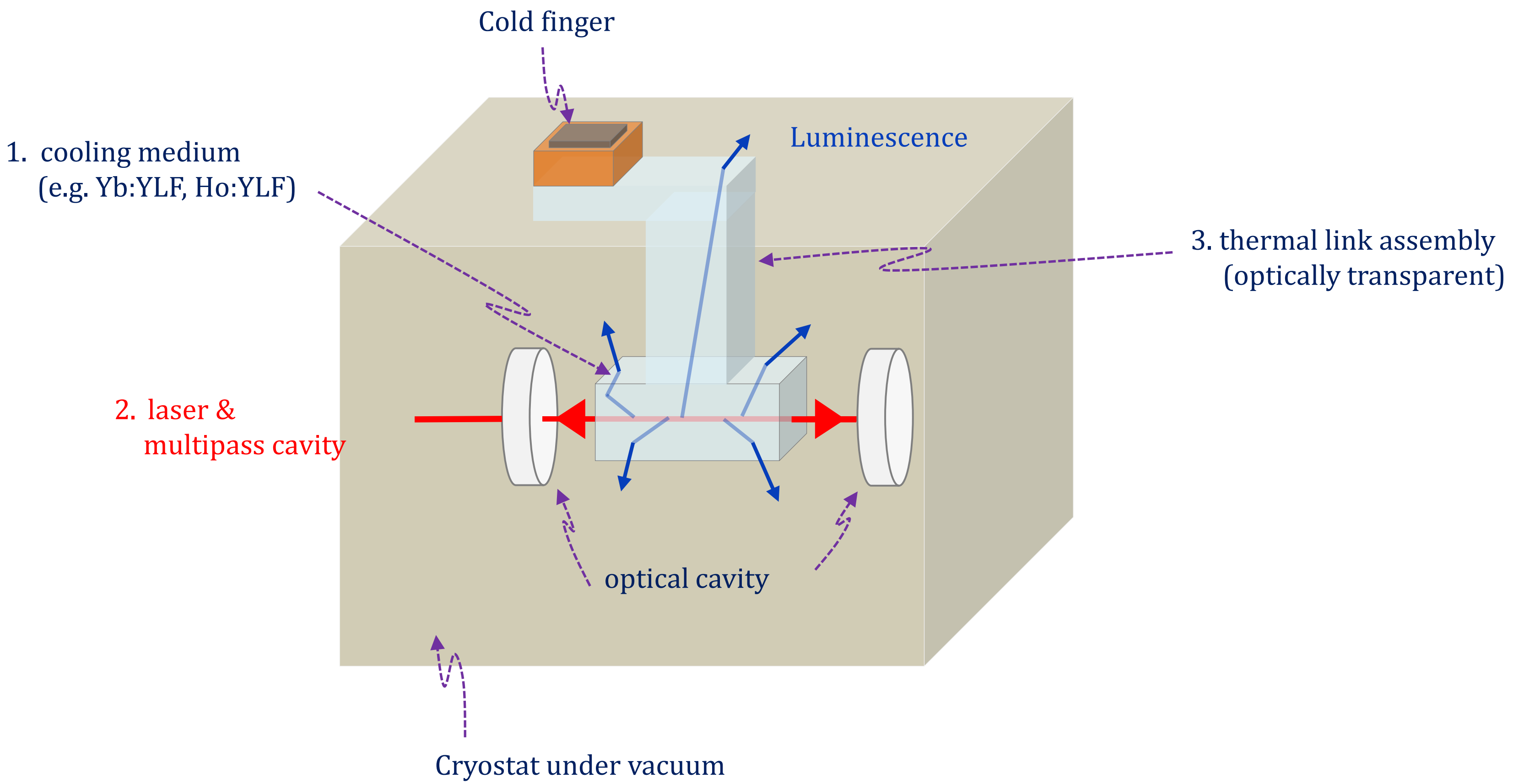
evolution of T records (no loads):



Yb:YLF
= Yb^{3+} doped $LiYF_4$ crystal
= today's best class of cooling media, developed at University of Pisa:



Schematic of optical cryocooler components



Potential advantages of optical cryocooling

Optical cryocooling is the *only* stand-alone and active cryocooling technology that is fully free from micro-vibrations, due to absence of moving parts *and* moving mass.

Advantages	Specifics
True all solid-state cooling → no moving parts *or* mass	• Zero μ–vibrations • Zero liquid or gas handling • Zero μ–gravity effects • Potentially very long life
Active and stand-alone	• Potential high temperature control • No pre-cooler needed
Cryogenic and intermediate temperatures	• Temperature range of interest: 100 – 180 K • Filling the gap between thermo-electric–, radiative– and mechanical cryocoolers
Allows miniaturization	• Suitable for on-chip cooling
Other benefits	• Zero electromagnetic interference • Efficient separation of hot and cold parts

Competitive with other vibration-free cryocooling methods:

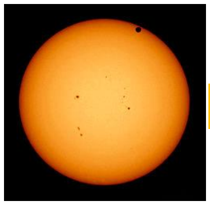
- thermo-electric coolers — cut-off $T \sim 180$ K
- radiative coolers — cut-off $T \sim 90$ K in low-earth orbit (LEO) and orientation contraints
- stored cryogens — limited operation duration
- sorption / dilution — requires precooling, gravity constraints
- adiabatic demagnetization — requires precooling

→ **However,** wall-plug efficiency of practical optical cryocoolers is projected to be relatively low with current approaches, e.g., a factor factor 10 – 15 difference at 150 K in comparison to pulse tube cryocoolers

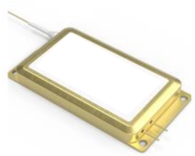
Potential advantage of using solar pumped lasers: #1

Conventional (indirect) PV route:

radiation to electrical power
(& storage) –70 to –80% loss



electrical power to
radiation (laser diode)
–40 to –50% loss



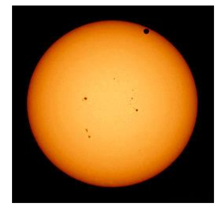
diode pumped
solid state (DPSS)
laser –50% loss

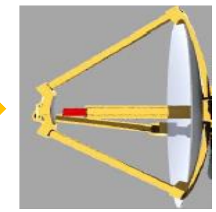
to laser cryocooler
(or other laser application)

Note: DPSS is needed for constraints on high power, wavelength & beam quality

Direct solar pumped laser (SPL) route:

direct solar pumped laser (SPL)
–95% loss *for current best SPL*





to laser cryocooler
(or other laser application)

The use of an SPL **avoids 2 conversion losses**, i.e., radiation → electrical, and electrical → back to radiation

- The vast majority of losses occur via *heat production*: reduction of losses also reduces thermal management constraints
- Other losses are *electrical and optical* coupling, transmission, conversion, reflection losses at multiple elements in the chain

Potential advantage of using solar pumped lasers: #2

Electrical power generation / consumption & thermal management

Conventional (indirect) PV route sequence:

1. $P_{electric}$ generation with PV arrays
2. laser radiation generation & conversion
3. optical cryocooling

- Non-optimal power generation
- Significant heating effects

Direct solar pumped laser (SPL) sequence:

1. concentration
2. selective spectral splitting
3. radiation conversion to laser
4. optical cryocooling

} $P_{electric}$ generation in all stages

- Potentially more effecient $P_{electric}$ generation, via
  - spectrally matched PVs
  - reduced surface area as result of concentration
  - high intensity radiation
- As a result of better matched $P_{electric}$ generation, also reduced thermal managament requirements

Q's:

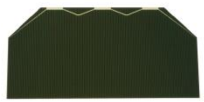
→ efficiency of electrical power generation, distributed over the system ?
→ reduction in PV surface area ?
→ Electrical power in the conventional PV route is *consumed* by optical cryocooler, but *generated* by the direct SPL route: at what point can cryocooler or other application come “for free” ?
→ trade-off in having to use a concentrator instead of PV array ?
→ constraints on the type of orbit / mission ?

Comparing *state-of-the-art* indirect and direct laser efficiency

conventional indirect PV driven laser:

Estimates from a combination of literature values:

PV system: e.g., Azure Space 4J at AM0/25^{0}C



BOL:	32%	
heating loss:	-25%	
PDCU conversion	-5%	
***effective* BOL:**		**23%**

Laser system:

laser diode (LD)	70%	(near limit, highly cooled)
heating loss	-10%	
Degradation	-2%	(ηLD = 62%, typical < 50%)
optical coupling	-12%	
solid state laser	-50%	(threshold + slope)

Laser efficiency: **28%**

Total (PV + laser) efficiency, BOL 6%

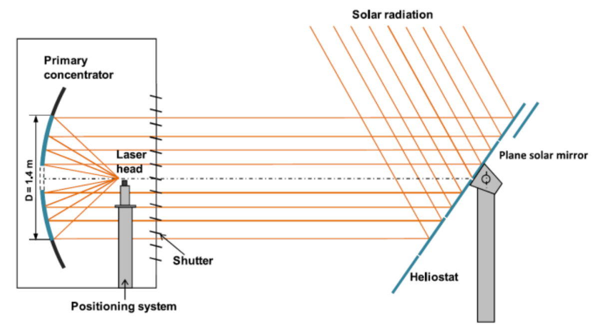
Assuming PV aging -4%/yr:
5 year life PV efficiency: **19%**
5 year system efficiency **5%**

- ➢ neglecting: thermal management, PV orientation, laser system aging
- ➢ Some room for further improvement, but very limited; efficiency ceiling considered to be ~ 8 - 10 % @ BOL

direct solar-pumped laser:

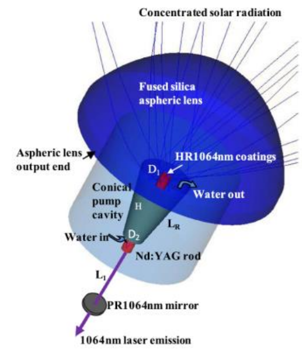
Demonstrated record-solar pumped laser: Liang *et al., Solar Energy Materials & Solar Cells* 159, 435 (2017).

Concentrator:
PROMES-CNRS



Solar concentrator efficiency: 59%

Laser system:
- Nd:YAG gain
- Additional non-imaging optic
- Conical cavity



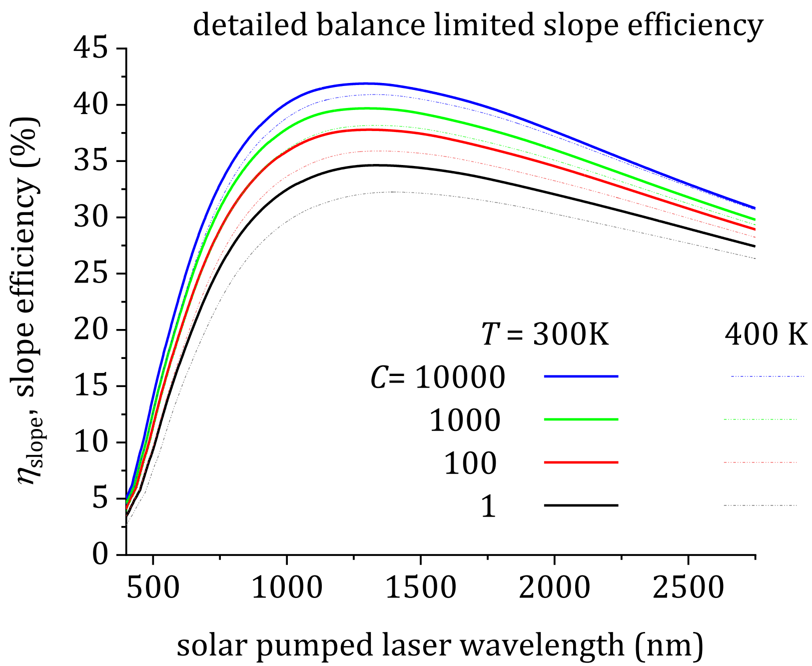
Laser efficiency: 5,3%

Total (concentrator + laser) efficiency, BOL 3 %

- ➢ neglecting aging effects (unknown)

Detailed balance limit of solar pumped lasers (SPLs)

Q: how much room for improvement is there for SPL's ?



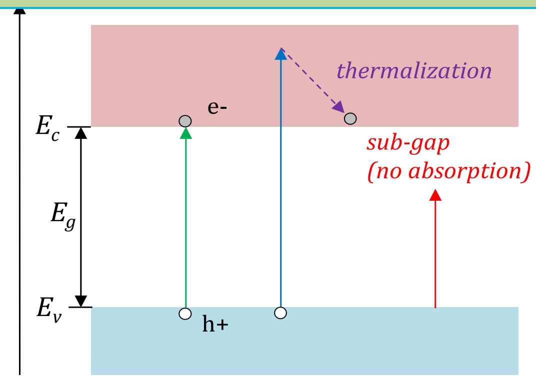
Efficiency limit is determined by mainly two losses:

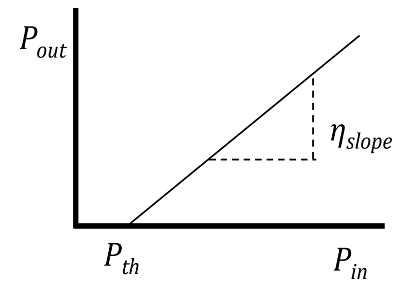
- Thermalization of excited states (spectral mismatch)
- Non-absorption of photons w. energy less than transition energy

→ Similar to efficiency limit in PV systems:

$$\eta_{SPL} = \frac{P_{out}}{P_{in}} = \eta_{th}\eta_{slope}$$

$$\eta_{th} = \left(1 - \frac{P_{th}}{P_{in}}\right)$$





- extension of the work of Roxlo and Yablonovitch, "Thermodynamics of daylight-pumped lasers", *Opt. Lett.* 8, 271 (1983), and Nechayev and Rotschild, "Detailed balance limit of efficiency of broadband-pumped lasers", *Sci. Reports* 7, 11497 (2017).
- shape and magnitude of the efficiency curve is very similar to the optimum conditions for solar photovoltaic (PV) optimization, i.e., the Shockley-Quiesser (SQ) limit of PV efficiency
- efficient SPL possible in range of 1 - 2 µm, of interest to optical cryocooling of Yb (1 µm) and Ho (2 µm)
- room for improvement in solar pumped lasers is significant from thermodynamic POV: possibly > 4 × higher efficiency limit in comparison to indirect PV → DPSS laser route
- Note: total SPL efficiency η_{SPL} approaches slope efficiency η_{slope} when operating far above threshold
- In addition, solar pumped laser can be accompanied by PV power generation subsystem

System analysis approach

Main focus of the project was on potential improvements in the state-of-the-art concentrators and solar pumped lasers (SPL), motivated by:

- Large room for improvement in theory
- Broad set of potential space and terrestial applications, besides optical cooling:
    - Laser communication
    - Remote power delivery
    - Laser-driven fuel generation
    - Laser-driven in-situ resource utilisation

Questions to address the potential for SPLs for optical cryocooling and other applications:

- What limits current state-of-the-art SPLs ?
- What can be done to significantly improve efficiency of SPLs ?
- What are practical limits ?
- How does this translate in overall system size / weight ?
- What is needed for space implementation ?
- What is the applicability ?

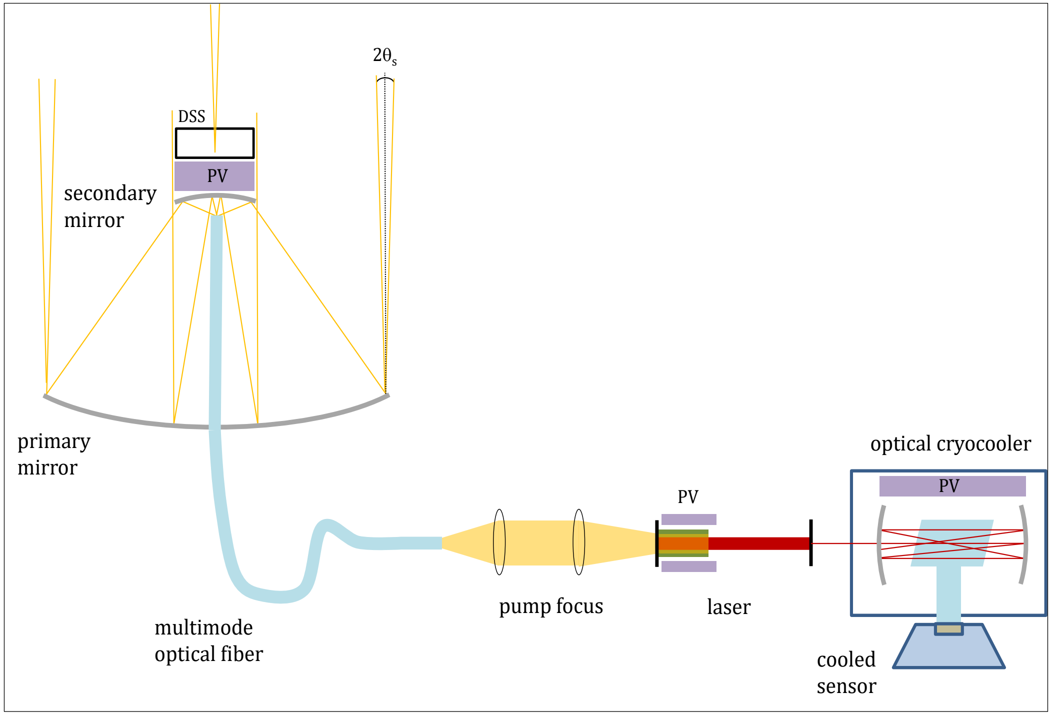
SPOC system analysis approach

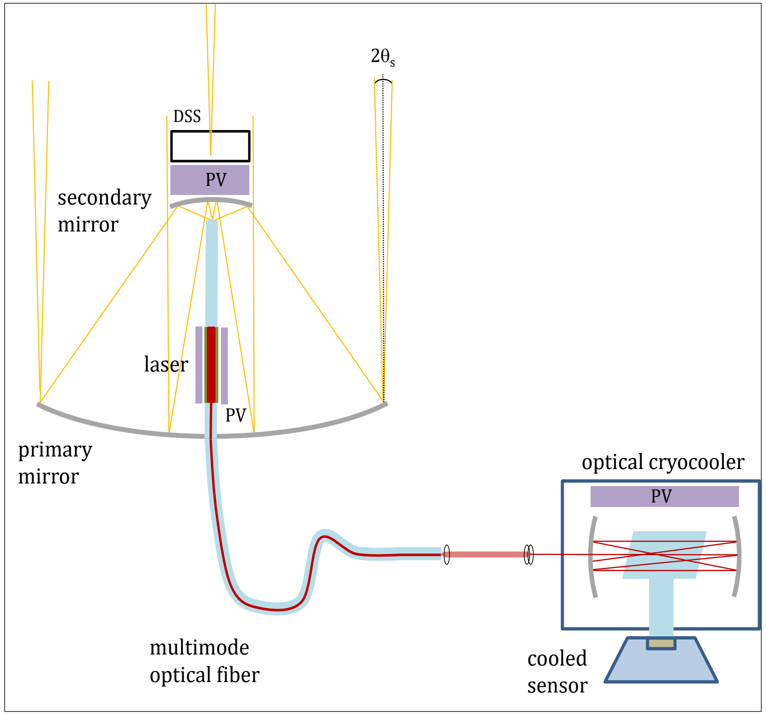
The project comprised an analysis of 4 system components and the combined system performance

- Concentrator
- Solar radiation pumped laser
- Laser cryocooler
- Electrical recuperation

→ Many possible permutations !

2 examples of possible system concepts:

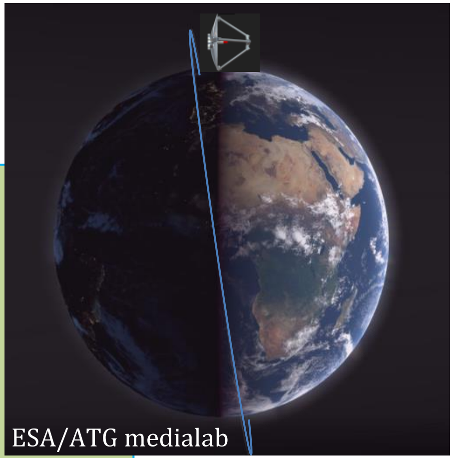




Orbits

The SPL or SPOC system is preferably operated under continuous solar exposure

- Largest advantage due to absense of power storage system and peripherals



Possible missions applicable to SPOC system

- ➢ Dawn-dusk LEO
  - provided it can compete with passive radiatiors (cut-off at ~90 – 110 K)
- ➢ Venus & Mercury missions
  - radiative coolers have higher cut-off temperature, and
  - SPOC should more more efficient then in earth orbits

Not applicable:

- ➢ GEO and L1 missions less suitable, since radiative coolers can achieve lower temperatures (40 K)

Possible missions applicable to SPL system

- ➢ E.g., any where localized remote power is needed (Moon, Mars, Earth, other spacecraft)

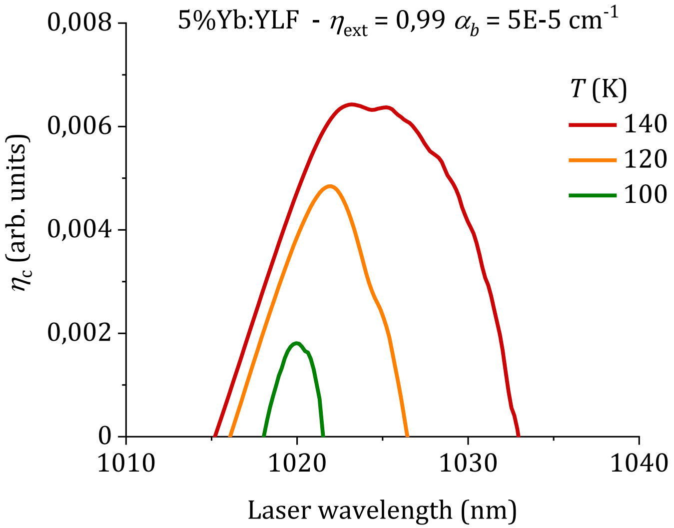
- ➢ In the analysis, we first assume continuous solar irradation, no need for batteries
- ➢ Depending on the eclipse time, mass can be adjusted for addional power storage requirements
  E.g., approximaly a factor 1,5 for a LEO orbit

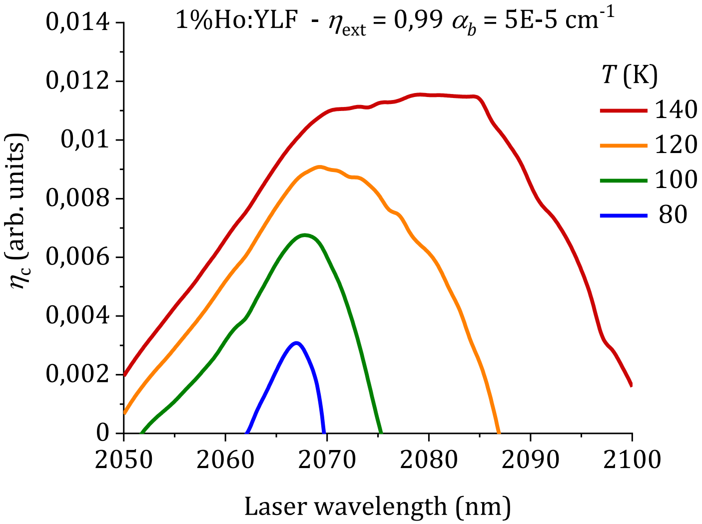
I: optical cryocooler constraints on system

2 main candidates for optical crycocooling:

- Yb:YLF – current record holding cooling medium
- Ho:YLF – potential performance enhancement and currently under investigation

Comparison of *demonstrated* (Yb:YLF) and *potential* (Ho:YLF) laser cooling efficiency η_c based on spectral coefficients for absorption and luminescence, *under similar materials conditions*:





Optimum laser wavelength	Type of laser
Yb:YLF: ~ **1020 nm**	certain **Yb lasers**
Ho:YLF: ~ **2067 nm**	certain **Tm lasers**

- ➢ Not included: role of energy transfer upconversion (ETU) in Ho:YLF comparison, but can be minimized (to be determined)
- ➢ Also not included: potential enhancement in Ho:YLF cooling by means of co-doping

Conclusions

Conclusions:

- → Significant improvement in state-of-the-art SPL efficiency possible on thermodynamic grounds, by reducing heat losses in two conversion steps. This should also reduce thermal management constraints.
- → Practical implementation of improved SPLs is feasible via combination of
  - Reduced aberrations in concentrator
  - Laser gain enhancement in compound gain medium
  - Use of broad-band sensitizer
  - Use of spectrally selective mirrors for enhanced matching
- → A solar pumped rare-earth laser was identified with potentiallyh 17% solar to laser effiency
- → Solar pumped VECSEL appears to have higher laser threshold
- → Electrical power generation can be implemented as an integral part of SPOC, allowing similar power levels to be generated with a fraction of PV surface area, at the expense of using a concentrator
- → Factor 2-3 reduction in mass possible using SPL instead of conventional PV-driven, using lightweigth concentrator materials like CRFP.
- → Factor 2 reduction in mass possible in SPOC system (other things equal)
- → System feasibility analysis is based on several assumptions to be demontrated
  - Efficiency of solar pumped laser concept
  - Cooling potential of Ho:YLF
  - Optical cryocooler system efficiency