Solar Tower Technology
- Status and R&D at DLR

Dr. Reiner Buck
German Aerospace Center (DLR)

April 10, 2014
Stellenbosch University, South Africa

DLR

DLR
German Aerospace Center

- Research Institution
- Space Agency
- Project Management Agency

- 34 research institutes and facilities, all over Germany
  - 820 Mio € for Research & Operation
  - 7,700 employees

    > 3,000 scientists

    > 500 doctoral students and junior scientists

Solar Research at DLR

about 140 staff members in

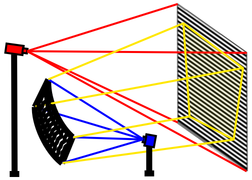
- Köln
- Stuttgart
- Almeria (Spain)
- Jülich

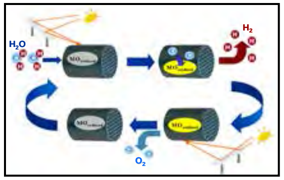
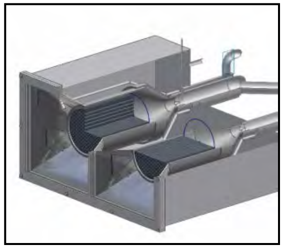
Institute of Solar Research
Prof. Dr. Pitz-Paal
Prof. Dr. Hoffschmidt

- **Line Focussing Systems** – K. Hennecke
- **Point Focussing Systems** – Dr. R. Buck
- **Qualification** – Dr. P. Heller
- **Solar Process Technology** – Dr. C. Sattler
- **Test Facilities and Solar Materials** – Dr. K.-H. Funken







Department „Point Focus Systems“

Department
Point Focus Systems
Dr. Reiner Buck

Systems and Concentrators Stefano Giuliano	Receivers Ralf Uhlig	Simulation and Open Air Receivers Peter Schwarzbözl
6 staff members ST	11 staff members ST	5 staff members KP +JL

- institutional funding: R&D with long term perspective
  - current focus: direct absorption receivers and systems
- third party funding: short- to mid-term perspective
  - technology transfer and continued development
  - component development
  - tool development
- 25 staff members, budget 2013: 3.5 Mio €

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Solar Research Test Facilities (Cologne)

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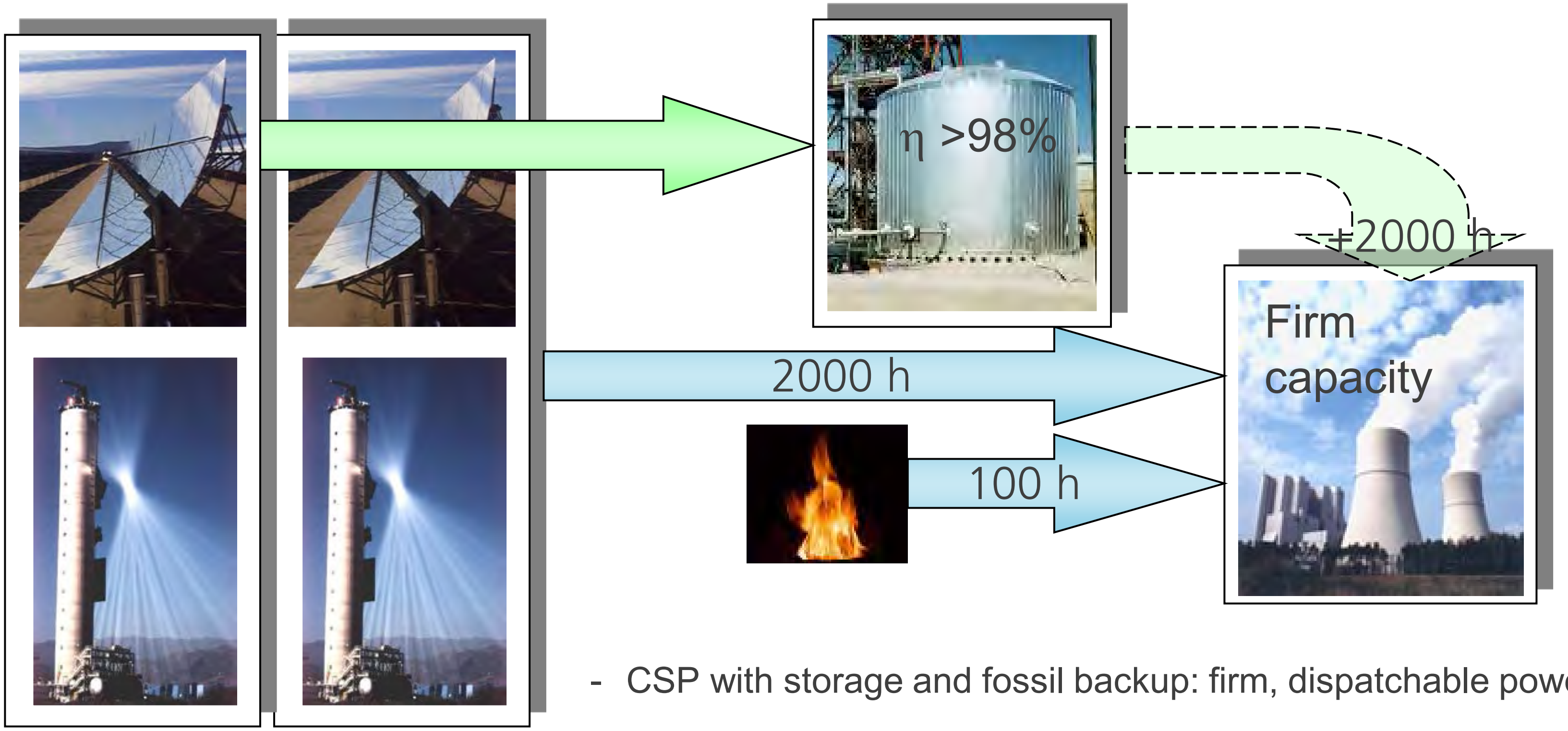
DLR owns Solar Tower Test Facility Jülich

Plataforma Solar de Almeria, Spain

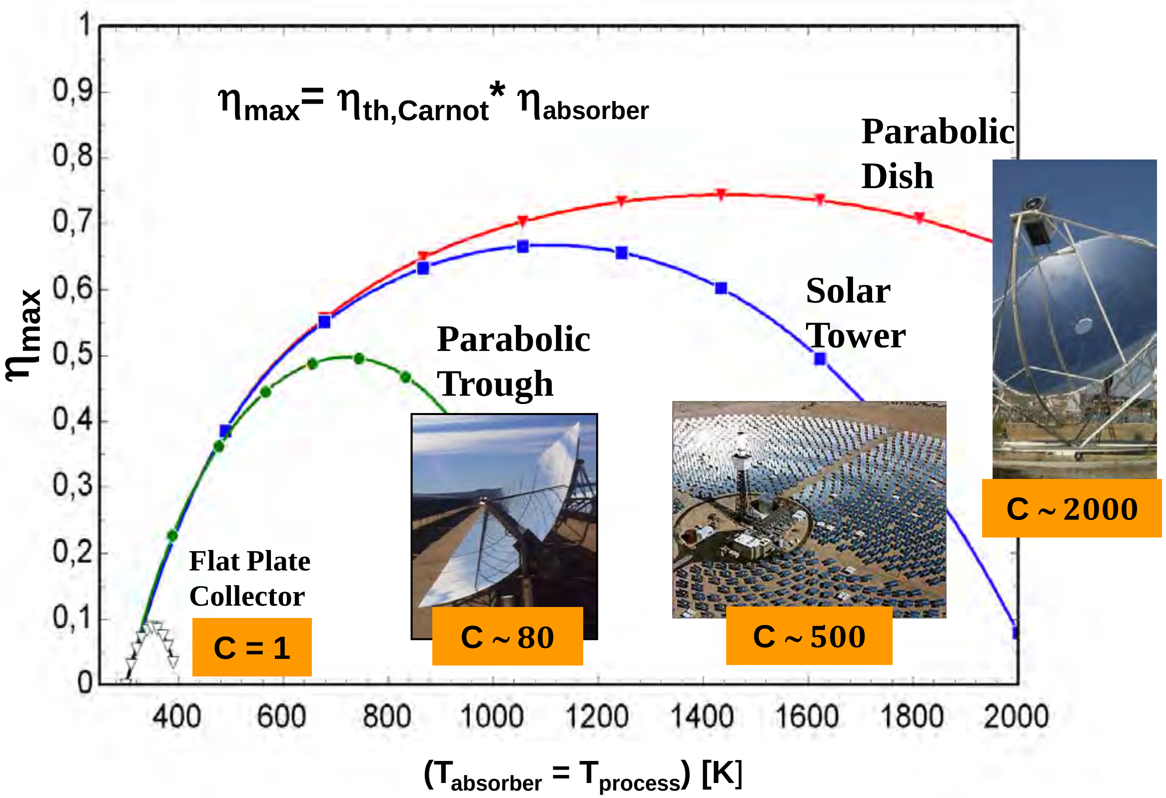
owned by CIEMAT; permanent delegation of DLR Solar Research

Advantages of Concentrating Solar Power Plants



- CSP with storage and fossil backup: firm, dispatchable power
- thermal storage lowers LCOE
- high local content possible

CSP Characteristics



solar tower:

⇒ higher concentration

⇒ higher process temperature

⇒ higher solar-to-electric efficiency

⇒ reduced collector area

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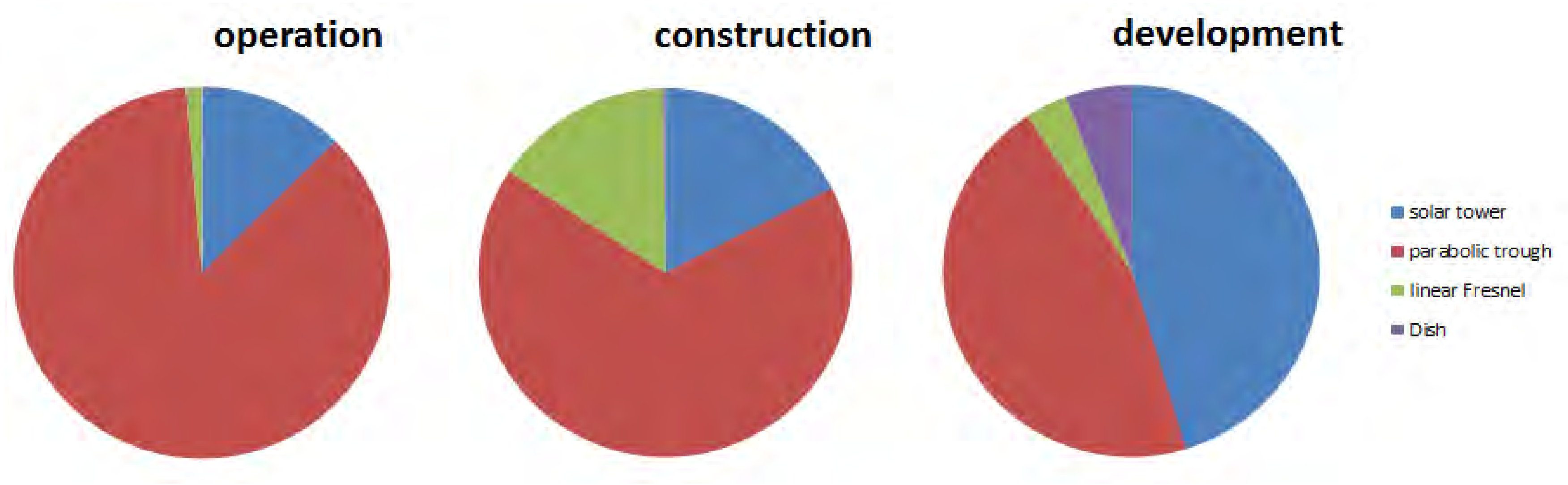
CSP Technology Perspective



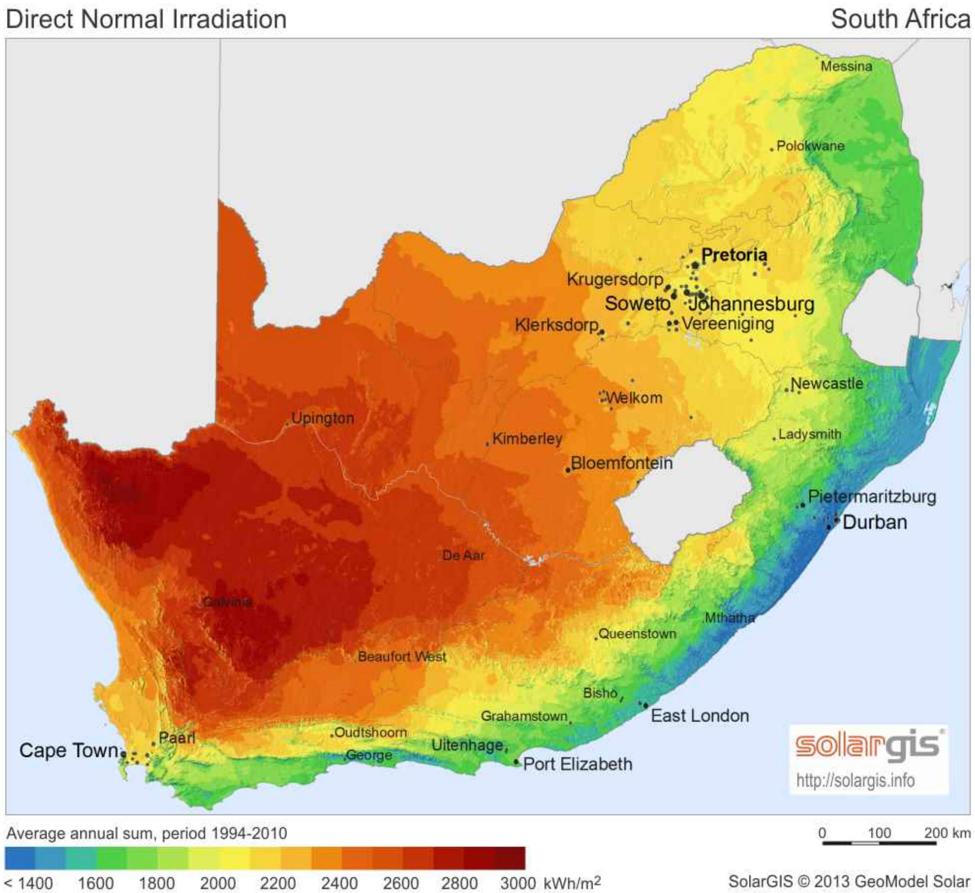
total: 3957 MW

total: 1212 MW

total: 2786 MW

data from CSPtoday Project Tracker, status: March 2014

Solar Resource in South Africa



- annual DNI level has strong influence on LCOE
- DNI levels > 2000 kWh/m²a are required
- South Africa has excellent DNI resources in several regions

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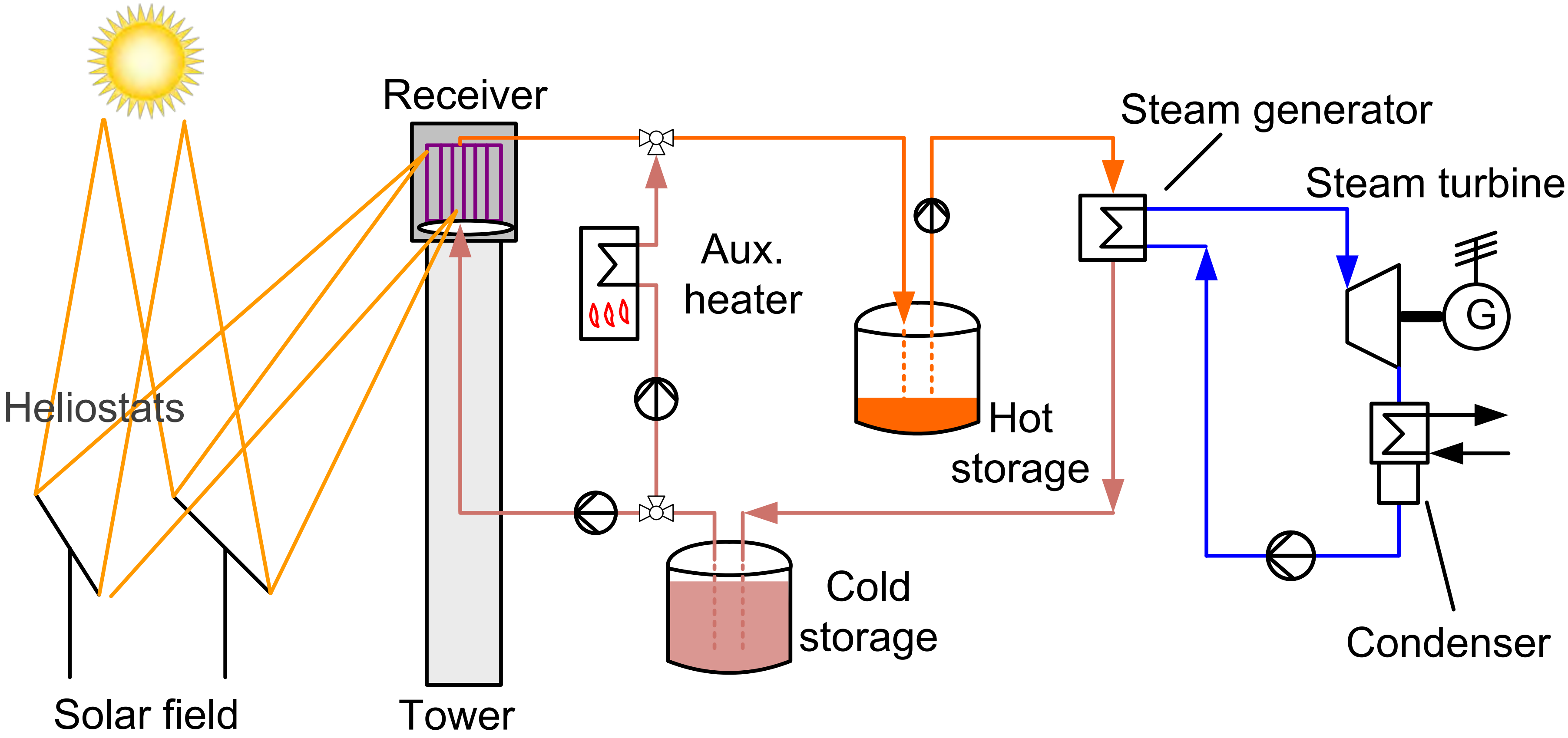
Scheme of a Solar Tower Plant



Operational Commercial Solar Tower Plants

Overview

- PS10/20: near Seville (Spain), 10 + 20MW, ~ 1h storage
- Gemasolar: near Seville (Spain), 20MW, 15h storage
- Ivanpah: near Las Vegas (USA), 377MW, no storage
- Sierra SunTower: Lancaster (USA), 5MW, no storage

Operational Solar Tower Plants: Gemasolar (Torresol)

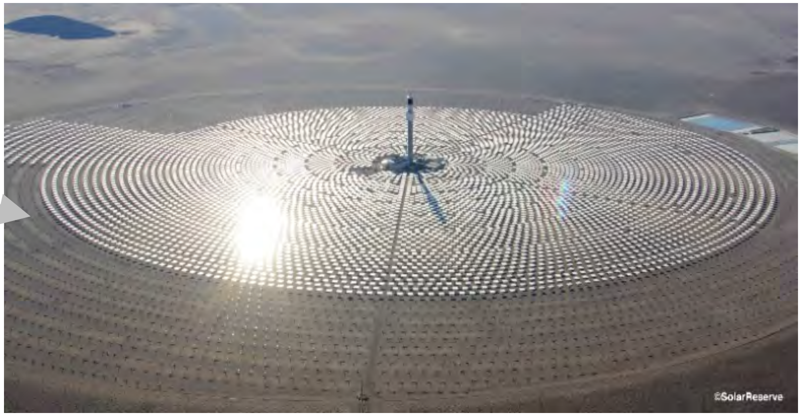
Power rating	19.9MW
Annual production	110 GWh/a
Capacity factor	74%
Heat transfer fluid	molten salt
Storage	molten salt, 15h
Power block	steam cycle, wet cooling

Operational Solar Tower Plants
Ivanpah (Brightsource)

Power rating	377MW
Annual production	1‘079 GWh/a
Capacity factor	33%
Heat transfer fluid	Water/steam
Storage	-
Power block	steam cycle, dry cooling

Future Solar Tower Plants

- Crescent Dunes, USA (SolarReserve)
  - 110MW, 10h storage
  - under commissioning
- Khi Solar One, South Africa (Abengoa)
  - 50MW, 2h storage
- Cerro Dominador, Chile (Abengoa)
  - 110MW, 17.5h storage
- Ouarzazate, Morocco
  - 110MW, storage
  - bidding process underway



Economics of Solar Tower Systems

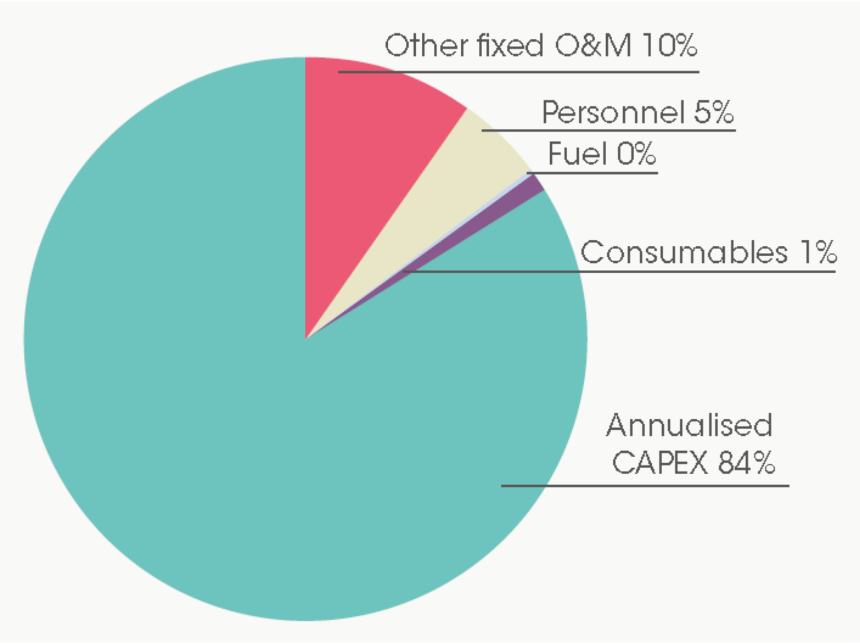
- relevant parameter is LCOE [$/kWh], not specific cost [$/kW]
- additional value from dispatchability and security of supply

- CAPEX is dominant cost fraction

  ⇒ financing conditions important!
- actual LCOE: 0.16 … 0.36 US$/kWh
- 2020 LCOE: 0.08 … 0.16 US$/kWh
- LCOE depends on
  - solar resource
  - financing

(all cost in 2010 US$)

solar tower, 100MW with 15h storage



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Summary

Solar Tower Technology:

- ascending renewable power technology
- firm capacity with high capacity factors
- significant cost reductions expected
  - technological development
  - improved manufacturing
  - increased maturity (financing)
- high local content achievable
- also suitable for HT process heat

R&D Activities at DLR Solar Research Department „Point Focus Systems“

Goal: Cost Reduction of CSP Plants (Solar Tower, Dishes)

- performance optimization
  - heliostat field, receiver, system
- cost reduction
  - component cost, O&M cost

R&D topics:

- receivers
- heliostats
- system aspects
- control
- simulation tools

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HelFer

Cost Optimized Heliostat Production

Aim

Cost reduction of heliostats by complementary development of production concepts and heliostat structures

Status

- Heliostat developed
- Design of central production unit almost finished
- Basic concept for integration of qualification methods in production process (photogrammetry and deflectometry) developed

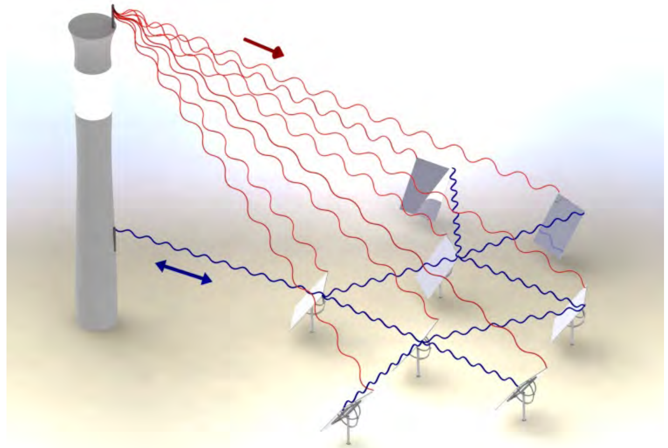
Partners

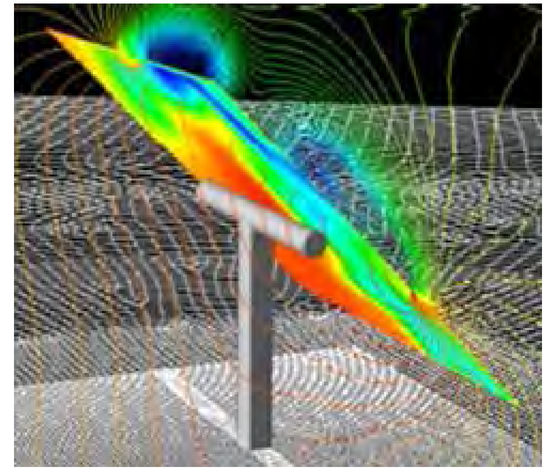
- Kraftanlagen München GmbH
- Heidelberger Druckmaschinen AG

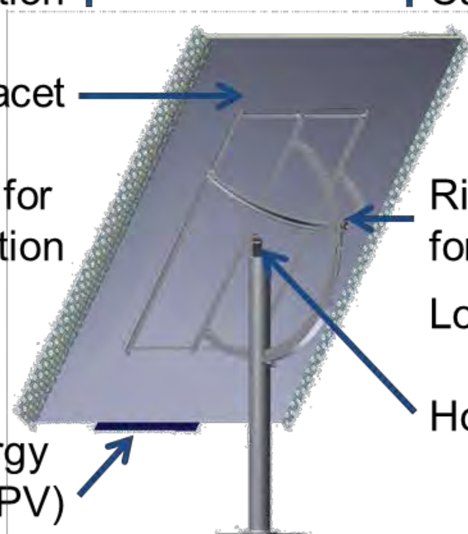
AutoR

Autonomous Light Weight Heliostat With **R**im-Drives

Aim
Cost reduction of heliostats by about 30% through complementary approaches





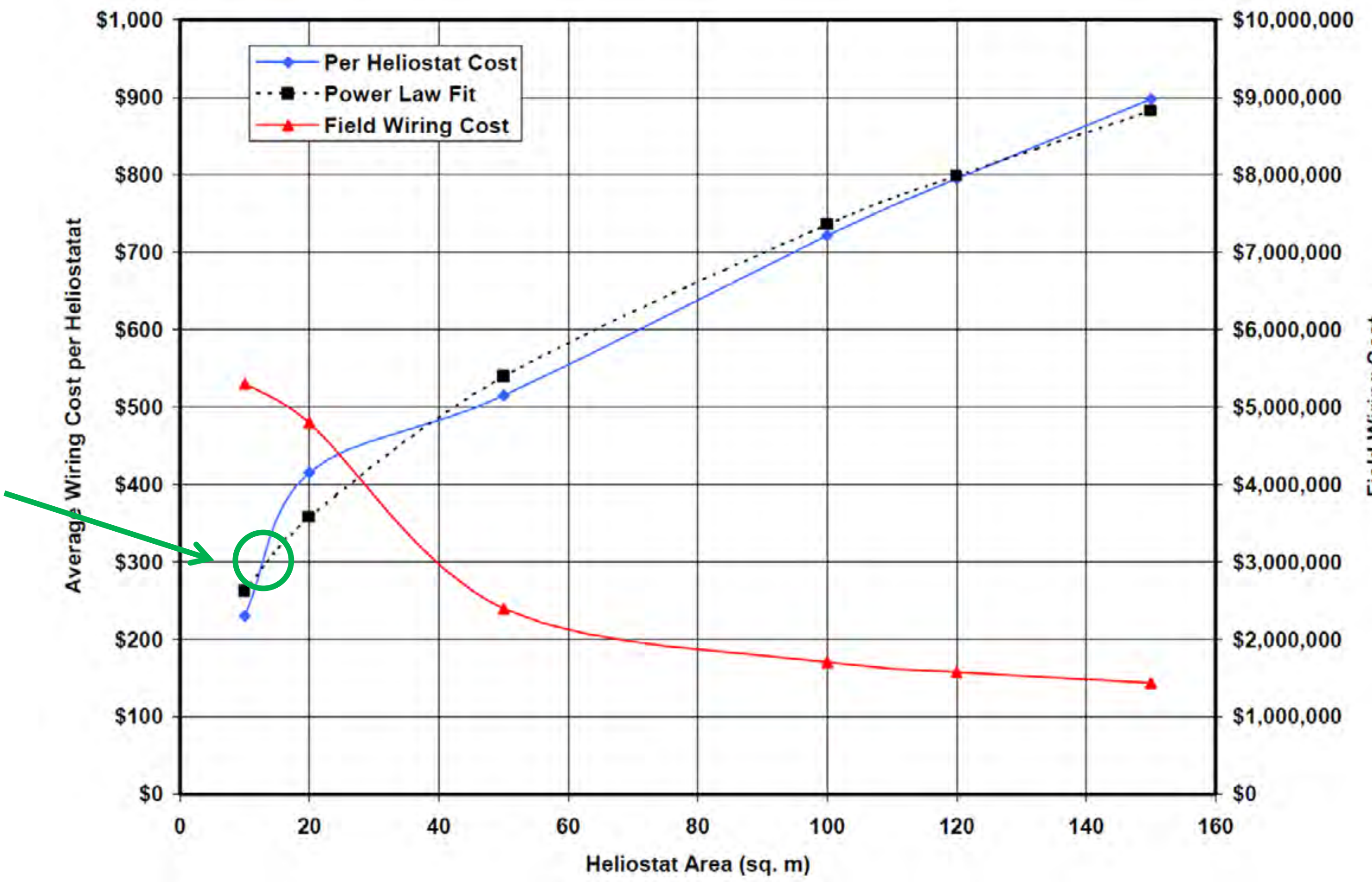


Partners
- Trinamic Motion Control GmbH
- Institute of Telematik, TU Hamburg Harburg

AutoR
Autonomous Light Weight Heliostat With **R**im-Drives

Cost reduction potential wireless:

- Wiring cost for one 14m² heliostat: 300$
- No lightning protection needed



Source: G. Kolb et al., Heliostat Cost Reduction Study, 2007

AutoR

Autonomous Light Weight Heliostat With **R**im-Drives

Cost reduction potential of drives and steel structure (cost estimations):

14m²	**BSE (Reference)**		**Rim Drive**	
Elevation drive	80 €	6 €/m²	30 €	2 €/m²
Azimuth drive	300 €	21 €/m²	30 €	2 €/m²
Central tilting device	65 €	5 €/m²	40 €	3 €/m²
Rims, guidance	0 €	0 €/m²	100 €	7 €/m²
Locking devices	0 €	0 €/m²	20 €	1 €/m²
Mirrors	168 €	12 €/m²	168 €	12 €/m²
Mirror support structure	400 €	29 €/m²	300 €	21 €/m²
Pylone and foundation	240 €	17 €/m²	240 €	17 €/m²
Control, wiring, installation	600 €	43 €/m²	600 €	43 €/m²
total (without impact of optics)	1853 €	**132 €/m²**	1528 €	**109 €/m²**

AutoR

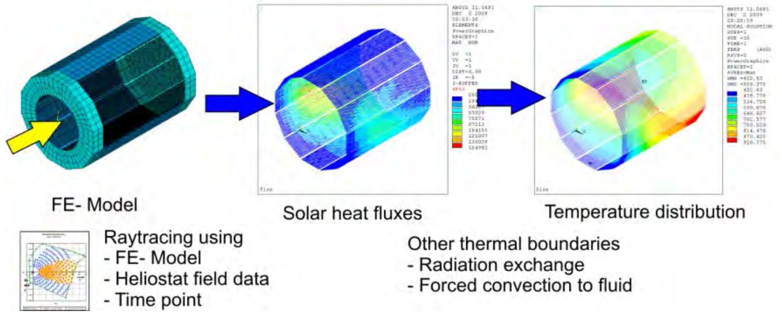
Autonomous Light Weight Heliostat With **R**im-Drives

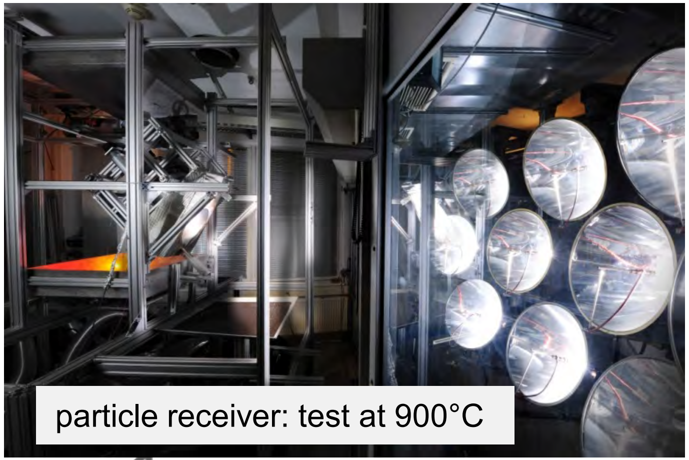
First prototype almost finished

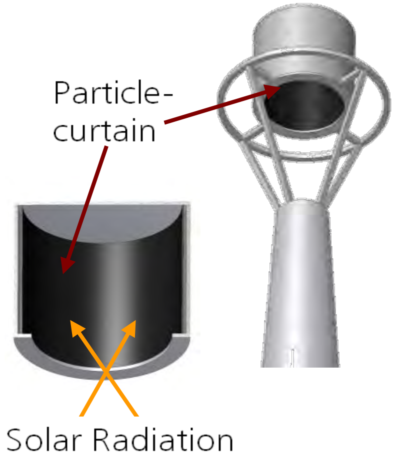
R&D on Receiver Technologies

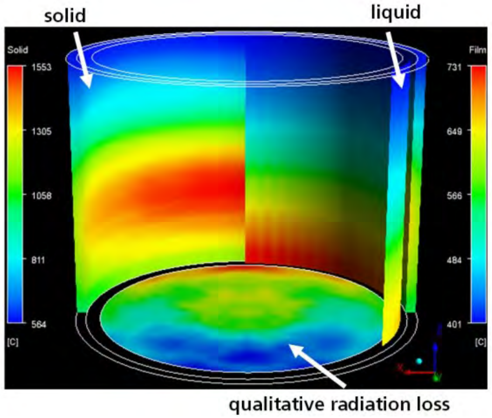
- development / technology transfer
  - open volumetric air receiver
  - pressurized volumetric air receiver

- development of receivers with liquid HTF
  - molten salt receivers
  - liquid metal receivers
- innovative concepts: direct absorption
  - particle receivers



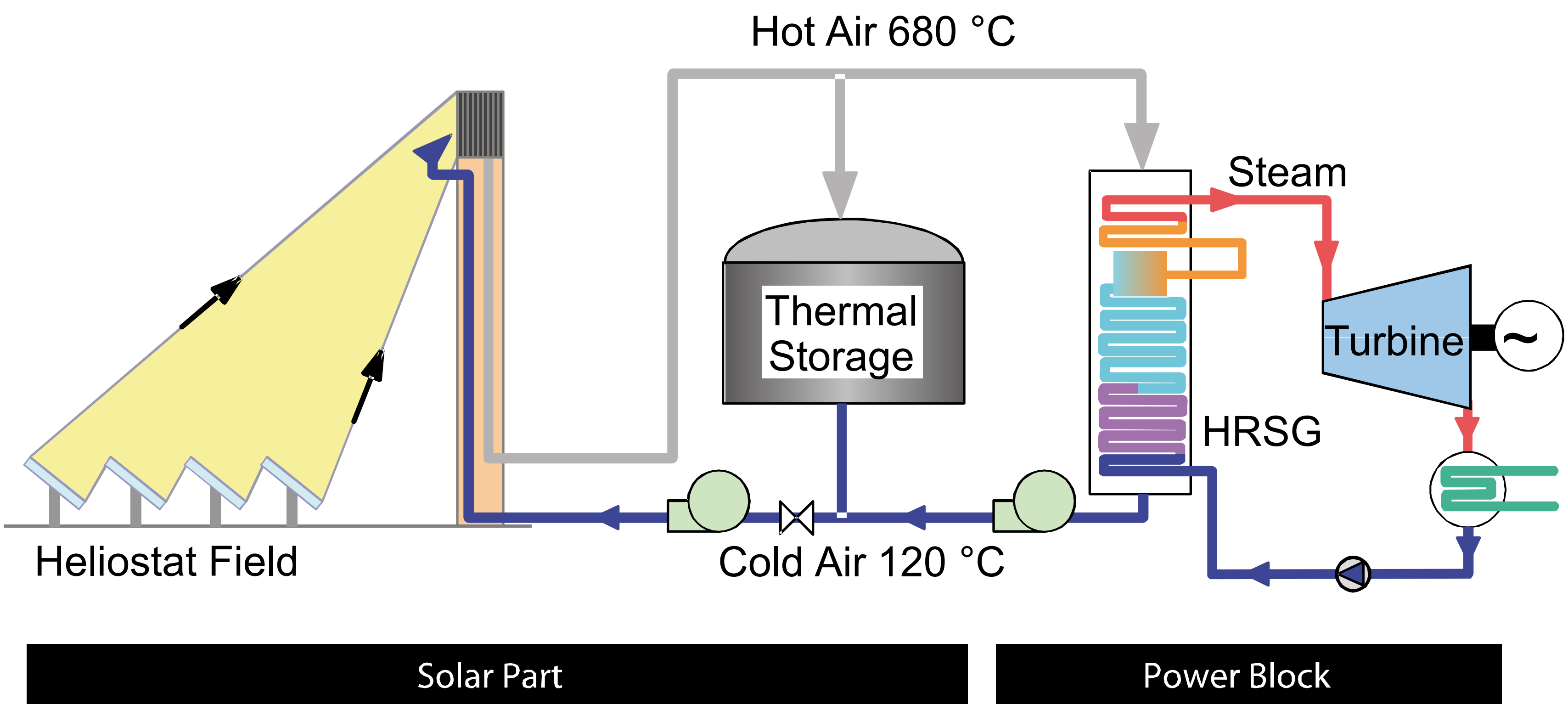




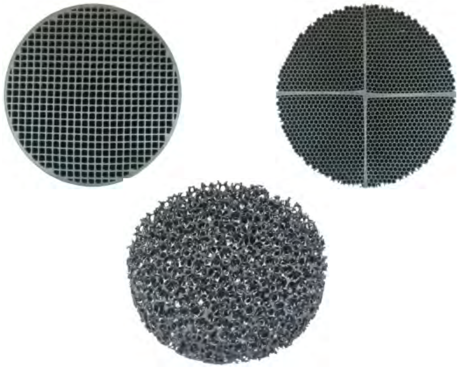


Tower Plant with Open Volumetric Air Receiver

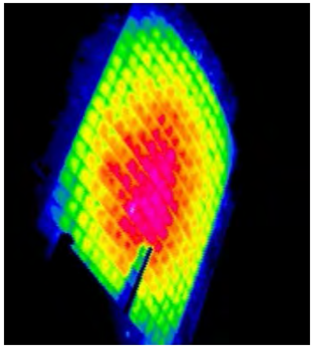
Solar Tower Demonstration Plant Jülich, Germany

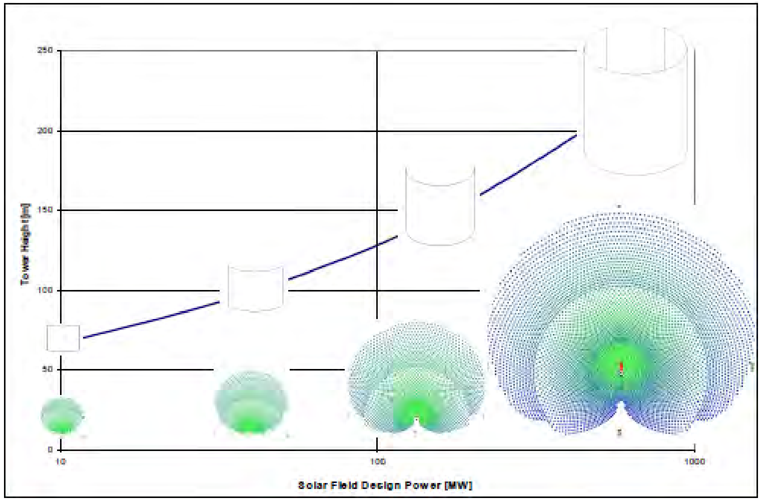


Open Volumetric Air Receiver



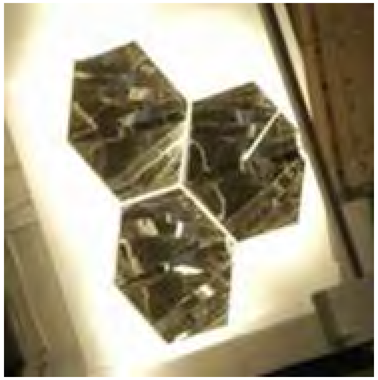
- improvement of volumetric absorber structures
- optimization of air receiver system
- dynamic simulation of receiver
- aim point optimization
- support of market introduction
    - scalable design
    - design of prototype plants
    - know-how transfer

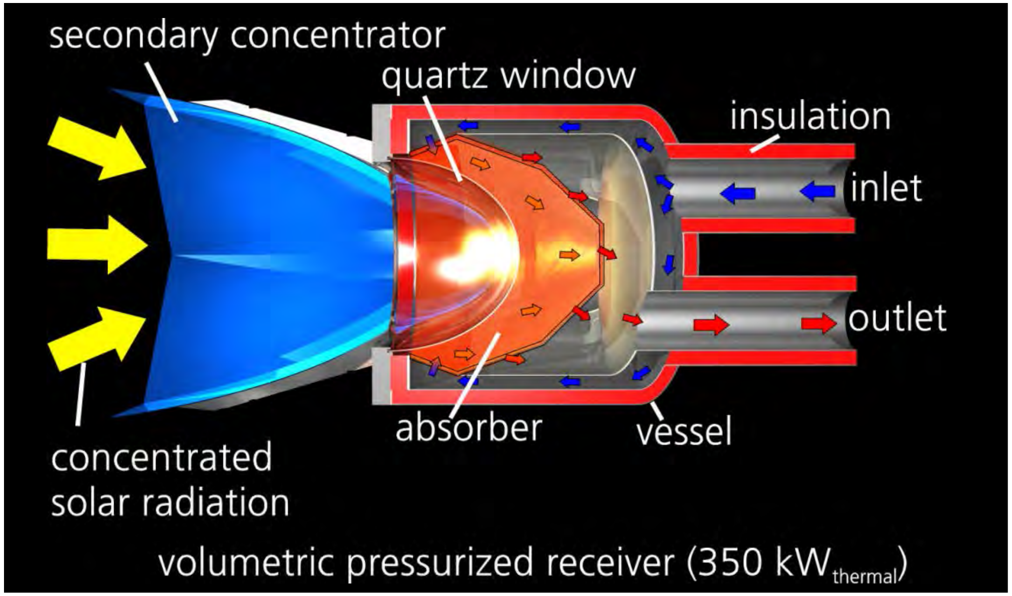




Pressurized Volumetric Air Receiver

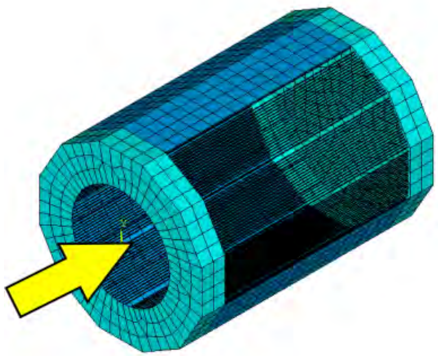
- volumetric absorber structures:
  - metallic wire grid (T < 800°C)
  - ceramic foam/matrix (T > 800°C)
- transparent quartz window
- tested at Plataforma Solar de Almeria:
  - temperature up to 1030°C
  - pressure up to 15bar
- modular design with secondary concentrator



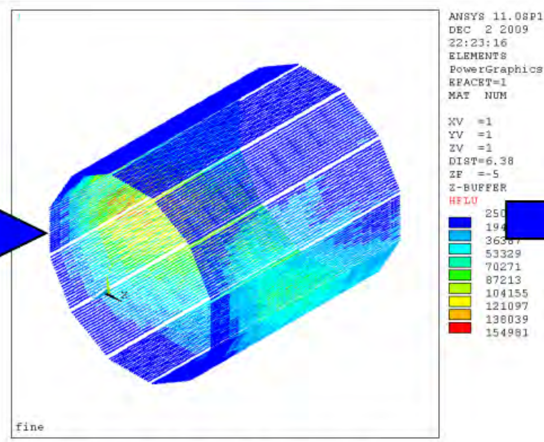


Tube Receiver Design and Analysis

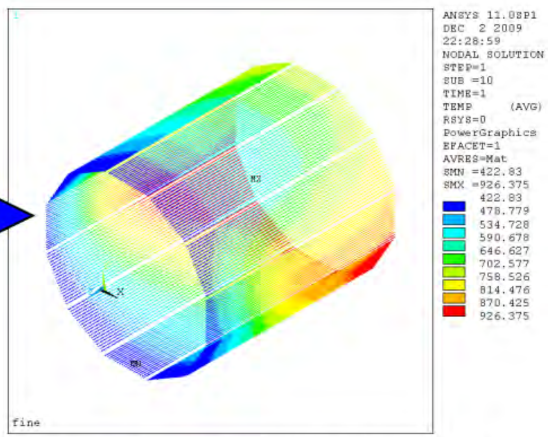
Example: SOLUGAS receiver



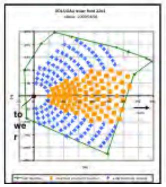
FE- Model



Solar heat fluxes



Temperature distribution



Raytracing using
- FE- Model
- Heliostat field data
- Time point

Other thermal boundaries
- Radiation exchange
- Forced convection to fluid

SOLUGAS facility
Abengoa, Seville

SOLUGAS
Tube Receiver in Solar Gas Turbine System

800°C reached

Abengoa
Solar Power Plants,
near Seville, Spain

installation of an additional 1000°C pressurized volumetric receiver module in preparation

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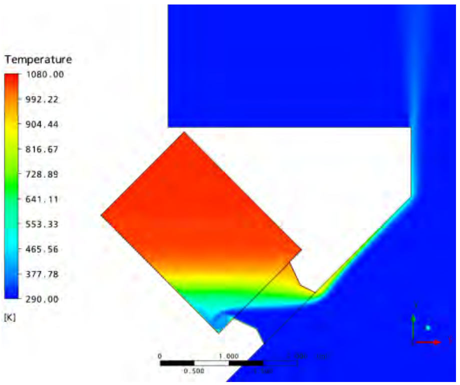
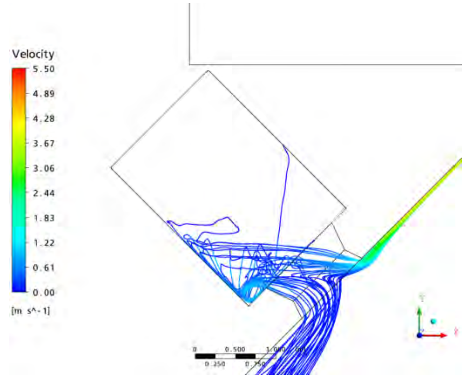
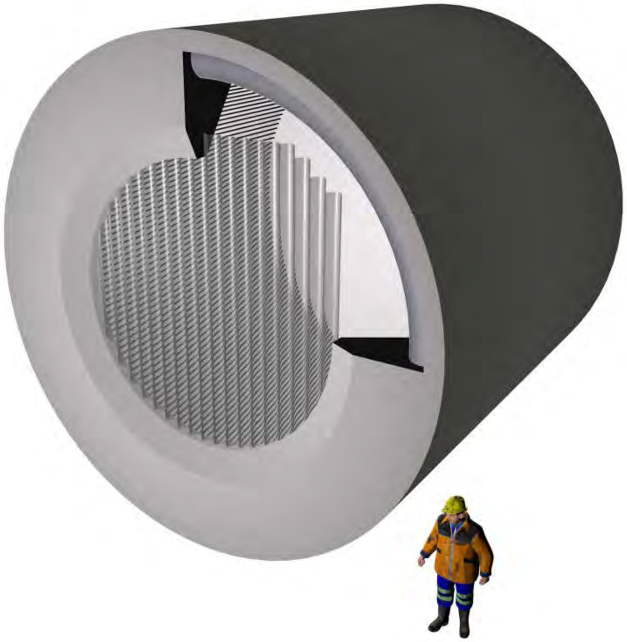
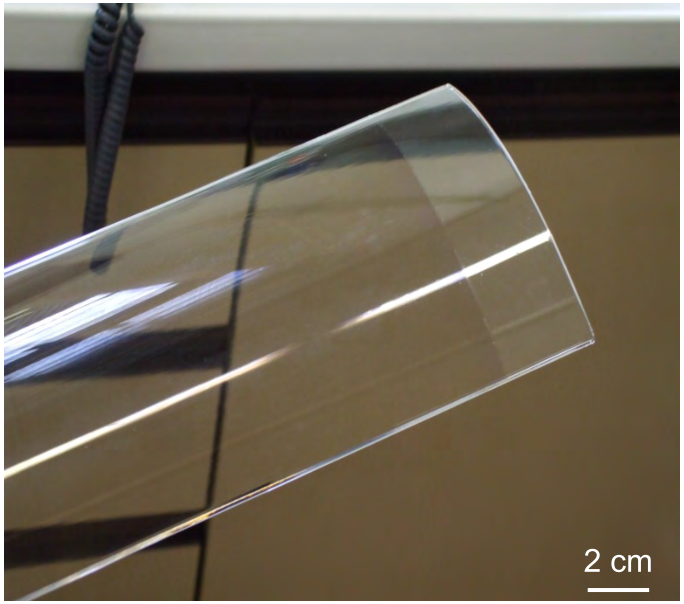
Receiver component development - antireflective coated segmented receiver window









LIMTECH: Systems using Liquid Metal as HTF

- large temperature range in liquid phase
- chemically stable

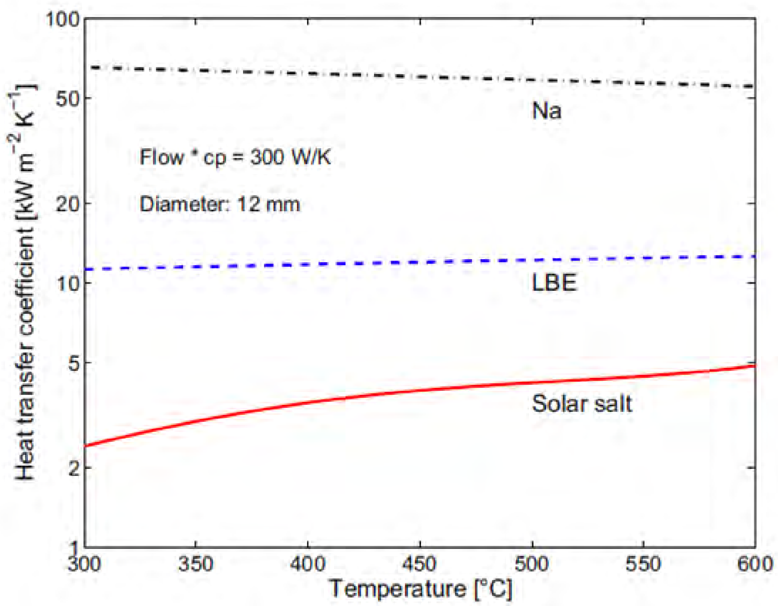
Fluid	Solar Salt	Na	LBE	Sn
Tmelt [°C]	220	98	125	232
Tboil [°C]	565	883	1553	2687

(at 1bar)

- high heat transfer coefficient

⇒ receiver with higher flux density, i. e. smaller receiver
⇒ higher receiver efficiency
⇒ lower levelised costs of electricity

- thermal storage concept?
- corrosion?
- cost?

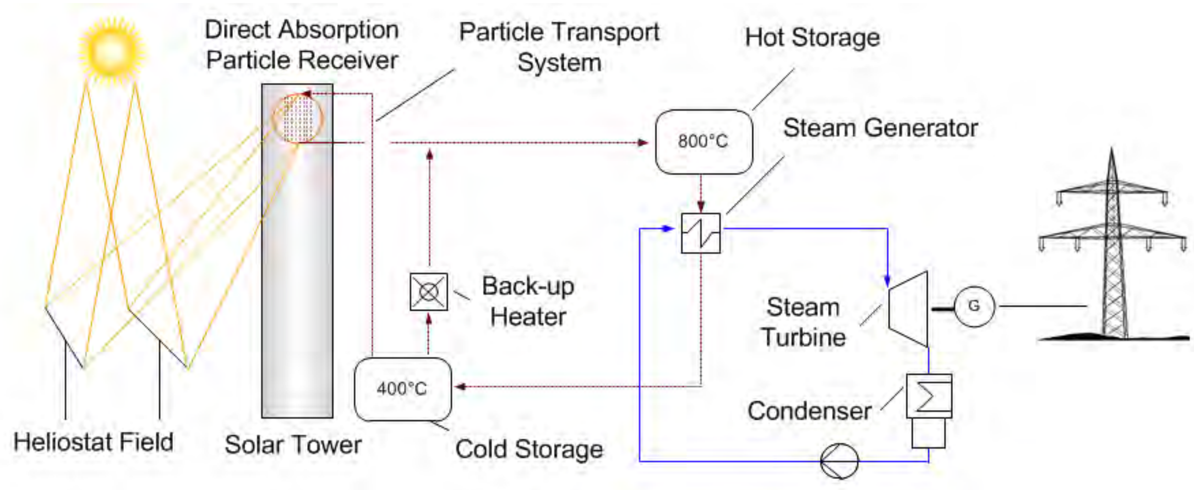


Particle Receiver Power Plant

- Solid ceramic particles as absorber, heat transfer and storage material

Advantages:
- Direct absorption
- No freezing
- No decomposition
- High temperatures
- Inherent Storage

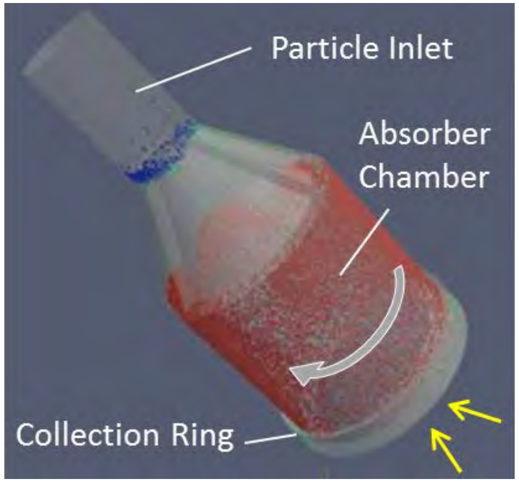
- Low Levelized Electricity Costs



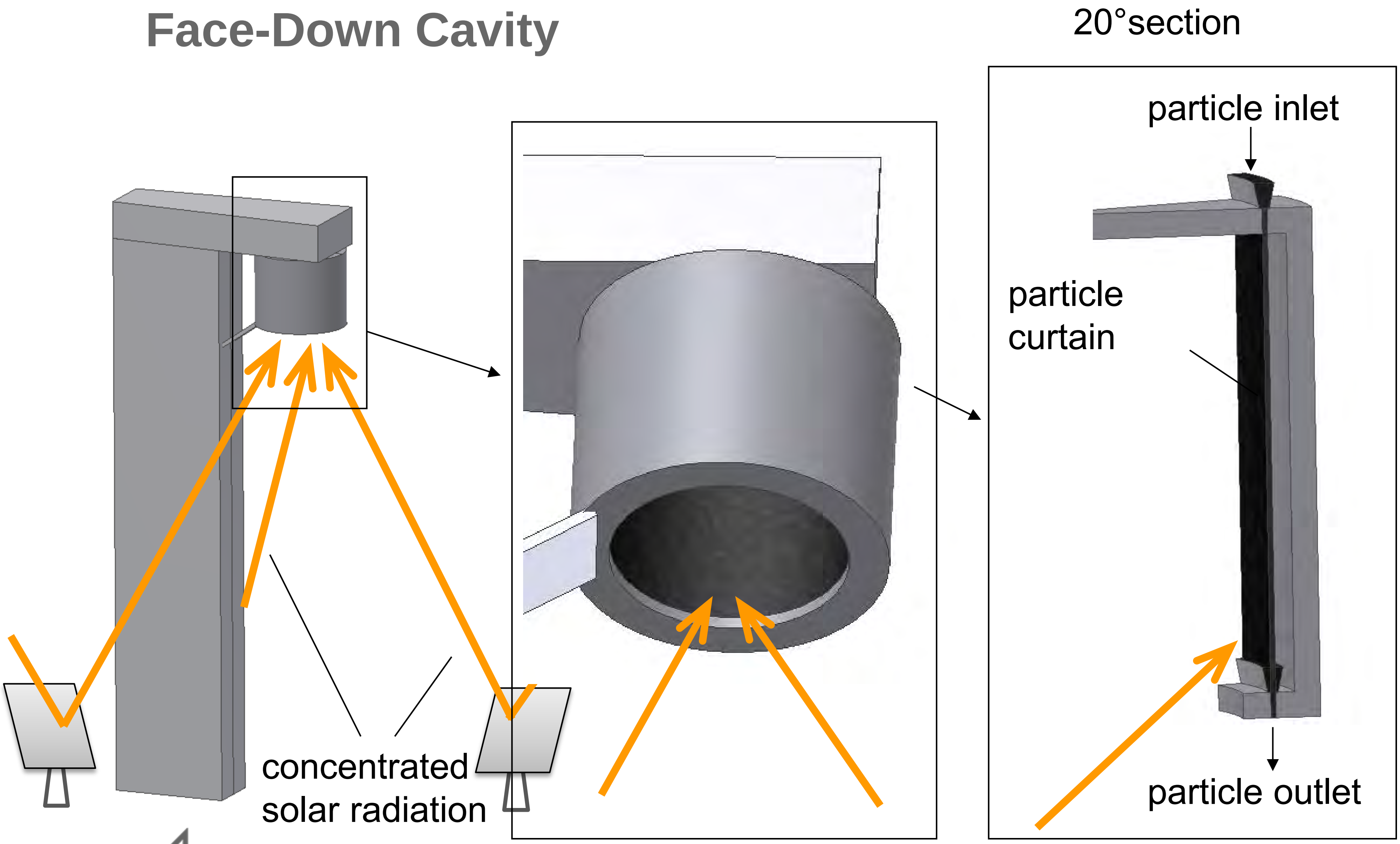
Particle Receiver Concepts

- direct absorption concept
  $\Rightarrow$ high efficiency

- different receiver approaches:
    - falling film receiver
    - centrifugal receiver
    - entrained particles

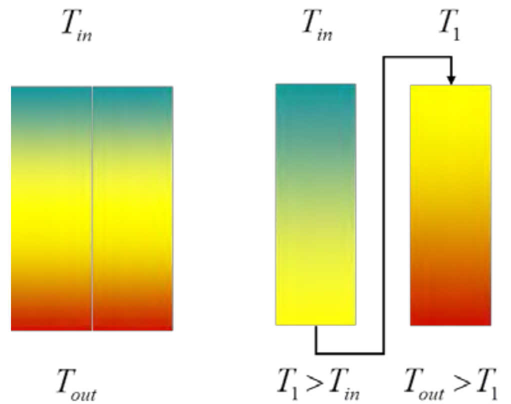


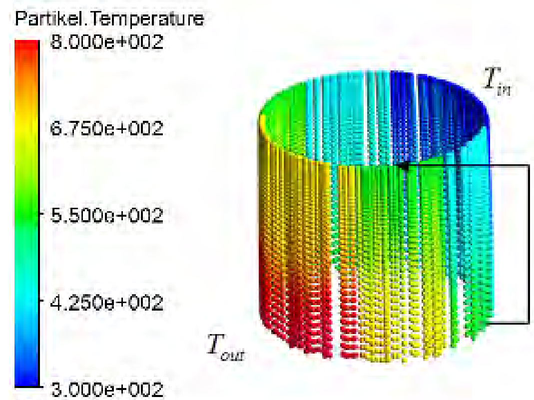
Falling Particle Receiver in Face-Down Cavity



Particle Receiver with Smart recirculation

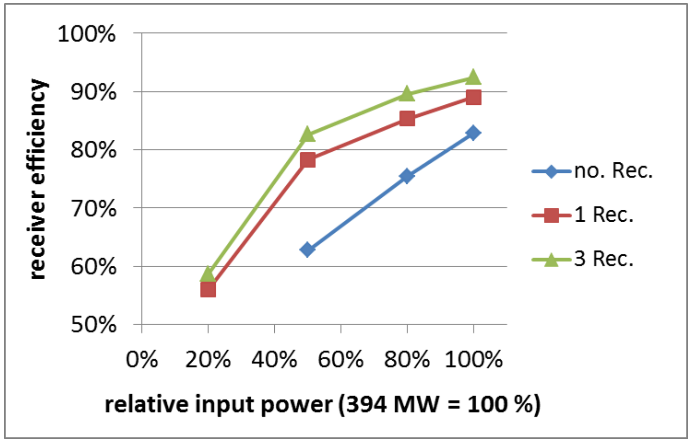
- different recirculation strategies studied
- MATLAB and CFD model for „smart“ recirculation predict higher efficiency
- further efficiency increase with more recirculations predicted
- gain in efficiency flattens → additional effort for more recirculations might not be justified





[C]

800°C particle exit temperature



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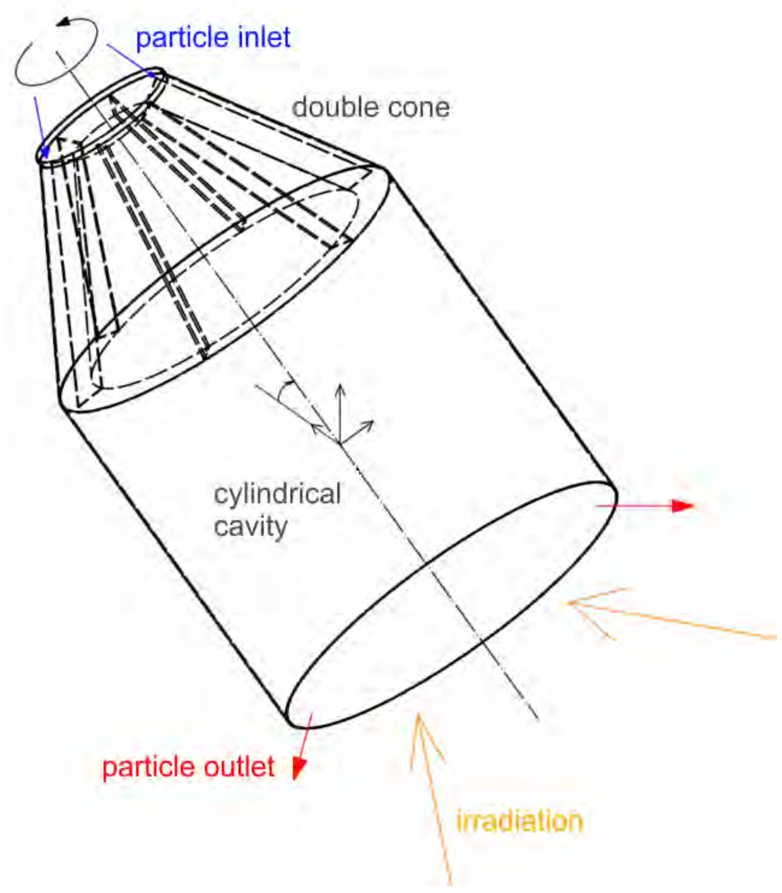
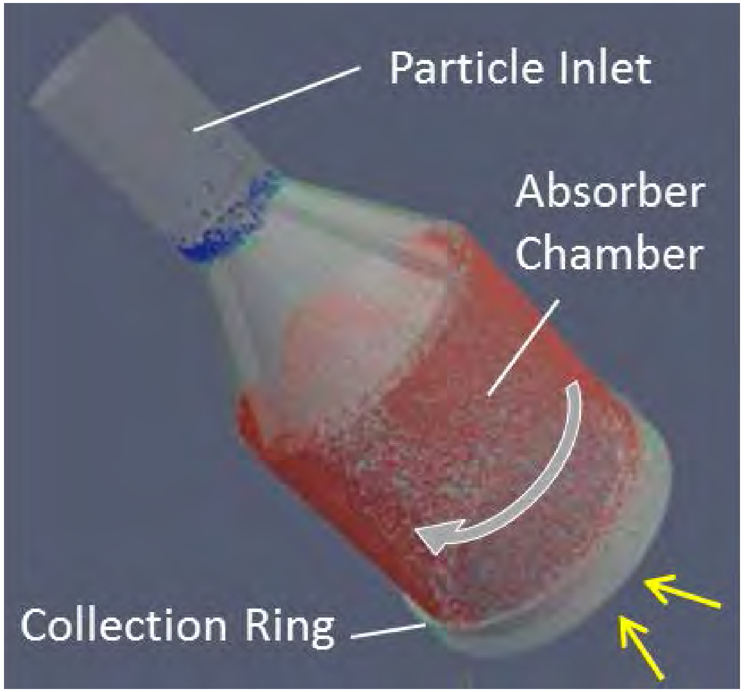
The Centrifugal Particle Receiver (CentRec)

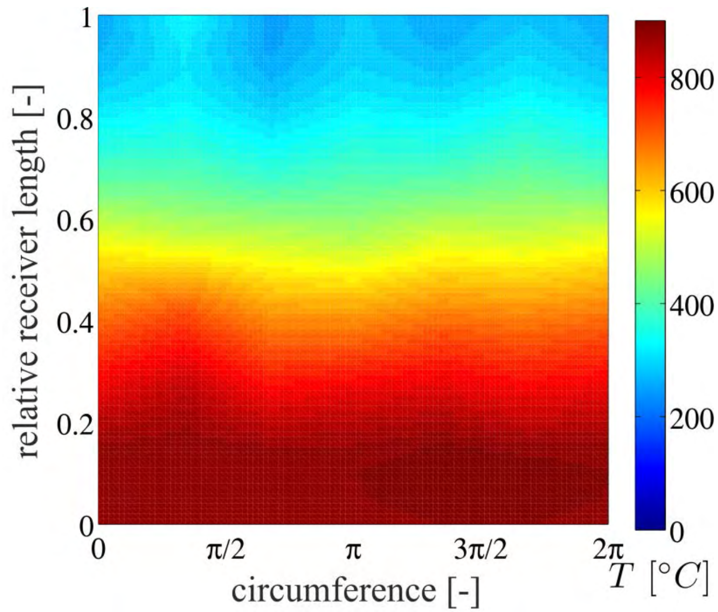


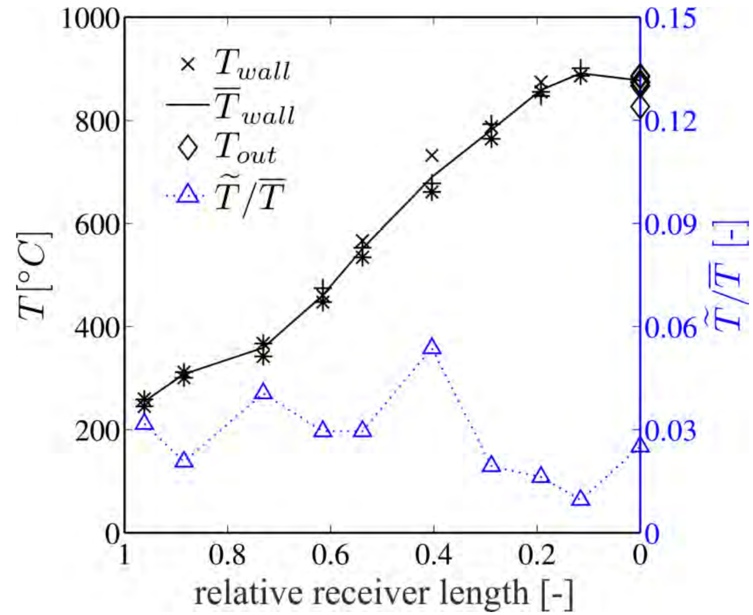


10kW Prototype in Laboratory Scale

CentRec: Experimental Results

- Measured wall temperatures indicate homogeneously distributed particle film
- Increasing temperature from receiver inlet (z/L = 1) to outlet (z/L = 0) demonstrates gradual heating of particles
- Particle outlet temperature of about **900°C** is reached
- film can be controlled by rotation speed





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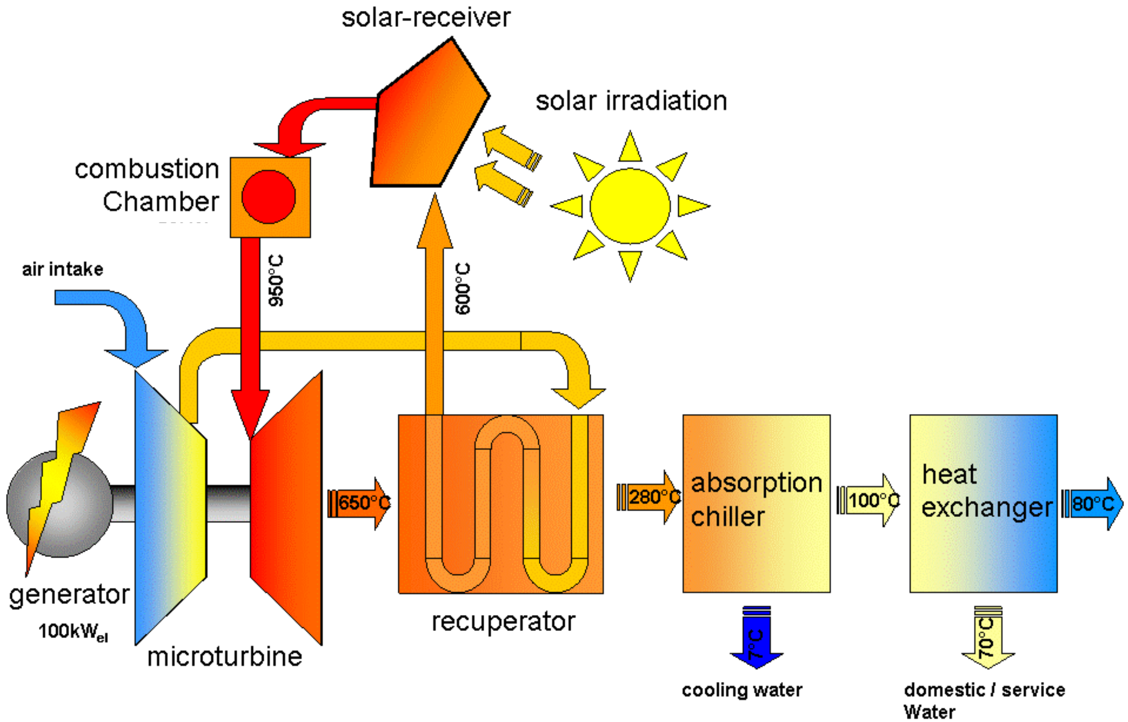
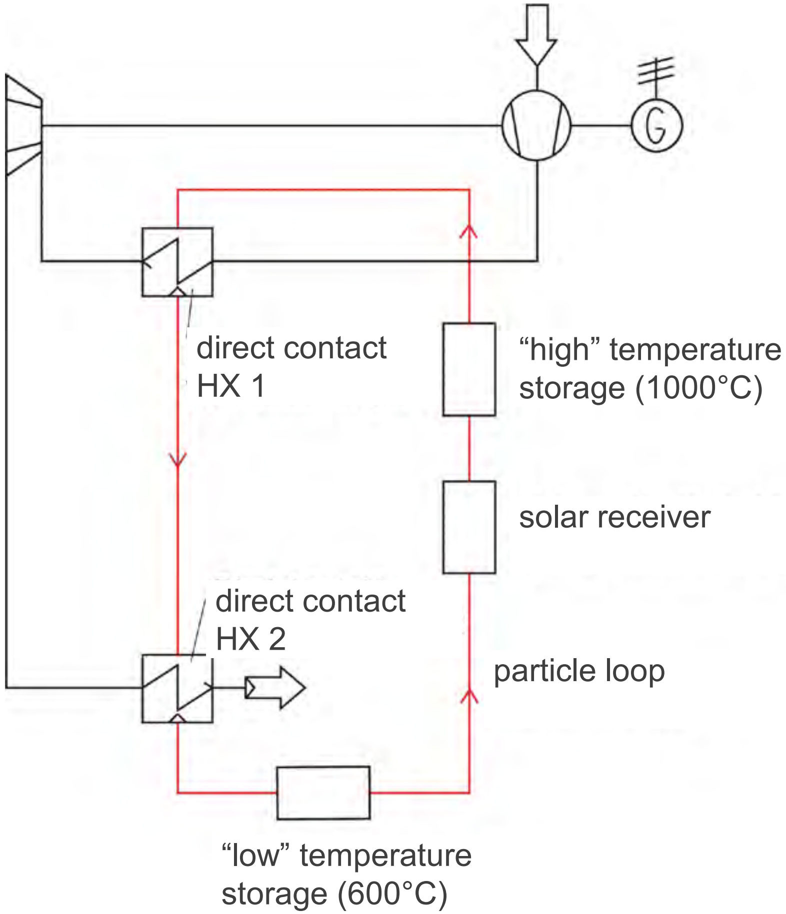
Solar-hybrid Microturbine System



Turbec T100 microturbine, P_{el}=100 kW
4.5 bar_{abs}, 950°C Turbine inlet temperature
600°C recuperator outlet temperature
$\eta \sim 31\%$ (standard unit)

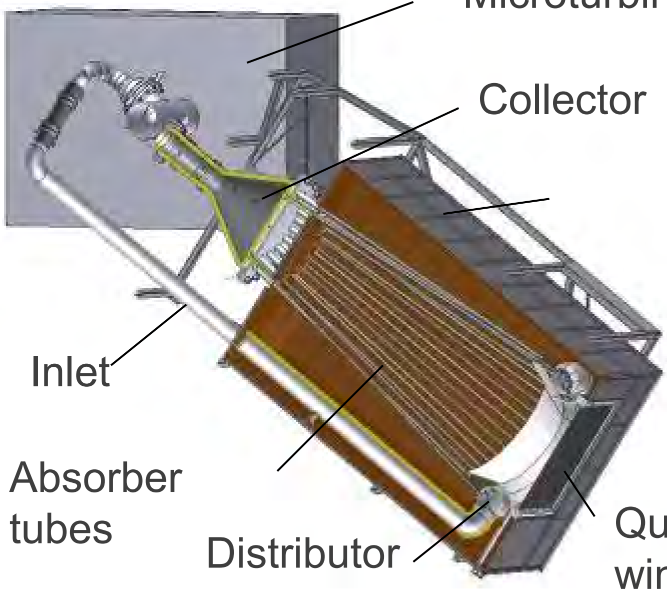
Solar-hybrid Microturbine System with Integrated Solar Particle Loop

- replaces standard recuperator with particle loop recuperator
- potential for significant cost reduction
- challenge: direct contact HX 1
  - pressurized
  - gate for particles



SMILE Project

- Installation of two solar-hybrid microturbine systems (100kW_{el}) in Brazil
- System test with metallic tube receiver for 800°C outlet temperature at PSA (>100h)
- Partners in Brazil: FUSP, SOLINOVA

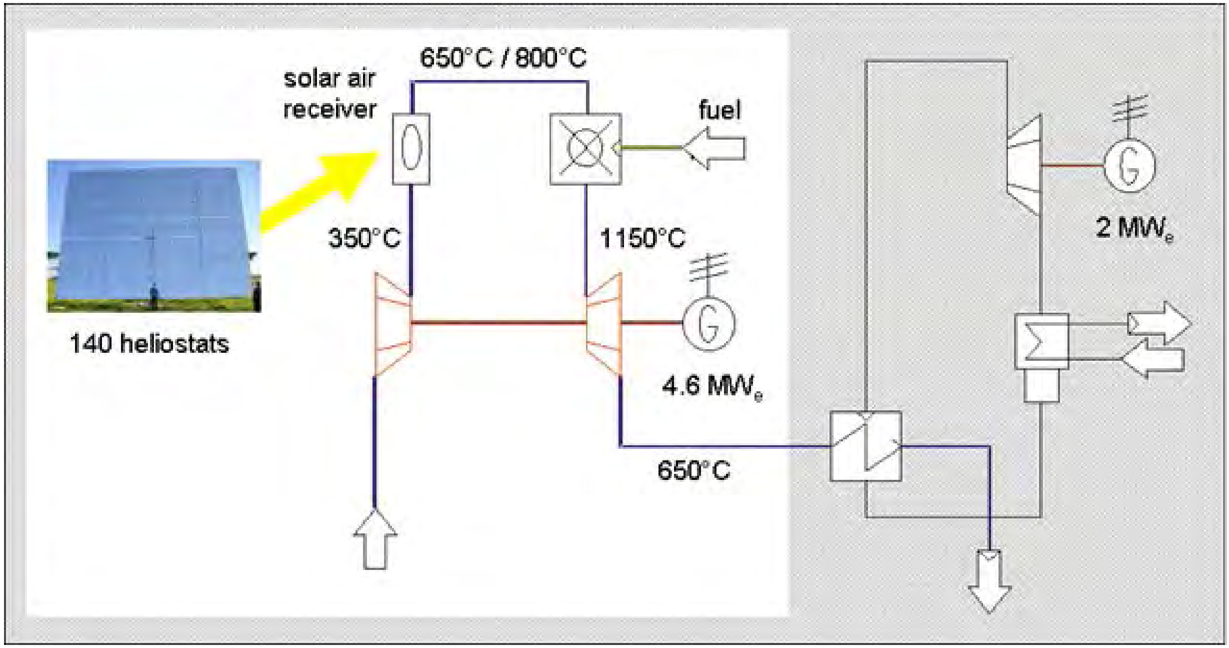


SOLUGAS Project

- demonstration of a pre-commercial solar-hybrid gas turbine system
- power level: 4.6 MW_e, solar air preheating to 650°C/800°C
- partners: **Abengoa**, GEA, Turbomach, DLR, NEAL
- co-funded by EC under FP7
- site: Sevilla

DLR tasks:
- receiver design
- field layout

in preparation:
- receiver temperature increase to 950°C



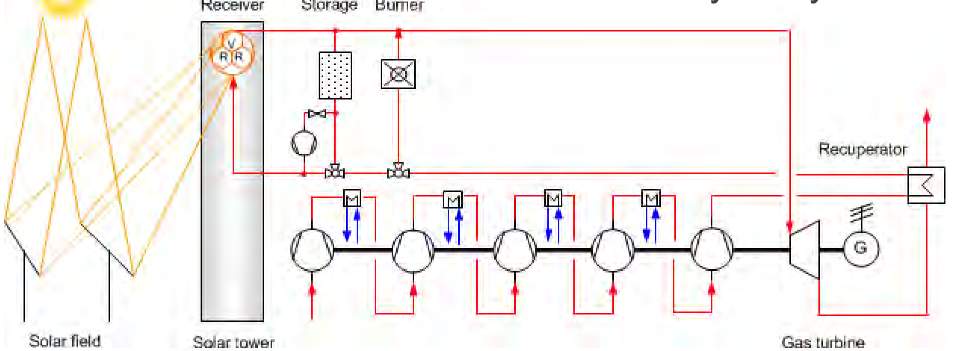
Solarized Gas Turbine Cycles

- several configurations:
  - Combined Cycle
  - recuperated cycles
  - intercooling

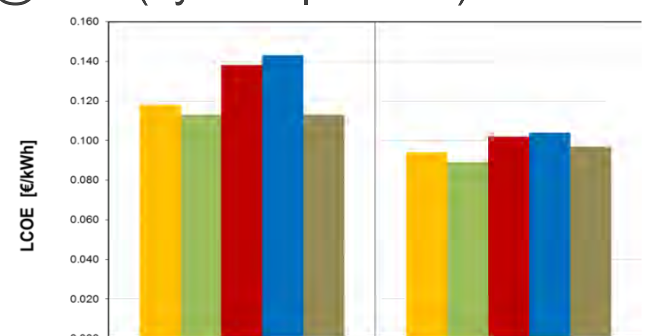
- solar-hybrid gas turbine cycles
  - high turbine inlet temperature:
    $\Rightarrow$ moderate solar share
  - low turbine inlet temperature:
    $\Rightarrow$ high solar share (950°C)
  - regenerator storage optional

- performance prediction:
  - intercooled Brayton cycle:
    - performance better or equal to MS system
  - Combined Cycle similar MS

intercooled Brayton cycle



LCOE @SM2 (hybrid operation)



	solar only	0…24
Combined Cycle SM2	0.118	0.0941
GT with isotherm. Compr. SM2	0.113	0.089
GT with ORC SM2	0.138	0.102
GT with ORC + Recu SM2	0.143	0.104
Molten Salt Tower SM2	0.113	0.097

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Overview of DLR CSP simulation tools

- DLR simulation tools cover all levels of CSP simulation

GREENIUS: analysis of performance / economics of renewable energy systems

ebsSolar®: detailed performance analysis of CSP systems

component layout:
- concentrators (parabolic trough, Fresnel, heliostats)
- receivers

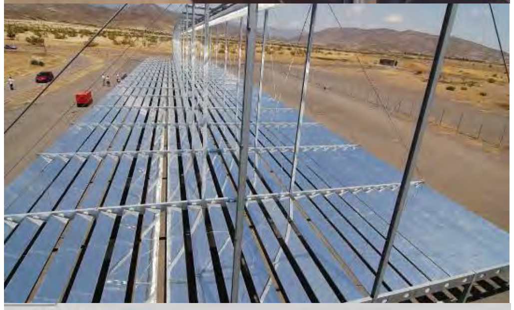
system layout optimization:
- solar field, receiver
- power block
- storage

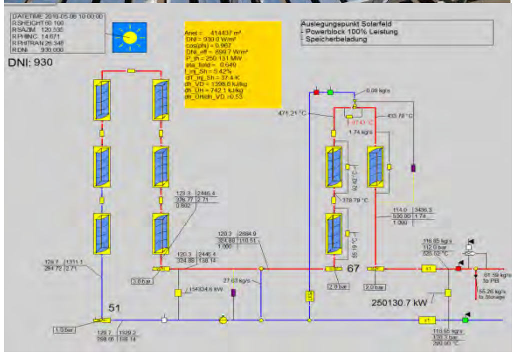
transient system simulation:
- real-time, high resolution performance simulation
- coupling of components and control

Detailed System Performance Simulation

using Ebsilon®

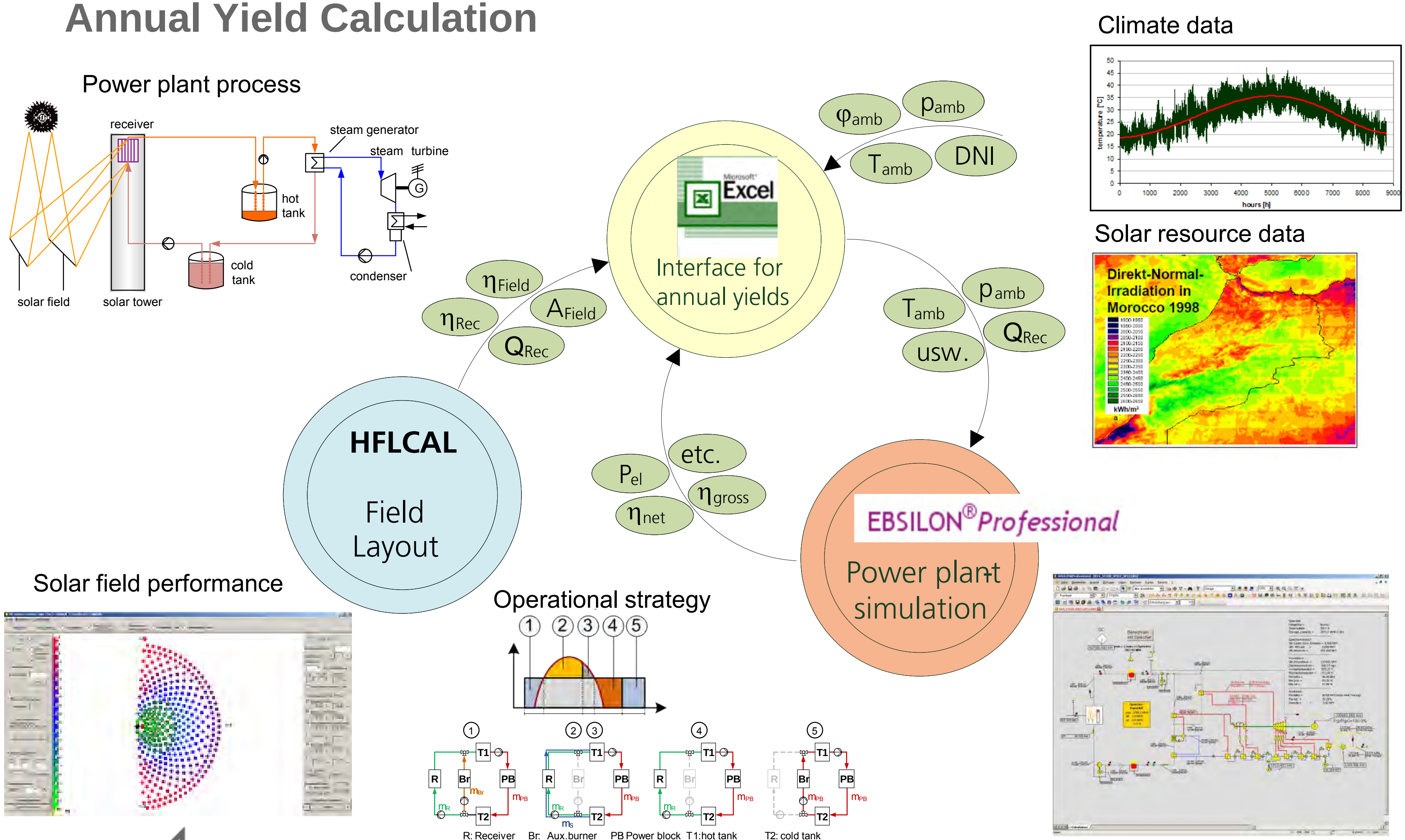
- „All in One" solution for detailed power plant modelling
- for development, acquisition und planning
  of all kinds of power plants and thermodynamic processes
- design and development of single components, subsystems
  and complete systems
- development of new solar library EbsSolar (steag and DLR):
  - thermodynamic modelling and yield analysis (e.g. annual yields)
  - components of solar thermal power plants
    (Dialog for time series calc., transient calc. for energy storage,
    fluid properties for solar applications)
  - 2010: library for line focussing systems
    -Parabolic Trough
    -Linear Fresnel
  - 2011: library for Solar Tower systems
  - currently more than 70 licences of EbsSolar are used





System Simulation: Workflow for Solar Towers

Annual Yield Calculation



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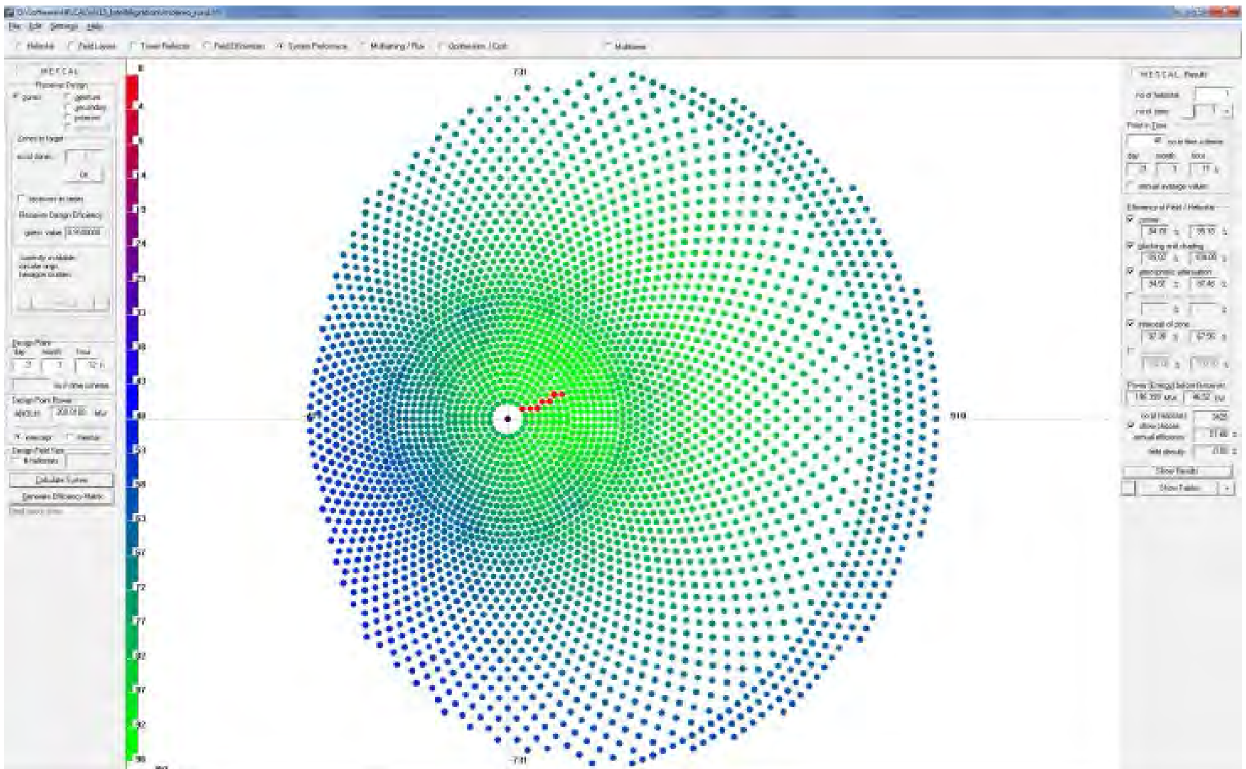
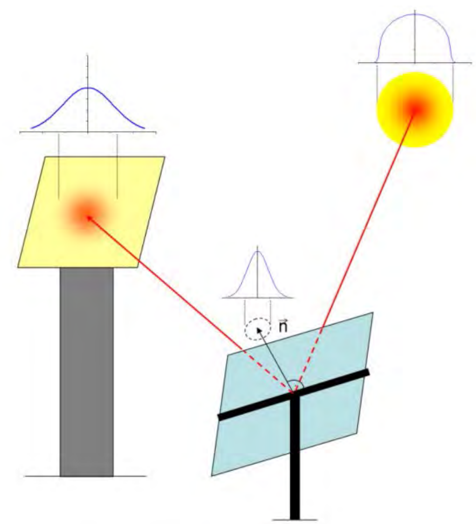
Solar System Layout
Visual HFLCAL: Heliostat Field Layout

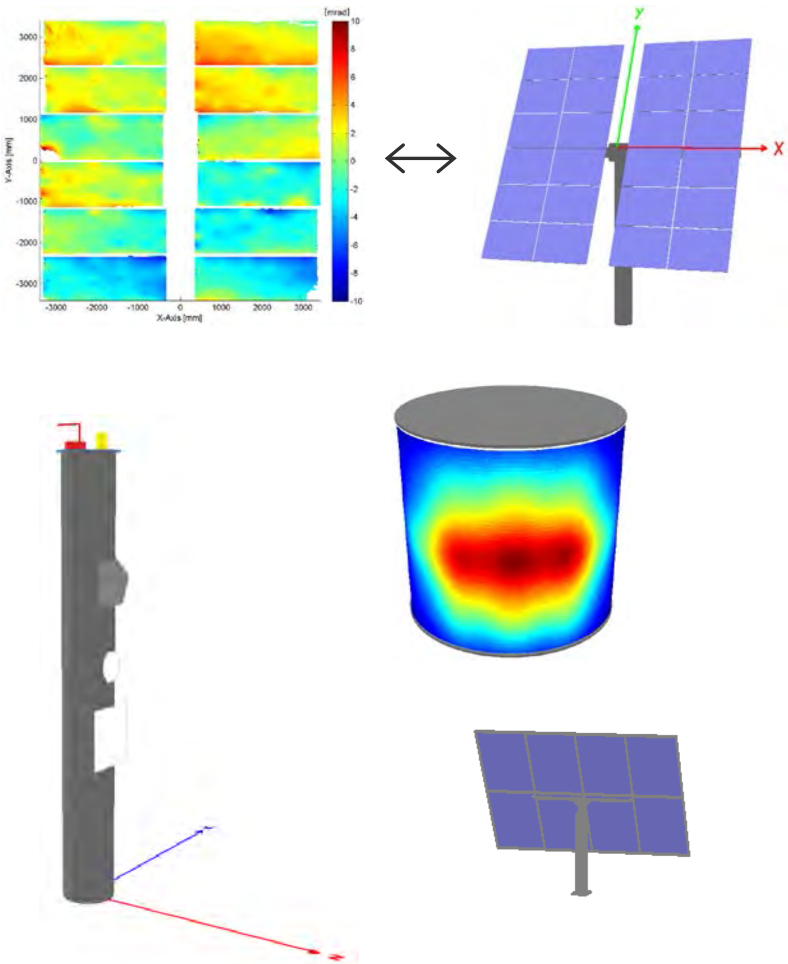
- fast optimization of heliostat field, receiver and tower



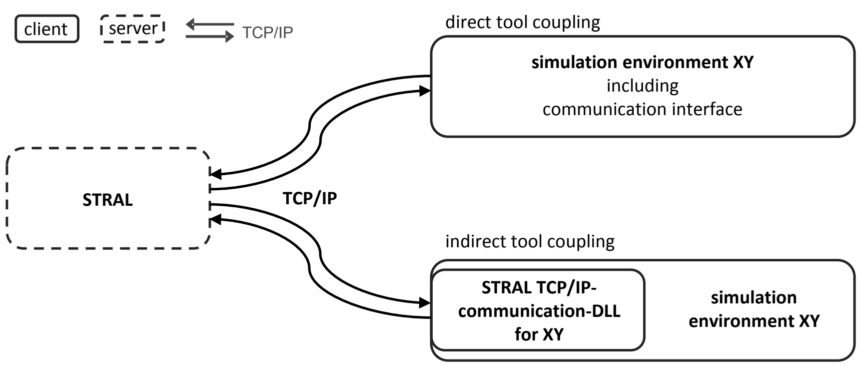
- simplified optical model
- very fast calculation
- optional: use of topography



Component Level:
High Precision Ray Tracing (STRAL)



- fast and accurate ray tracing of concentrator systems (tower, trough, ..)
- can use measured heliostat surface data
- aim point optimization
- tool coupling features
  - best simulation environment for specific modeling problems
  - exchange data during co-simulation via network
  - MATLAB® / Simulink®; Dymola©; LABVIEW©; Excel®



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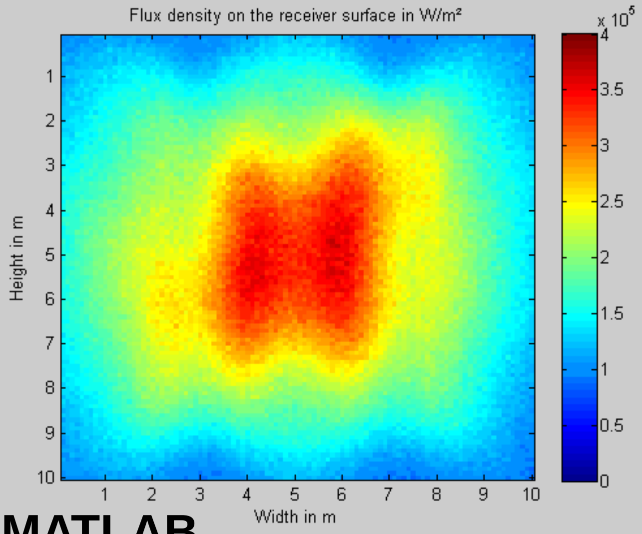
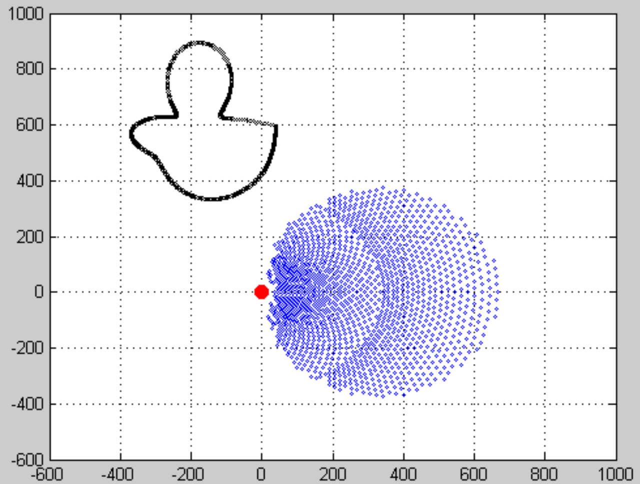
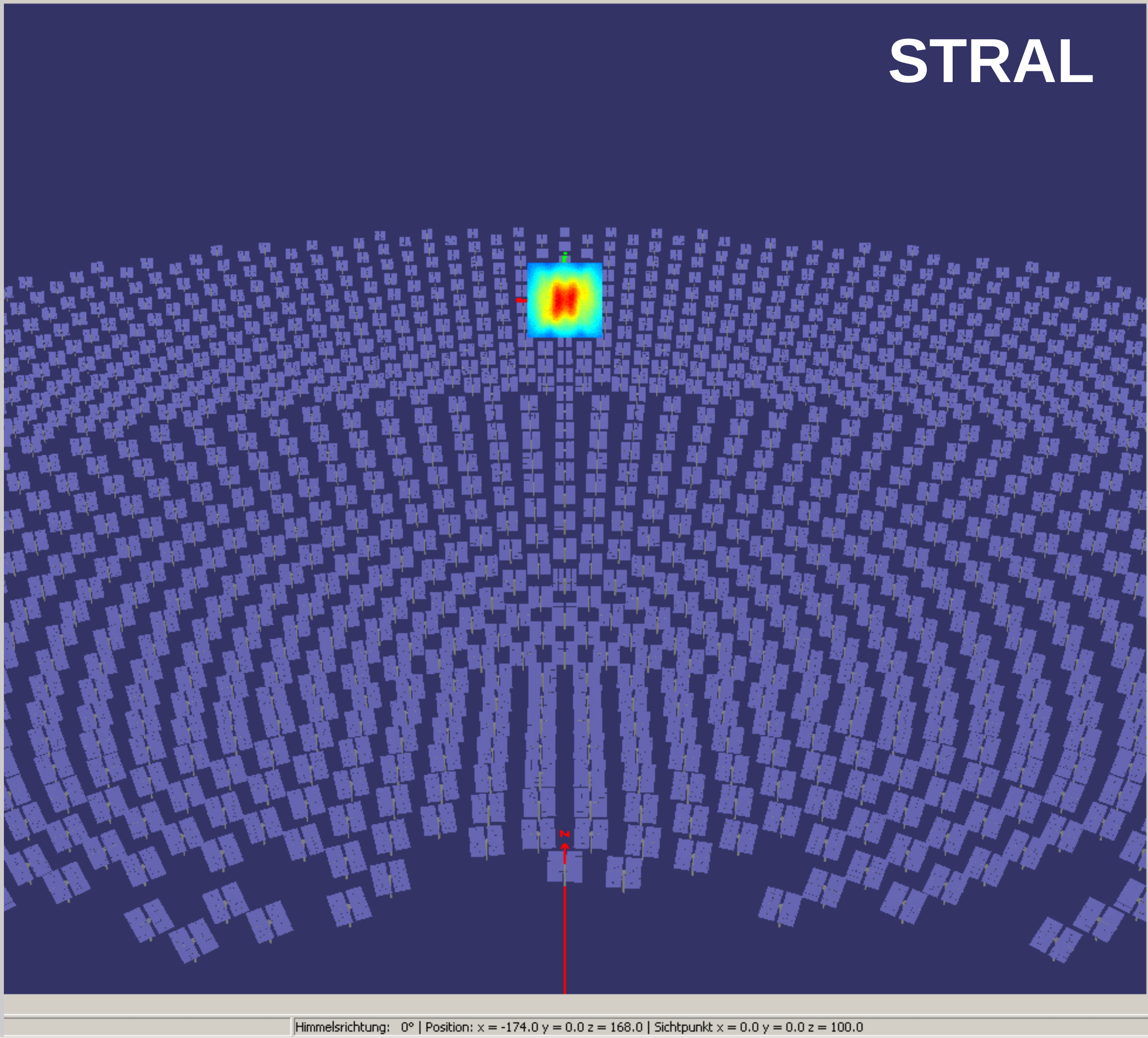
Tool Coupling Example: Cloud Passage



MATLAB



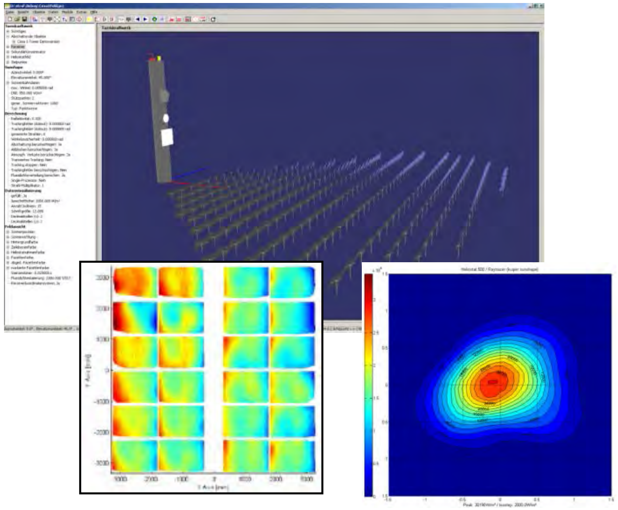


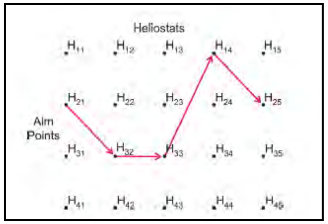
Aim Point Optimization

- STRAL (Solar Tower Ray-Tracing Laboratory):
    - fast ray-tracer for precise flux calculation
    - based on heliostat deflectometry data
- assignment of heliostats to aim points is a combinatorial problem of dimension $D = {n_A}^{n_H}$

$\Rightarrow$ use ant colony optimisation meta-heuristic

- concept proven theoretically by simulation
- 2014: validation at solar tower Jülich
- applications:
    - during design phase
    - operation assistance system
    - integrated in flux/temperature control unit





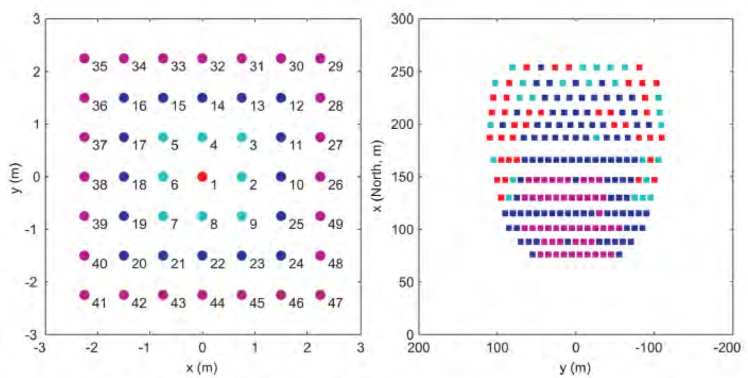


Fig. 7 Optimized aim point configuration on the 7 × 7 raster and the corresponding heliostat positions

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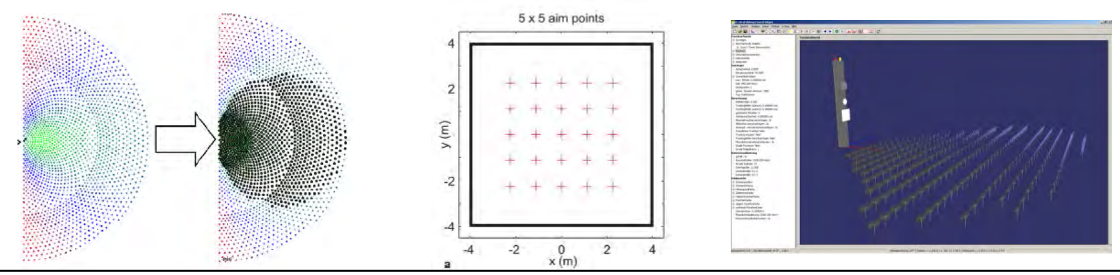
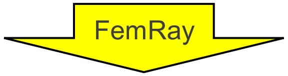
Integrated Solar Tower System Layout

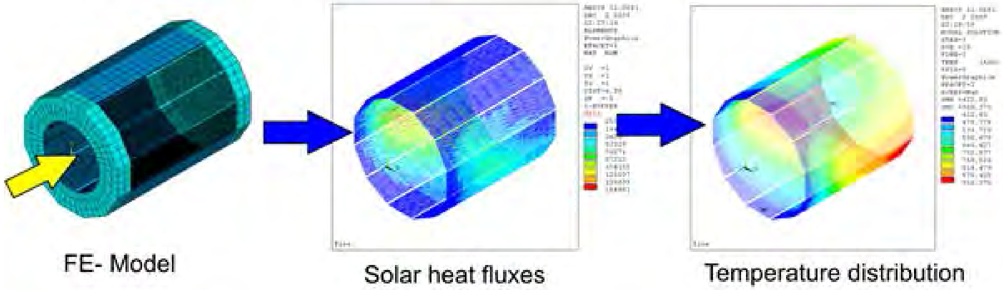
- integrated tool under development: combination of
  - field layout (heliostat positions)
  - aim point distribution
  - receiver design (e.g. FEM stress analysis)



STRAL:
- field layout
- aim point optimisation
- flux calculation



ANSYS:
- FE-modelling
- heat transfer calc.
- temp. and stress analysis

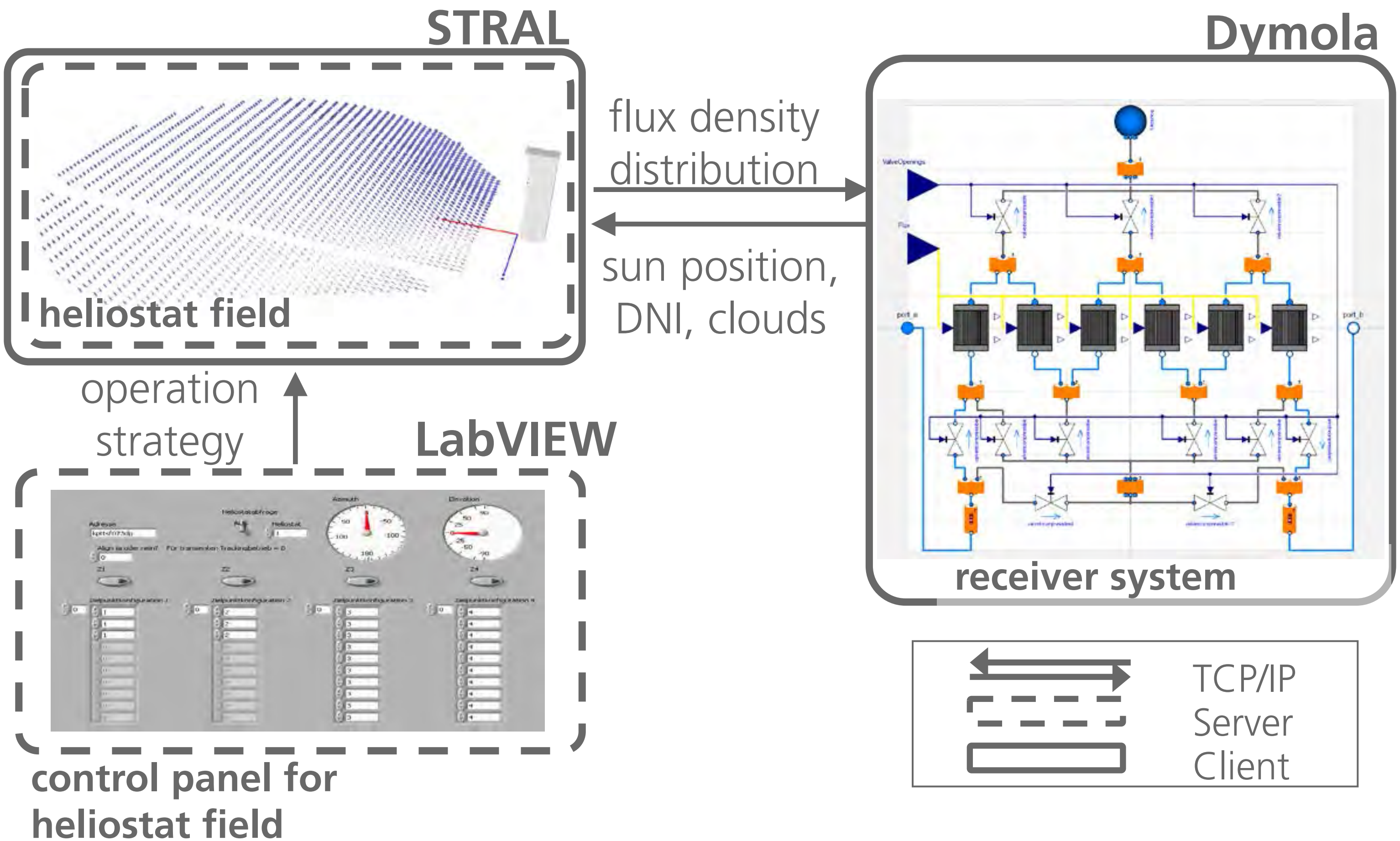


Dynamic Modelling of Receivers

- dynamic modelling of an open volumetric air receiver in Dymola/Modelica for analysis of transient operation
- dynamic modelling of a tubular salt receiver in Dymola/Modelica for analysis of start-up & shut-down, cloud passage, fill&drain
- dynamic calculation of flux density distribution on receiver surface by STRAL
- combination of Dymola models with Simulink for modelling of operation & control structures

Co-Simulation of total plant behaviour

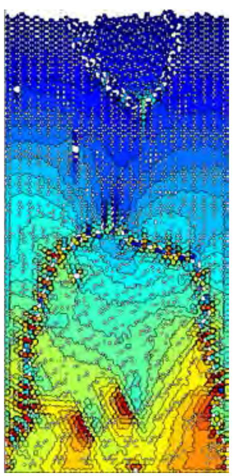
- philosophy: use best suitable simulation tool for each component

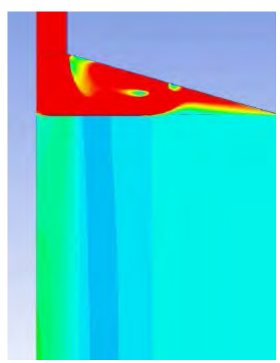


High-temperature storage with solid media

Regenerator storage, Packed bed storage with hot gas HTF

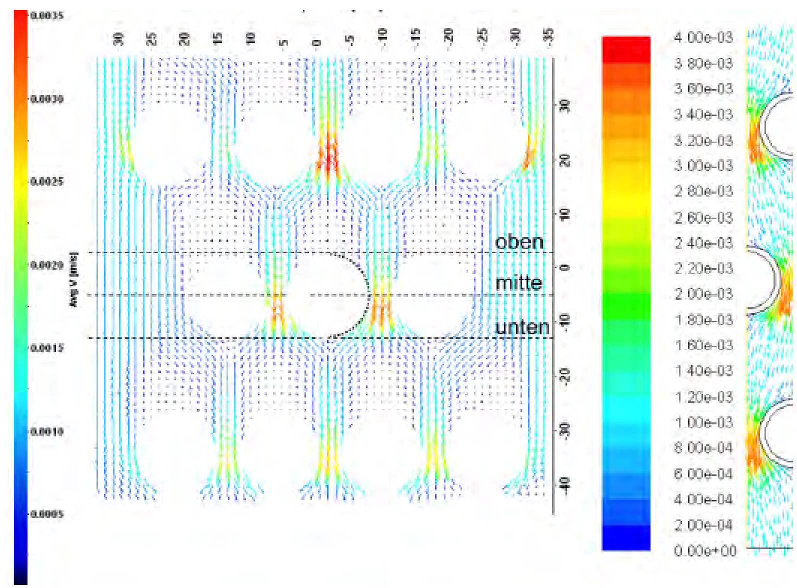
- Thermo-mechanical aspects (thermal ratcheting): particle-discrete models to calculate inter-particle forces
  ⇒ design of protective measures
- Uniform flow distribution with “low pressure-loss designs”: CFD-based prediction of pressure loss and flow





Particulate storage and heat exchangers

- CFD-multiphase models for the prediction of flow field and thermal heat exchange in high-temperature granular flows



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Thank your for your attention!

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Contact: reiner.buck@dlr.de