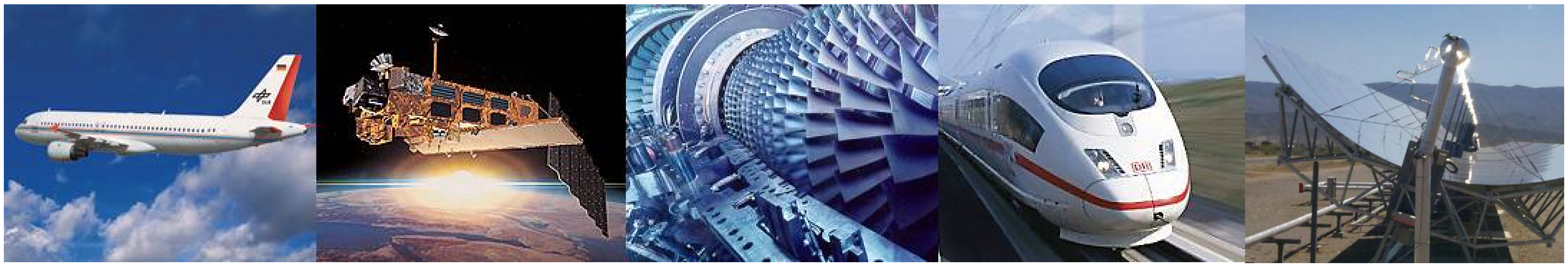
Solar Tower Technology
- Status and R&D at DLR

Dr. Reiner Buck
German Aerospace Center (DLR)

April 10, 2014
Stellenbosch University, South Africa

DLR
German Aerospace Center

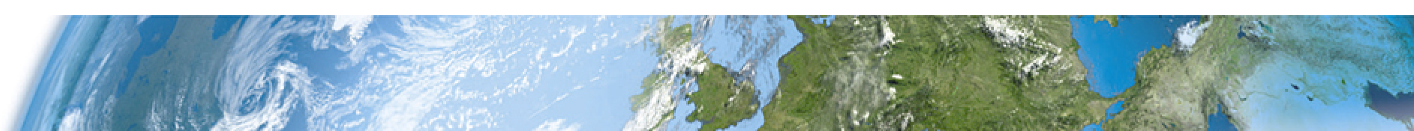


- Research Institution
- Space Agency
- Project Management Agency

- 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

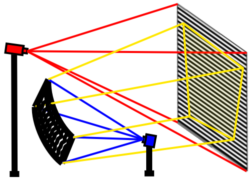
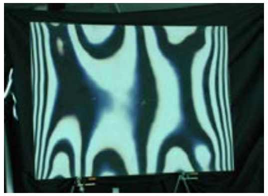
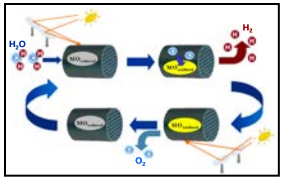
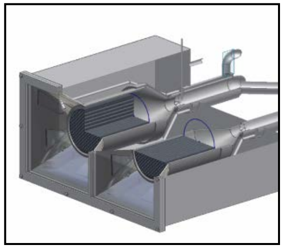
about 140 staff members in
- Köln
- Stuttgart
- Almeria (Spain)
- Jülich

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

Line Focussing Systems	Point Focussing Systems	Qualification	Solar Process Technology	Test Facilities and Solar Materials
K. Hennecke	Dr. R. Buck	Dr. P. Heller	Dr. C. Sattler	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)

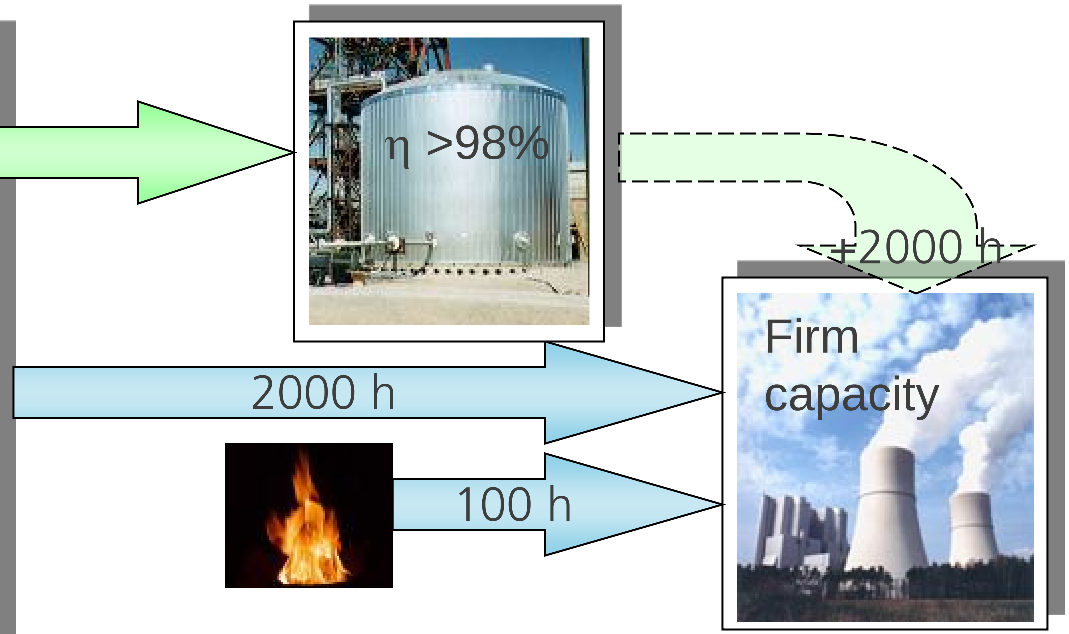
DLR

DLR owns Solar Tower Test Facility Jülich

Plataforma Solar de Almeria, Spain

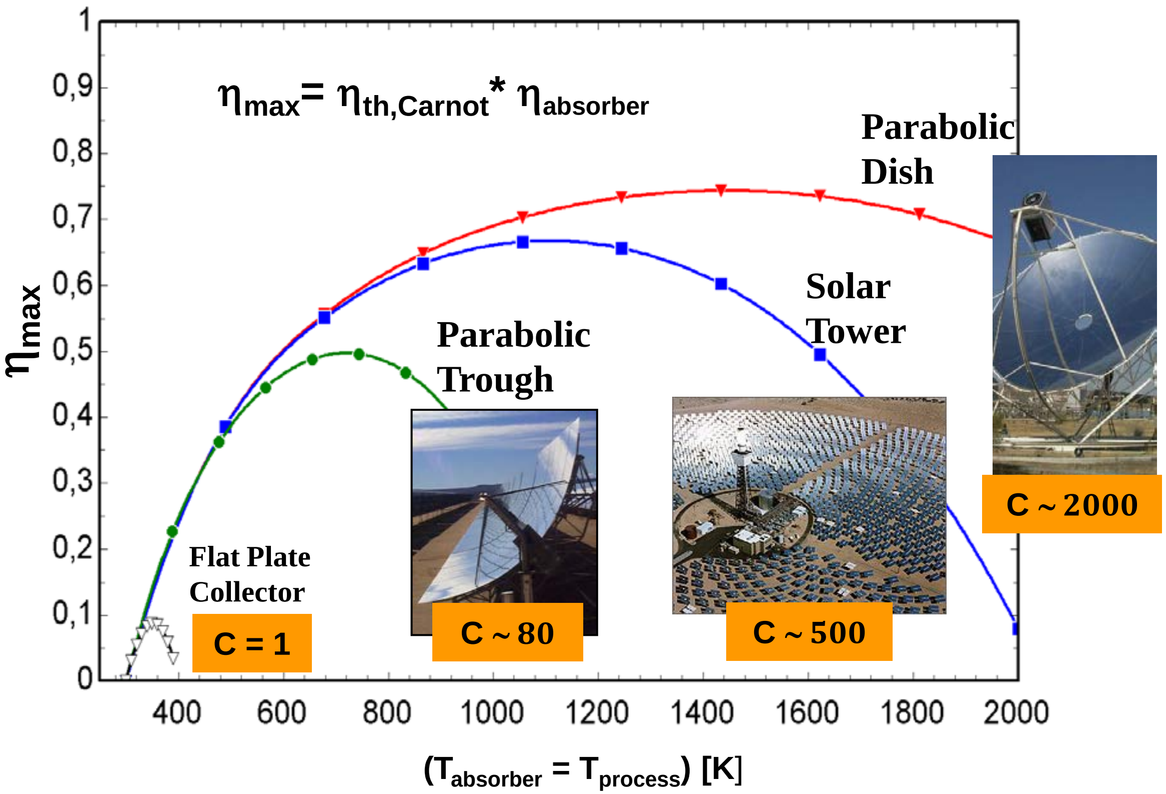
owned by CIEMAT; permanent delegation of DLR Solar Research

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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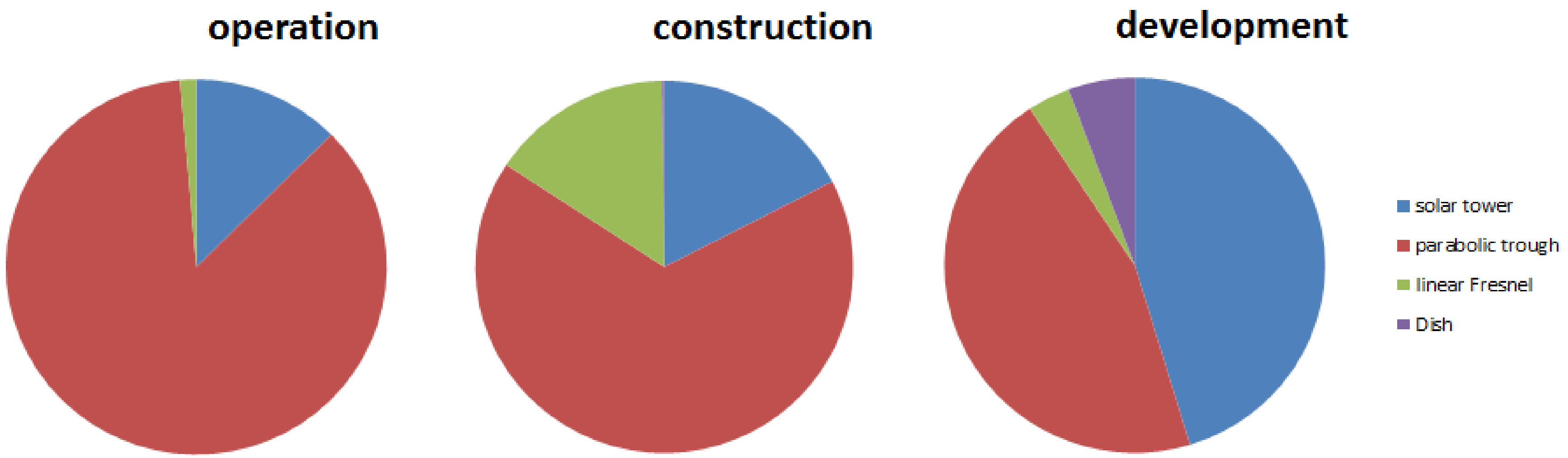
CSP Technology Perspective



total: 3957 MW

total: 1212 MW

total: 2786 MW

data from CSPtoday Project Tracker, status: March 2014

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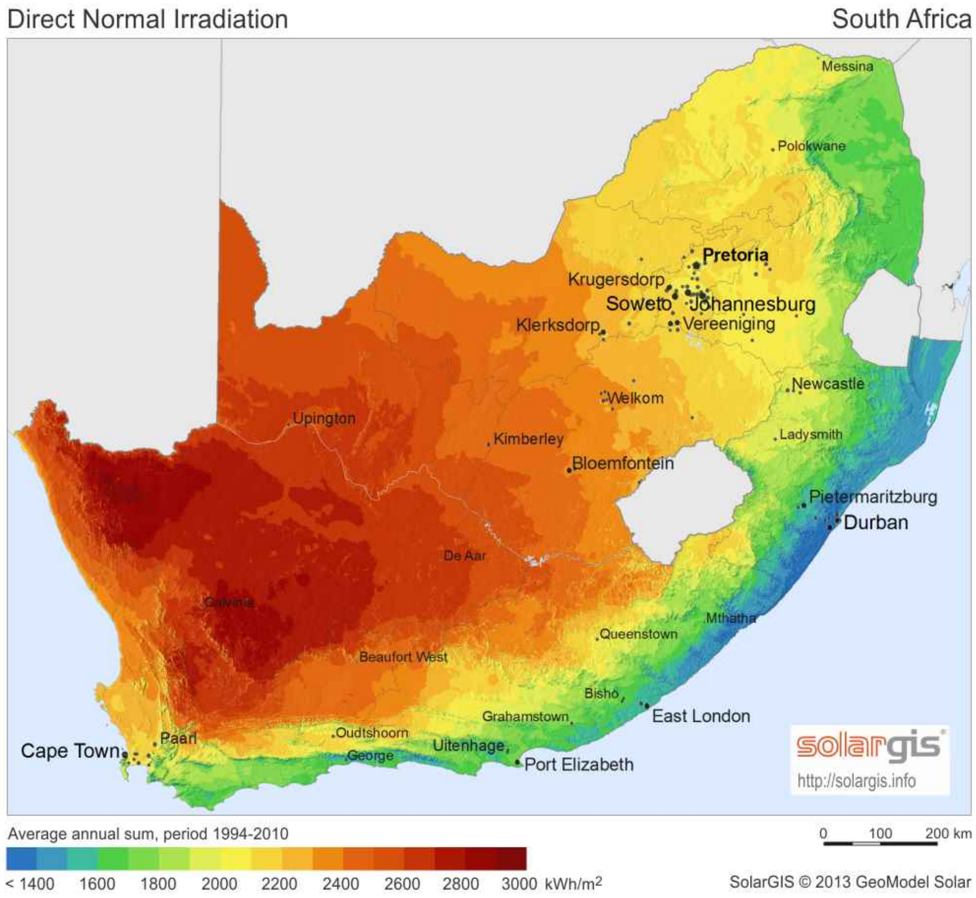
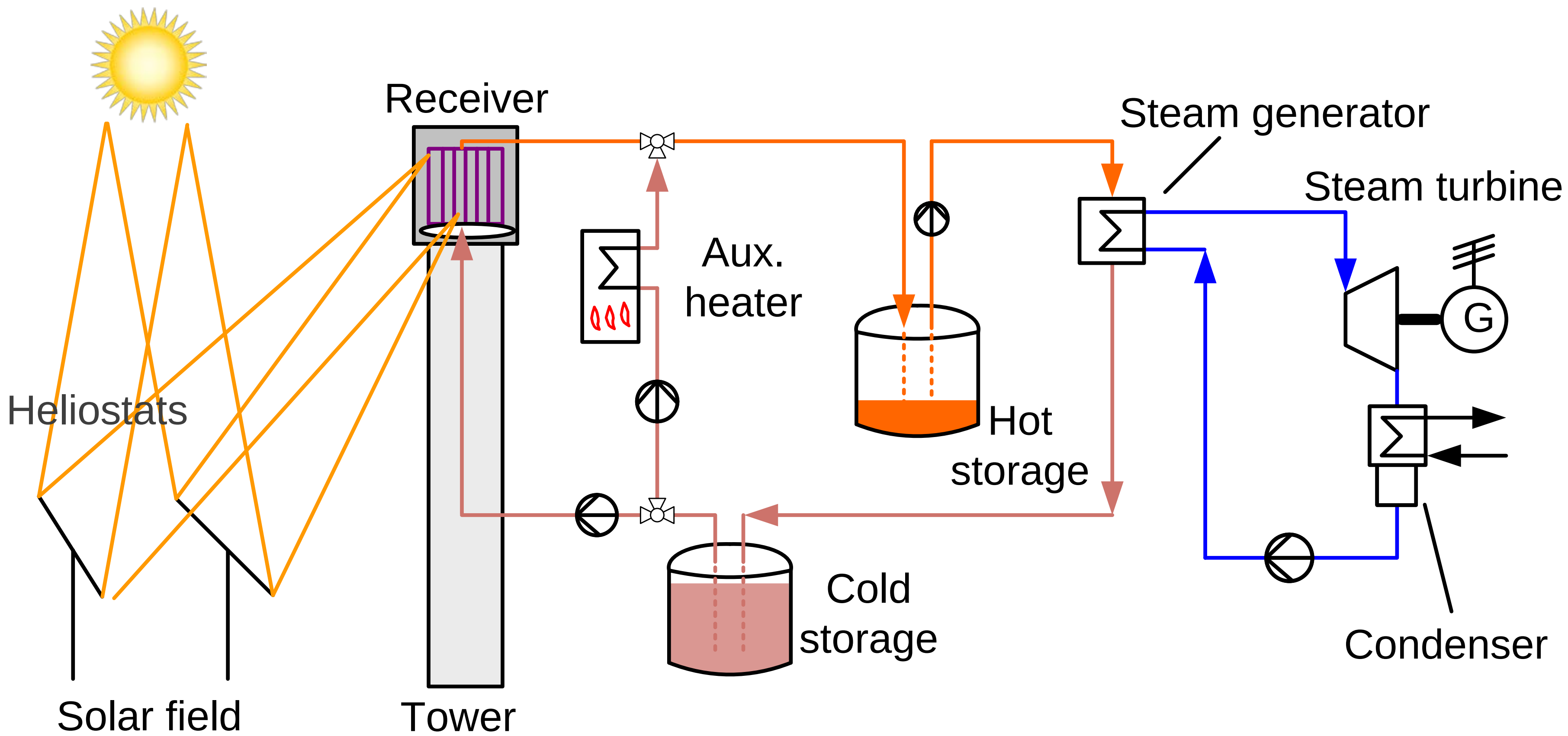
Solar Resource in South Africa



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

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

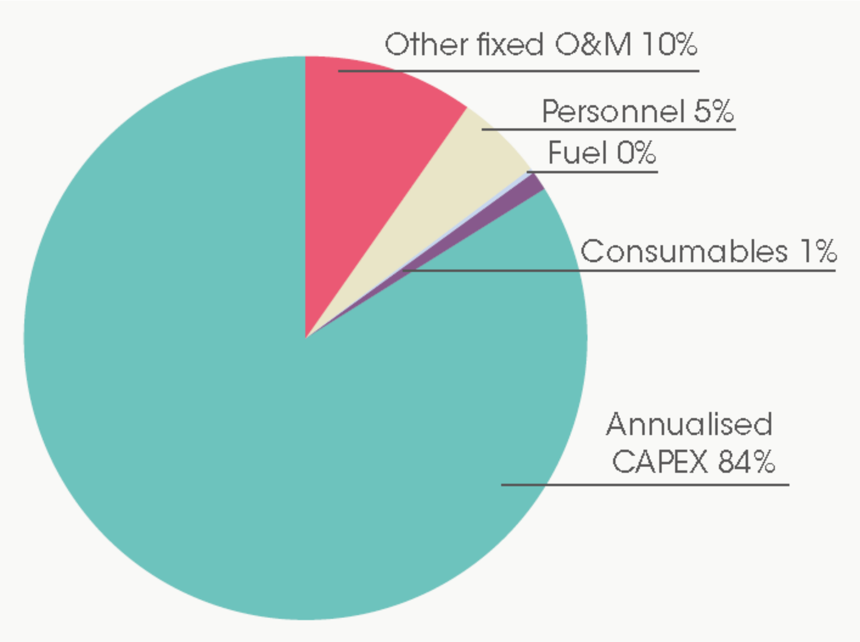
- relevant parameter is LCOE [$/kWh], not specific cost [$/kW]
- additional value from dispatchability and security of supply

- 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



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

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

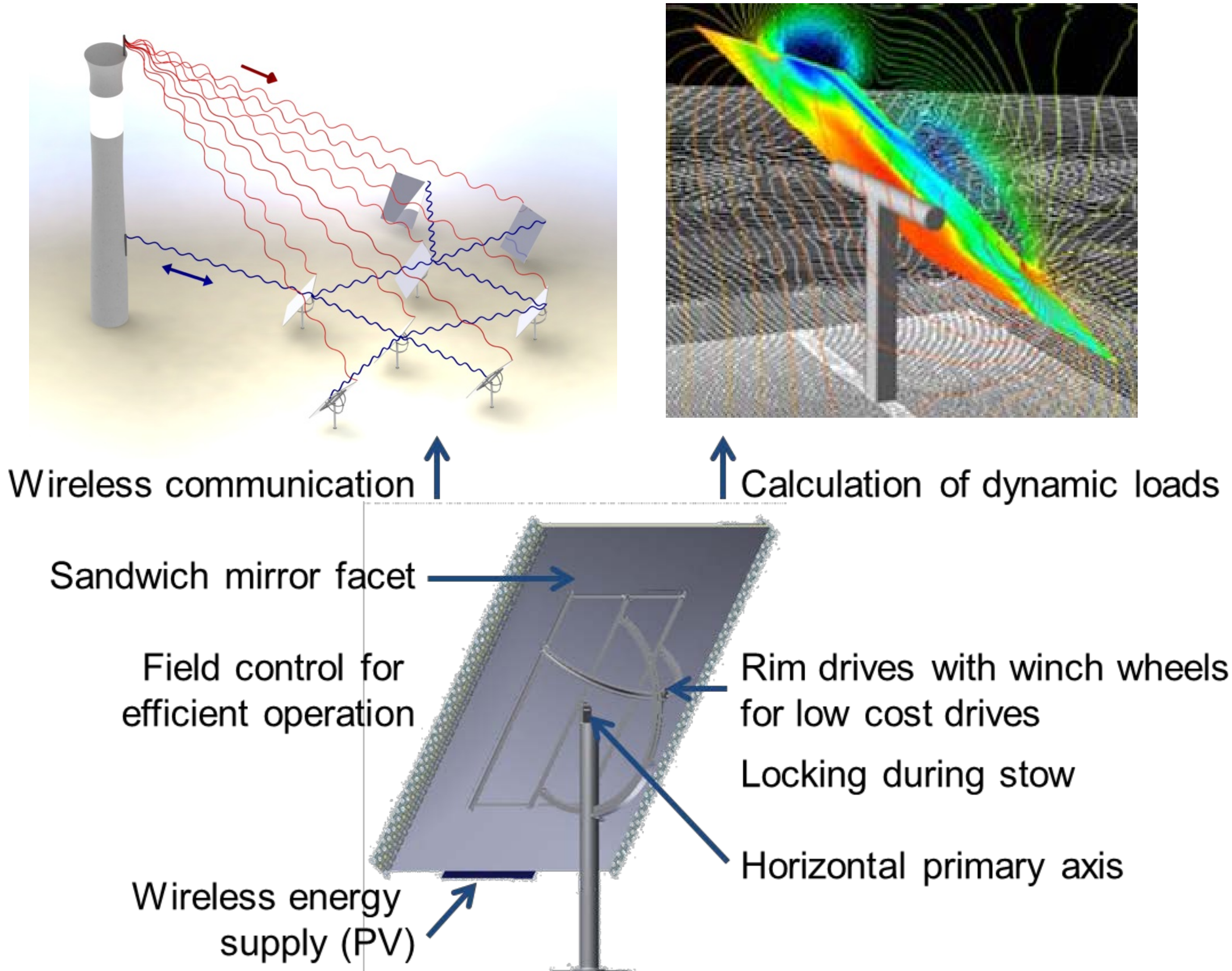
Autonomous Light Weight Heliostat With **R**im-Drives

Aim

Cost reduction of heliostats by about 30% through complementary approaches

Partners

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



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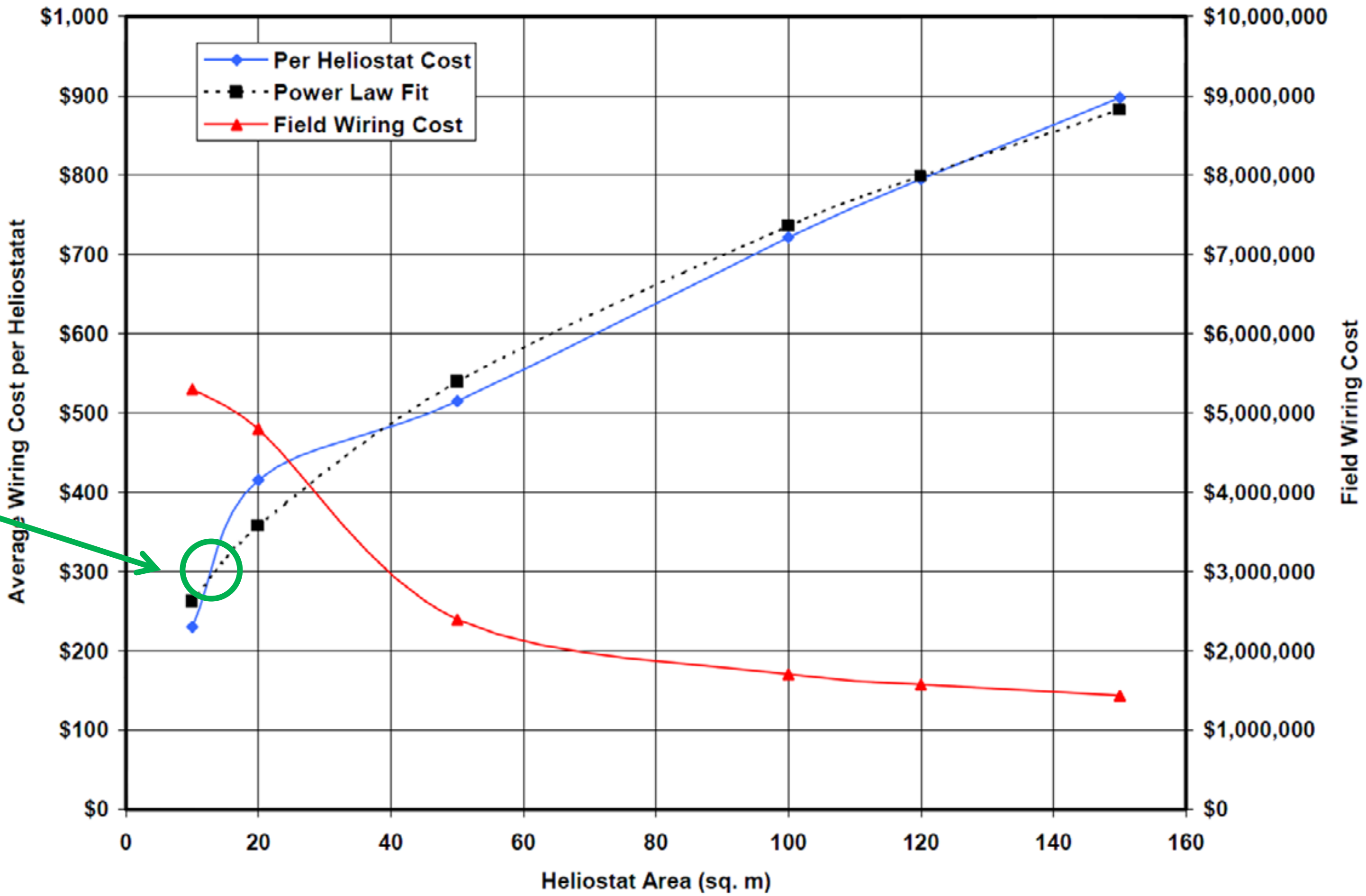
AutoR
Autonomous Light Weight Heliostat With **R**im-Drives

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

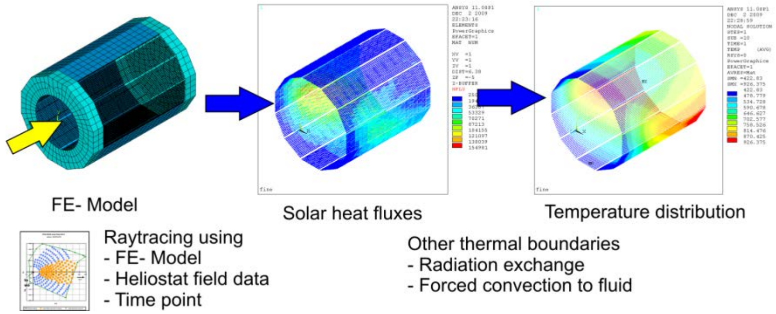
Autonomous Light Weight Heliostat With **R**im-Drives

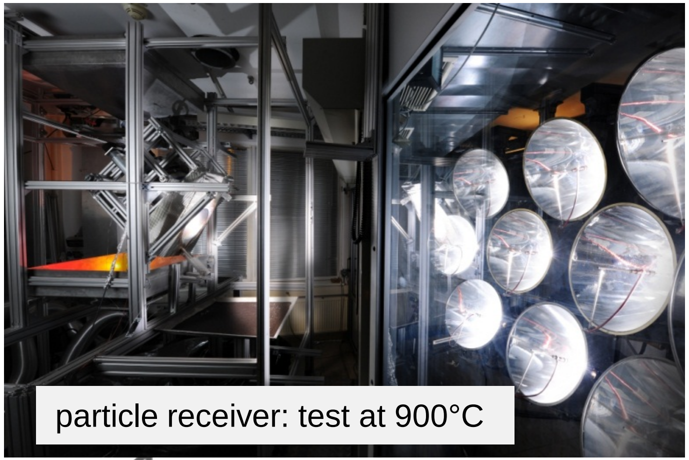
First prototype almost finished

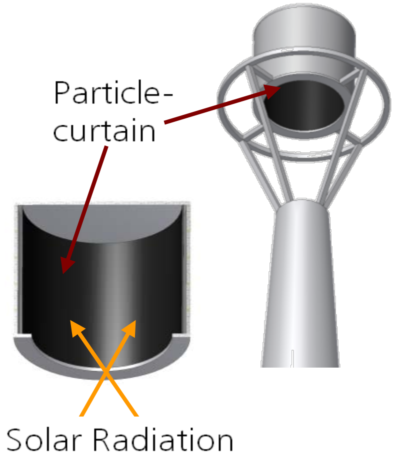
R&D on Receiver Technologies

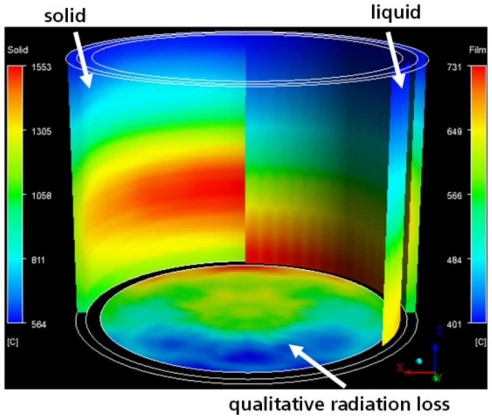
- development / technology transfer
  - open volumetric air receiver
  - pressurized volumetric air receiver

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

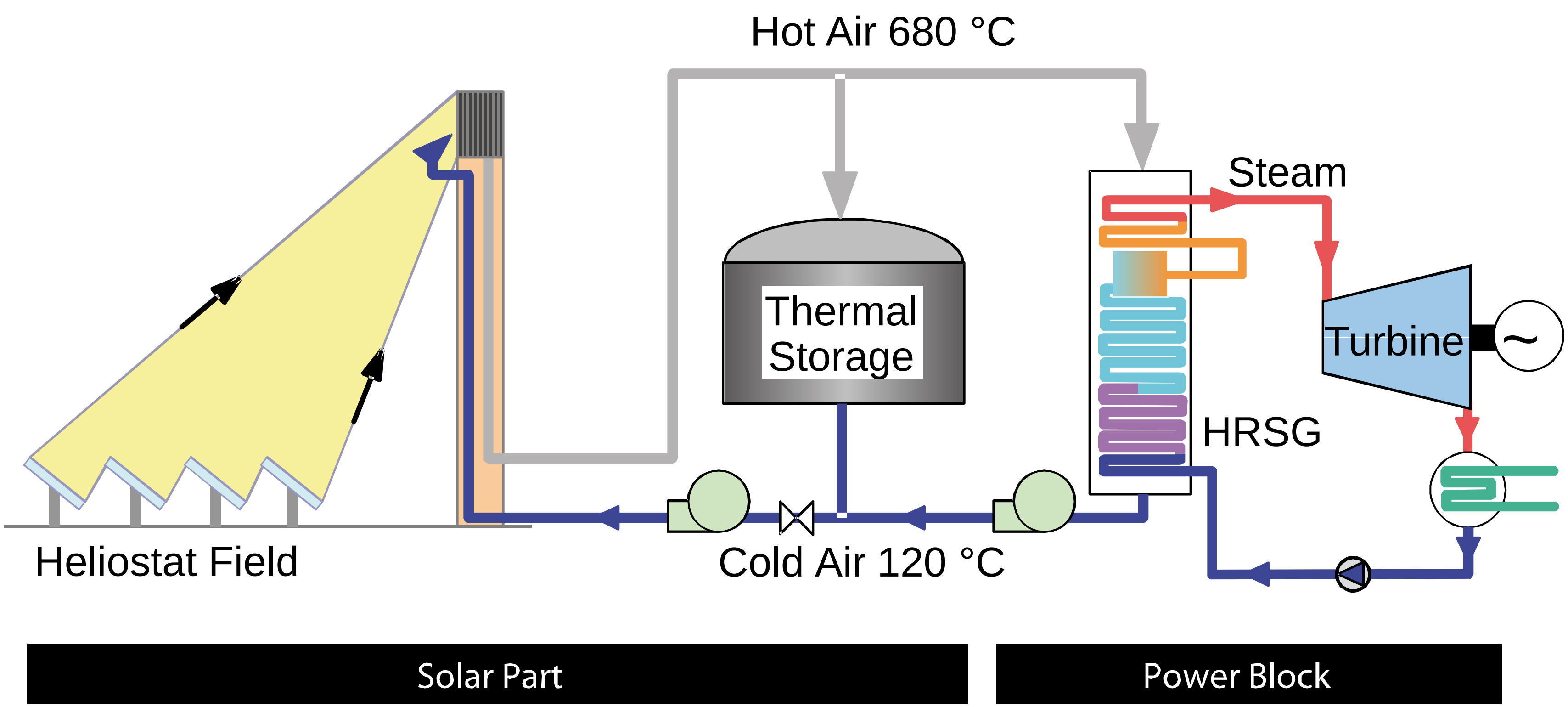








Tower Plant with Open Volumetric Air Receiver
Solar Tower Demonstration Plant Jülich, Germany



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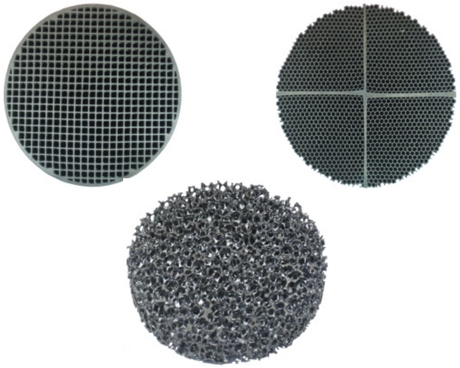
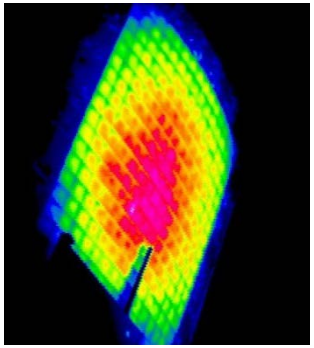
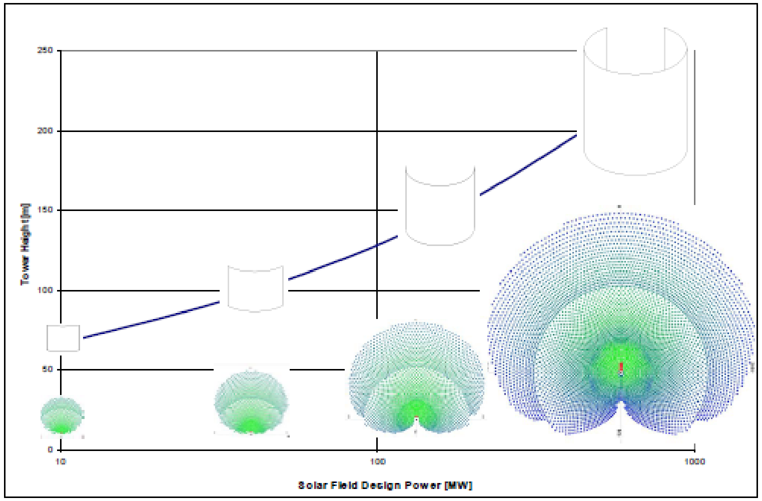
Open Volumetric Air Receiver



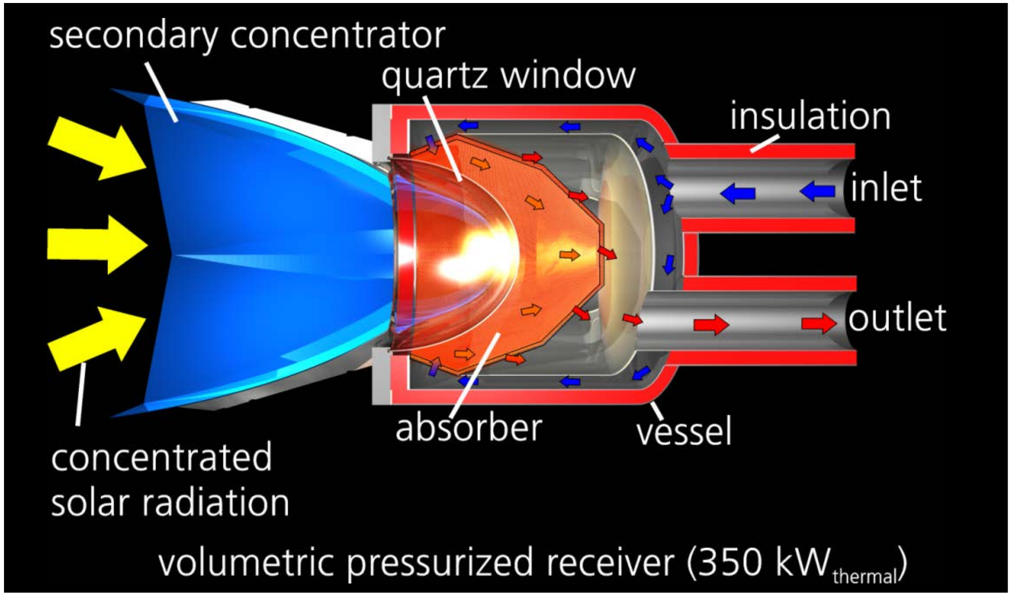
- improvement of volumetric absorber structures
- optimization of air receiver system
- dynamic simulation of receiver
- aim point optimization
- support of market introduction
    - scalable design
    - design of prototype plants
    - know-how transfer





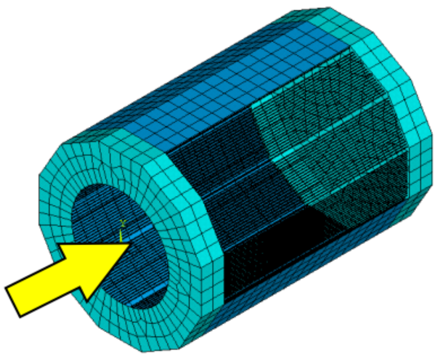
Pressurized Volumetric Air Receiver

- 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

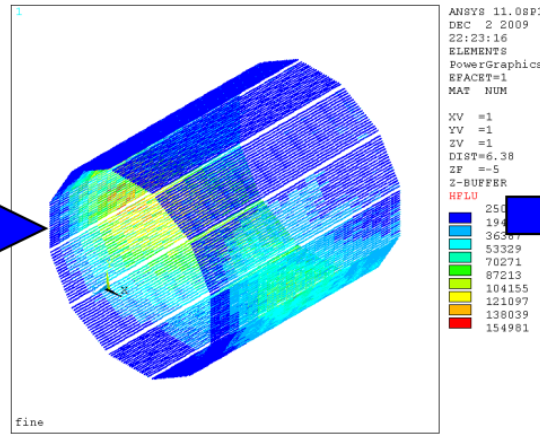


Tube Receiver Design and Analysis

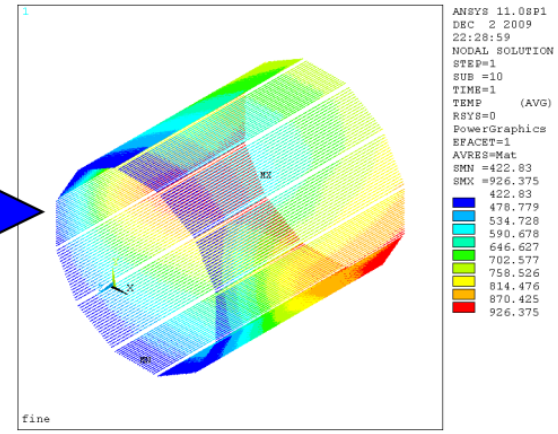
Example: SOLUGAS receiver



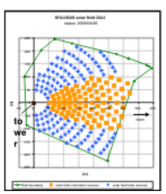
FE- Model



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

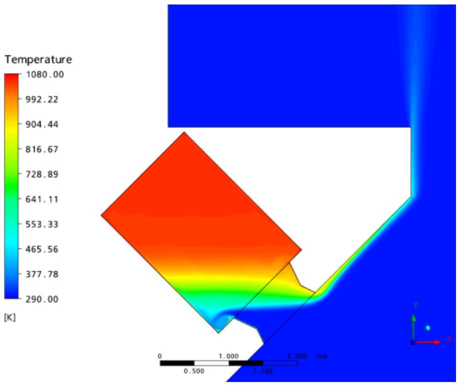
SOLUGAS
Tube Receiver in Solar Gas Turbine System

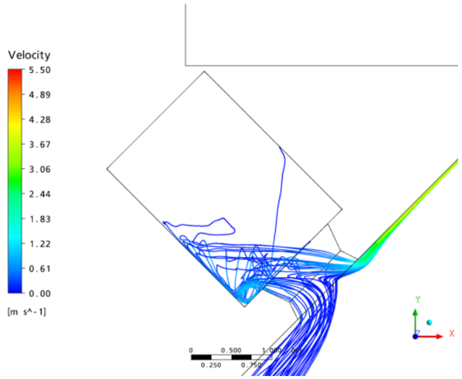
800°C reached

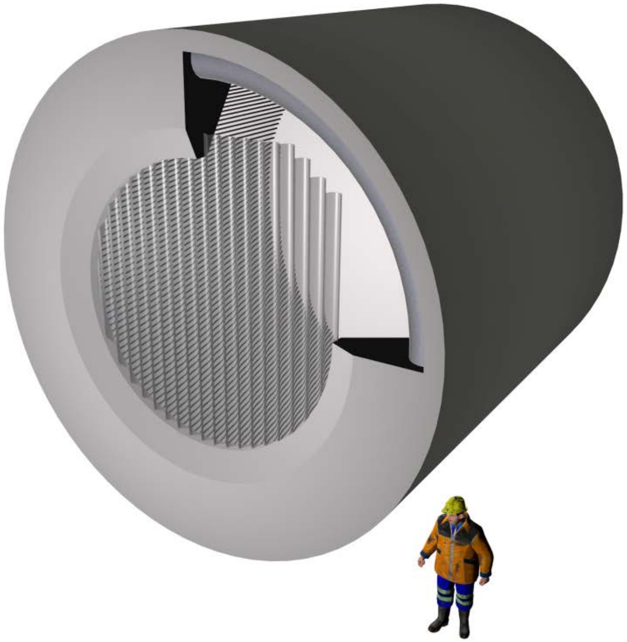
Abengoa
Solar Power Plants,
near Seville, Spain

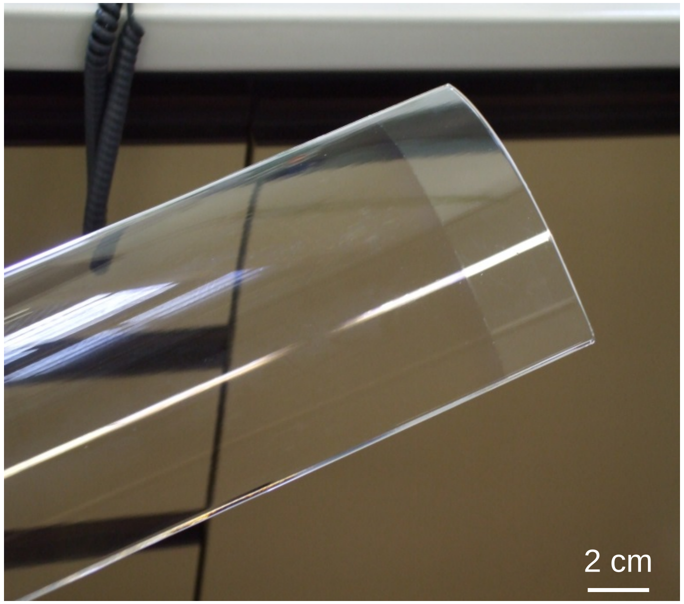
installation of an additional 1000°C pressurized volumetric receiver module in preparation

Receiver component development - antireflective coated segmented receiver window









LIMTECH: Systems using Liquid Metal as HTF

- large temperature range in liquid phase
- chemically stable

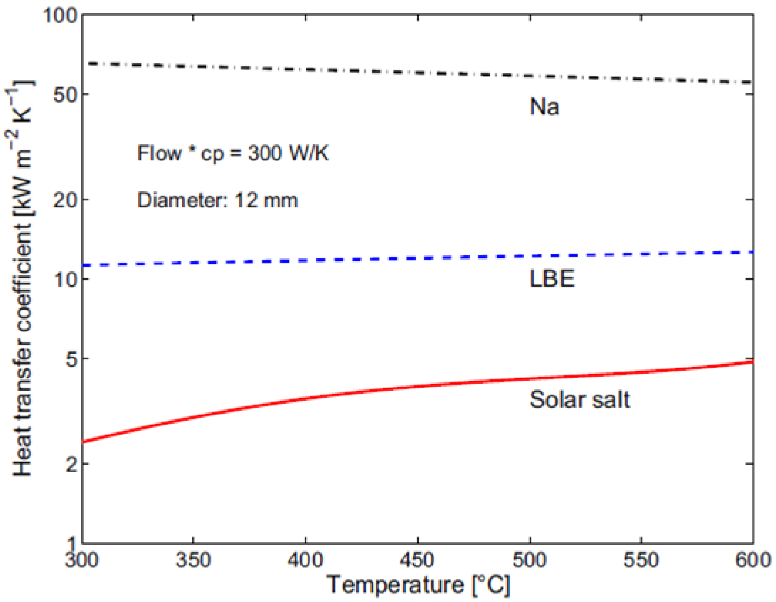
Fluid	Solar Salt	Na	LBE	Sn
Tmelt [°C]	220	98	125	232
Tboil [°C]	565	883	1553	2687

(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?



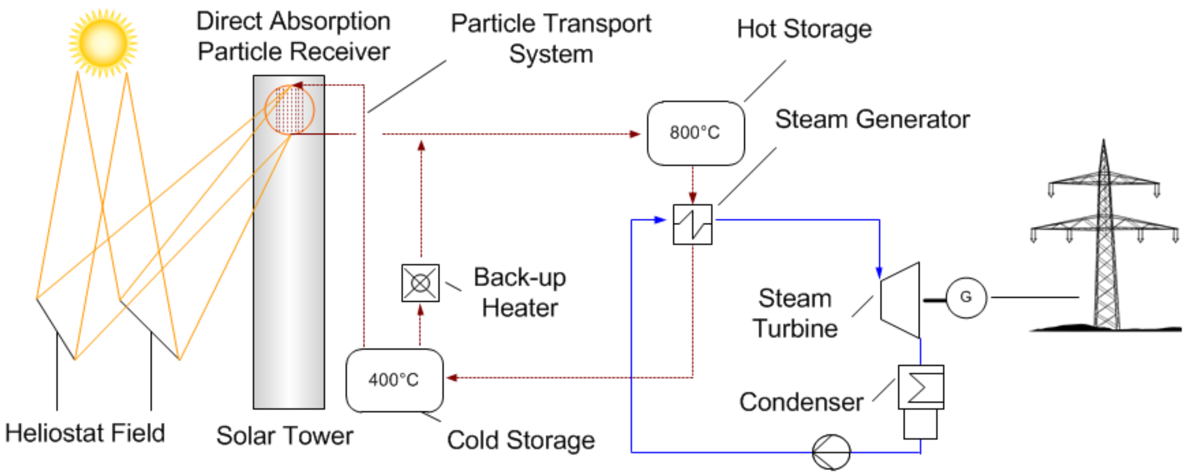
Particle Receiver Power Plant

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

Advantages:

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

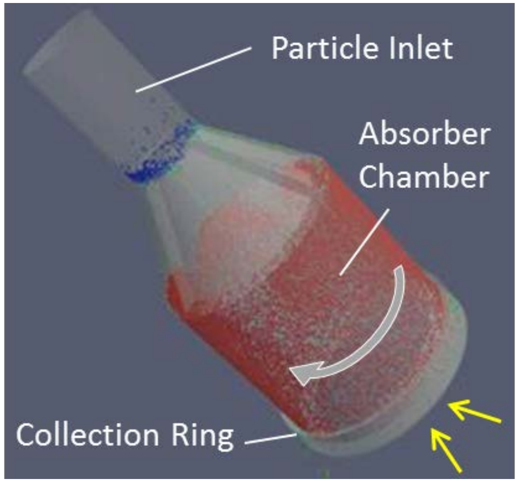
- Low Levelized Electricity Costs



Particle Receiver Concepts

- direct absorption concept
  ⇒ high efficiency

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



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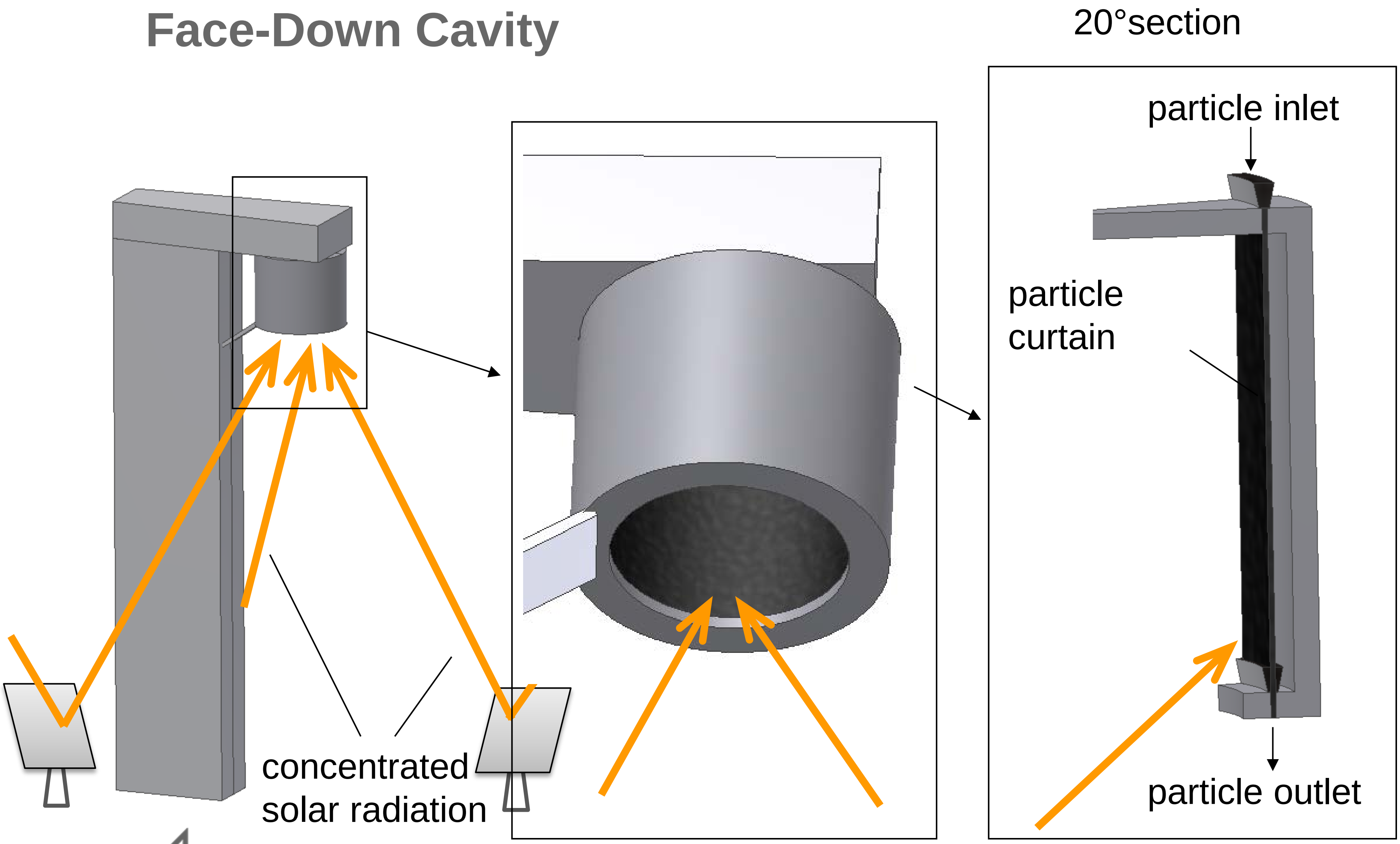
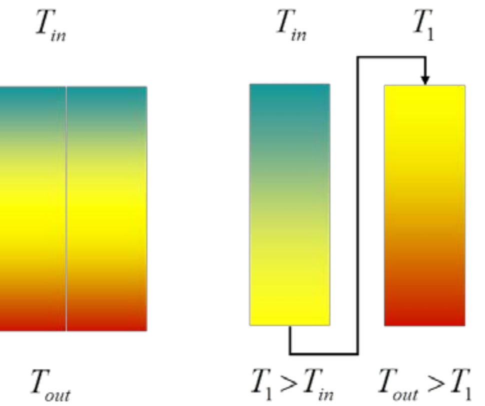
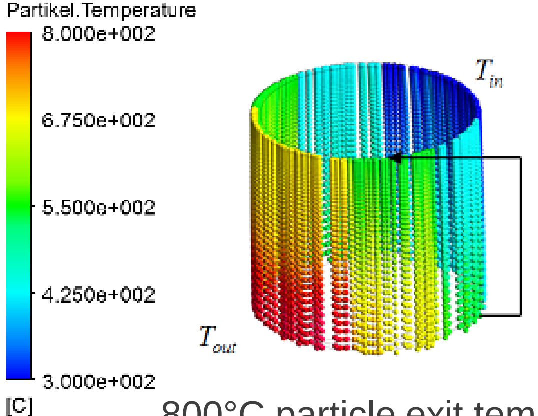
Falling Particle Receiver in Face-Down Cavity



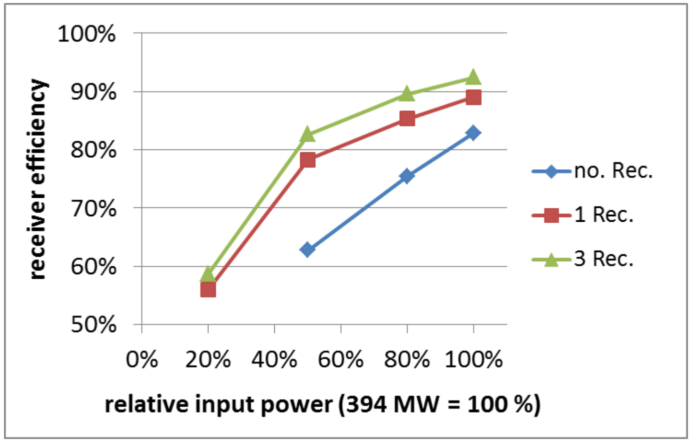
Particle Receiver with Smart recirculation

- 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

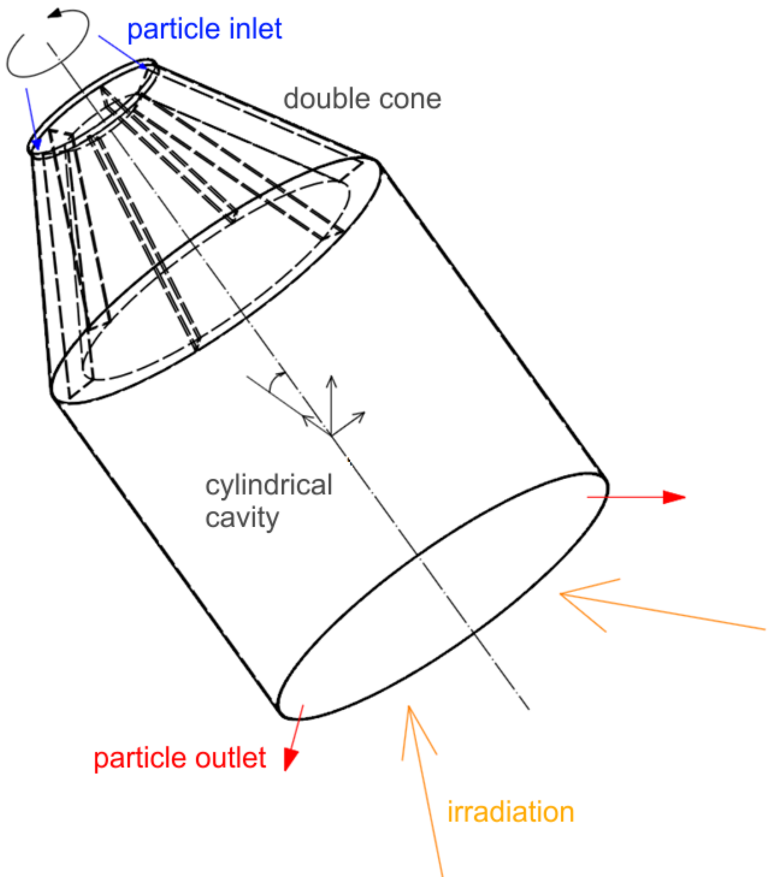


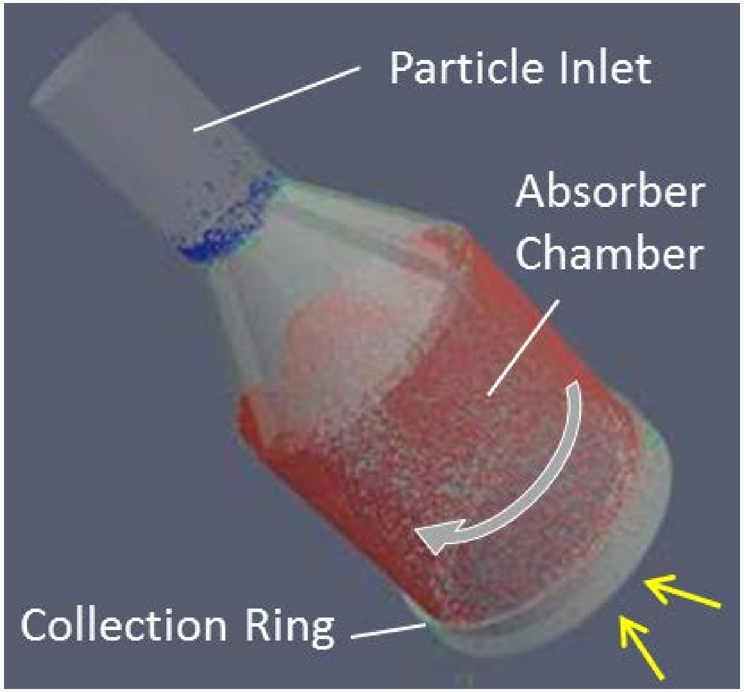


800°C particle exit temperature

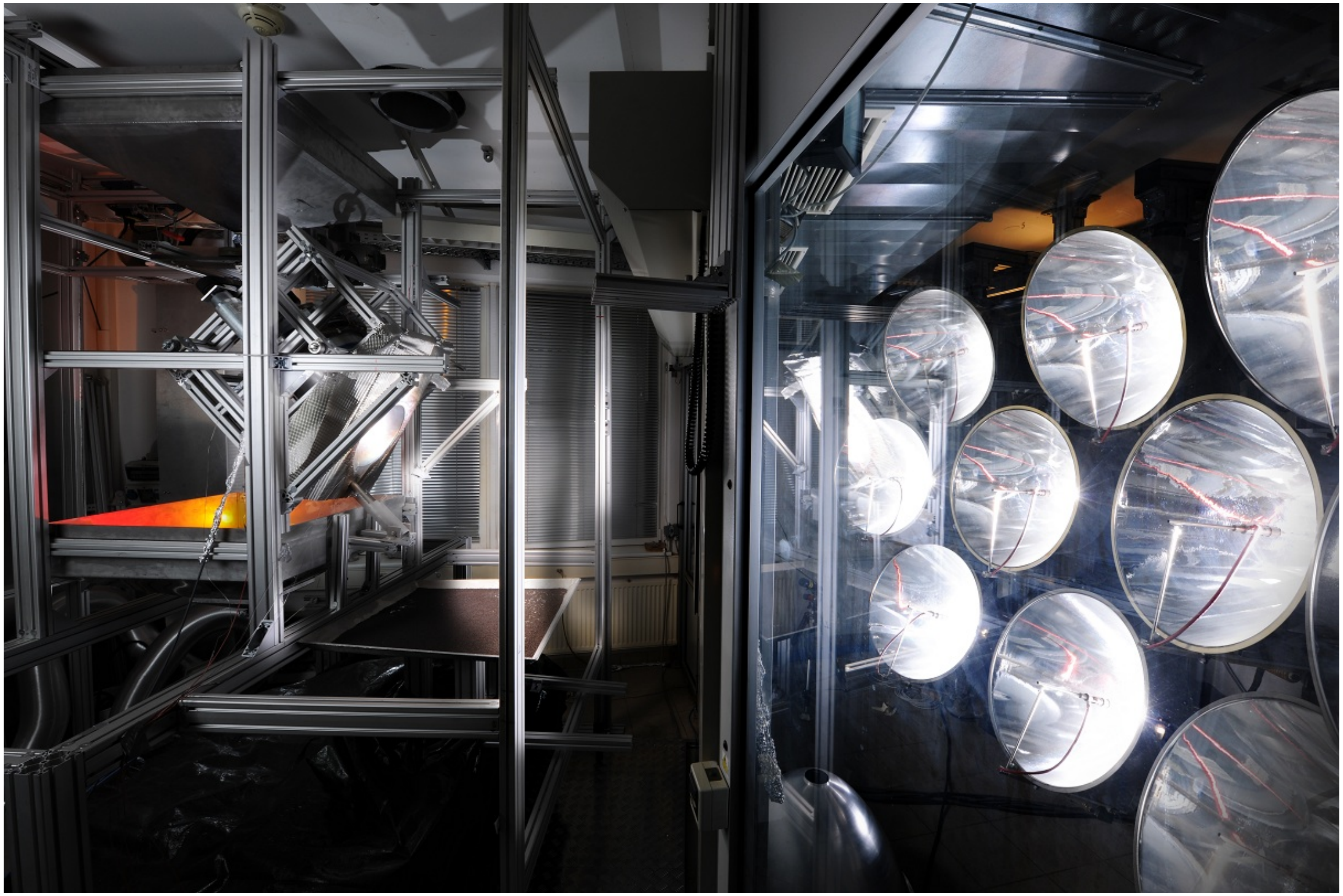


The Centrifugal Particle Receiver (CentRec)





10kW Prototype in Laboratory Scale



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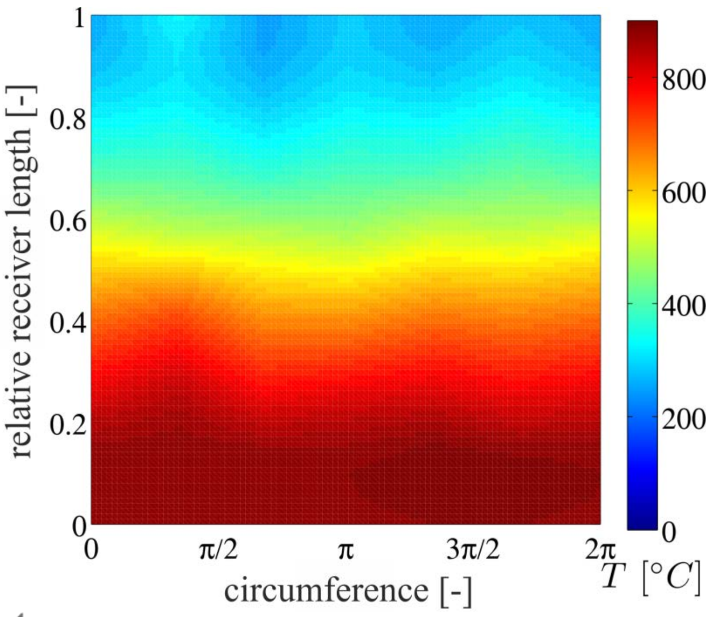
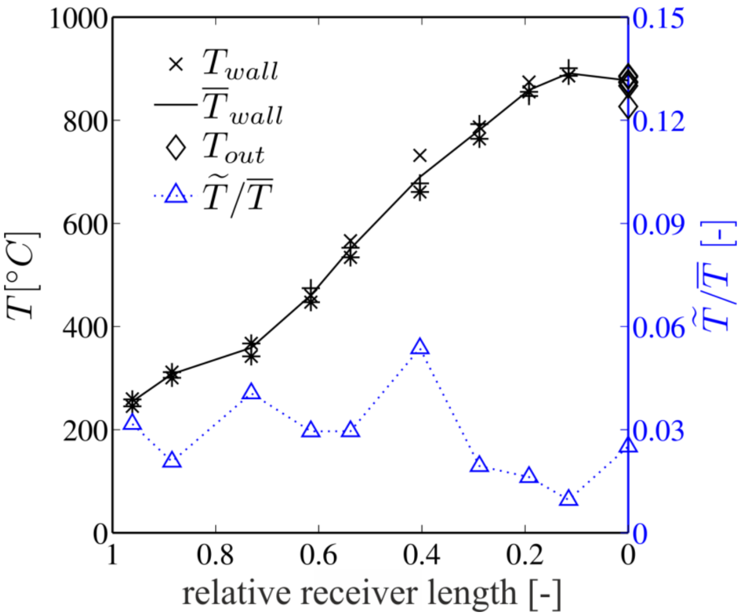
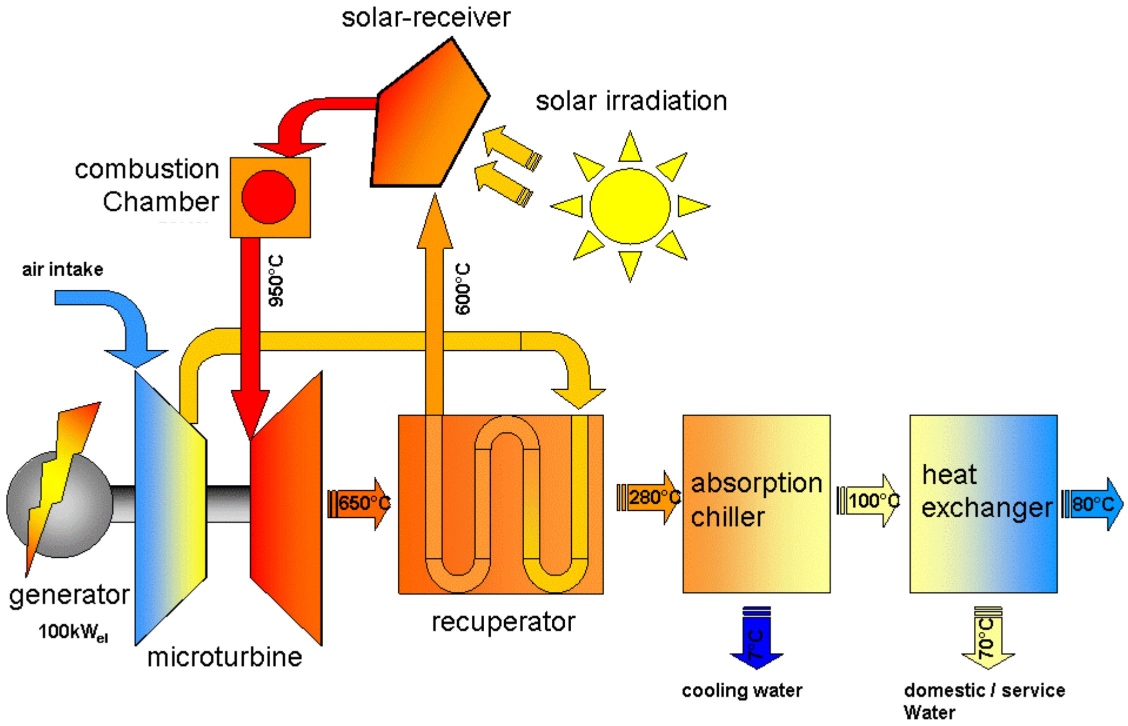
CentRec: Experimental Results

- 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





Solar-hybrid Microturbine System

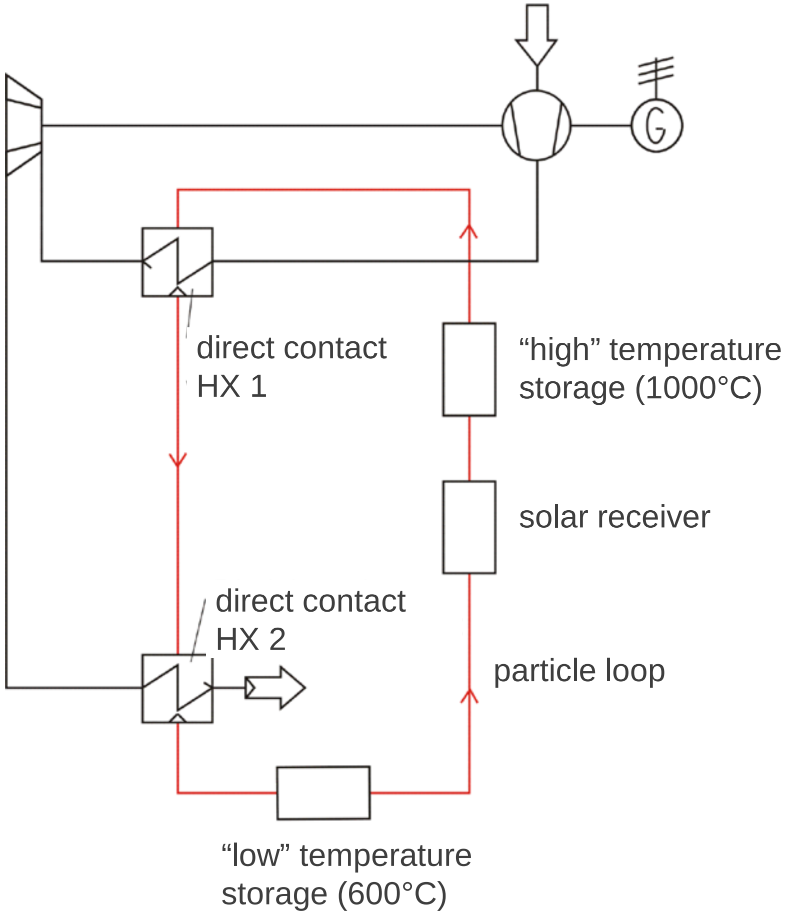


Turbec T100 microturbine, P_{el}=100 kW
4.5 bar_{abs}, 950°C Turbine inlet temperature
600°C recuperator outlet temperature
η ~ 31% (standard unit)

DLR

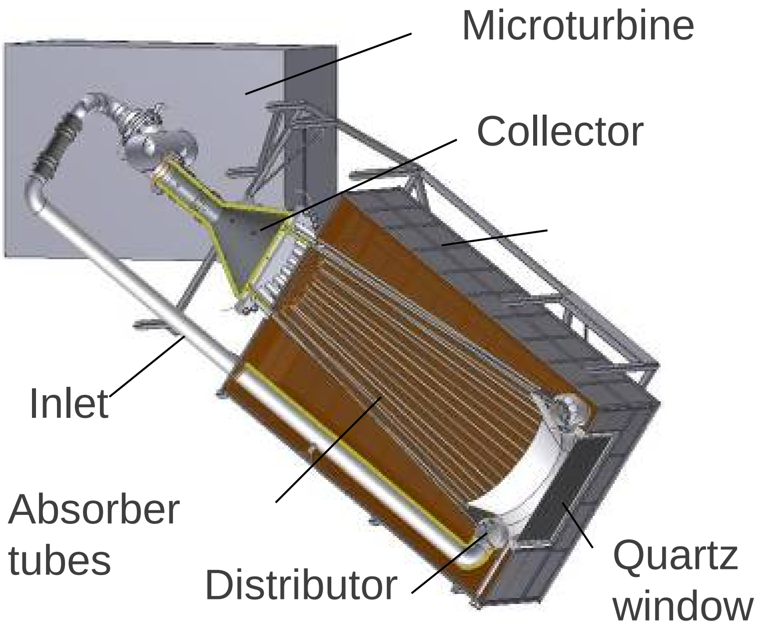
Solar-hybrid Microturbine System with Integrated Solar Particle Loop

- 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

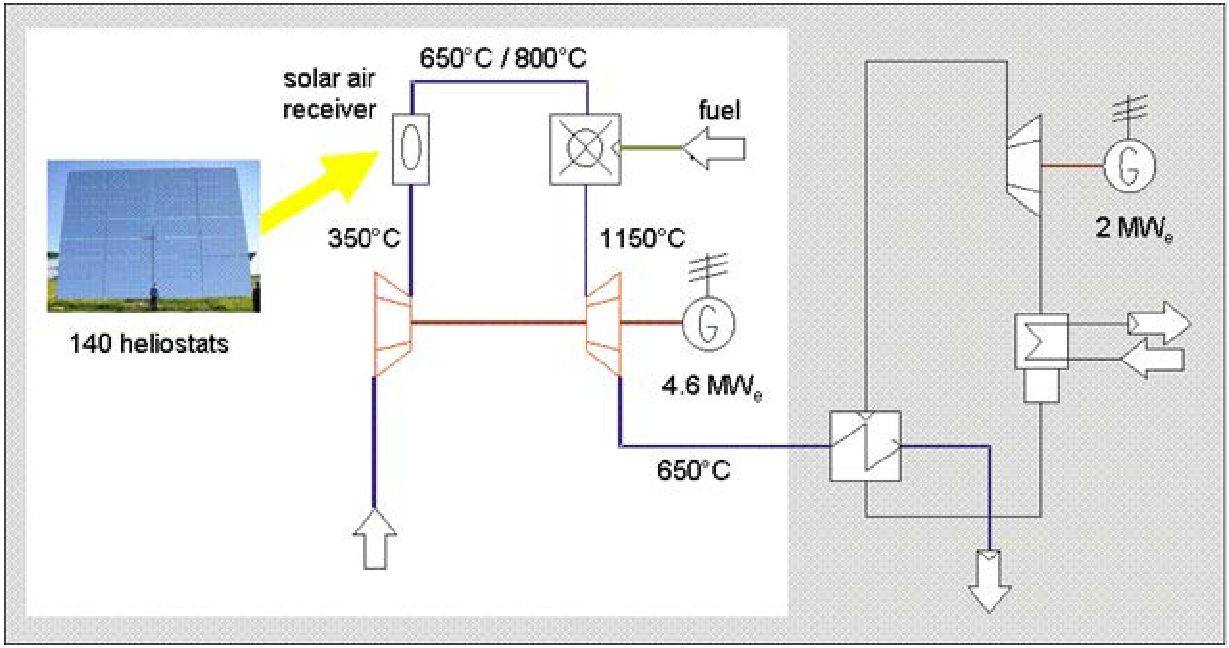


SOLUGAS Project

- 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



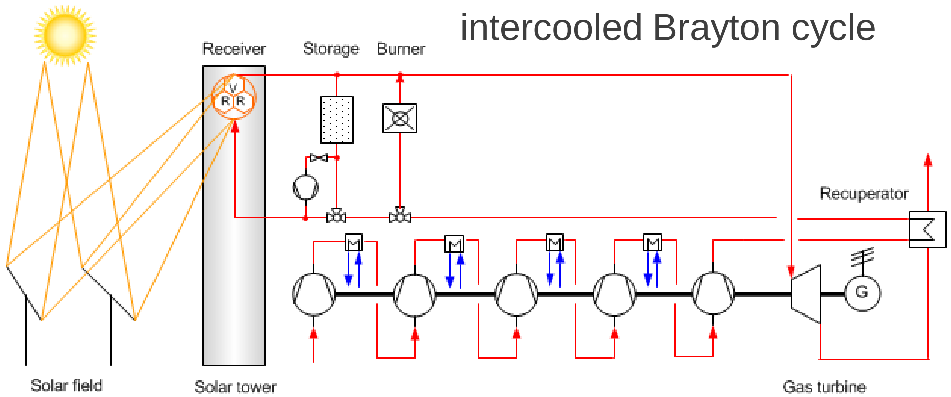
Solarized Gas Turbine Cycles

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

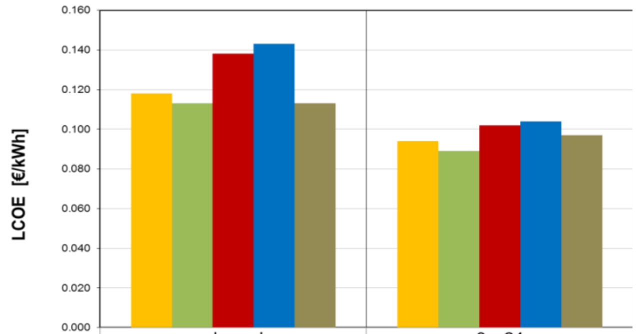
- solar-hybrid gas turbine cycles
  - high turbine inlet temperature:
    ⇒ moderate solar share
  - low turbine inlet temperature:
    ⇒ high solar share (950°C)
  - regenerator storage optional

- 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

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

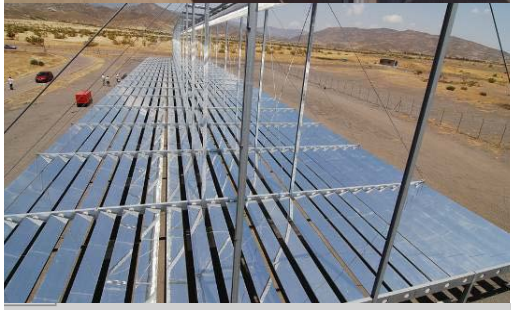
system layout optimization:
- solar field, receiver
- power block
- storage

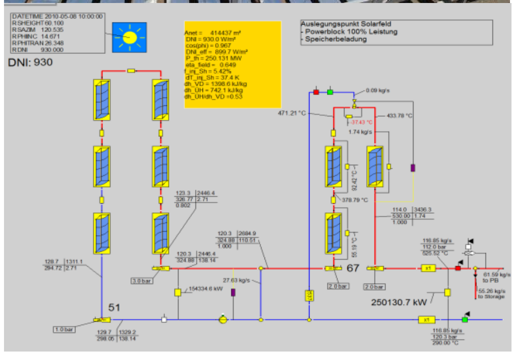
transient system simulation:
- real-time, high resolution performance simulation
- coupling of components and control

Detailed System Performance Simulation

using Ebsilon®

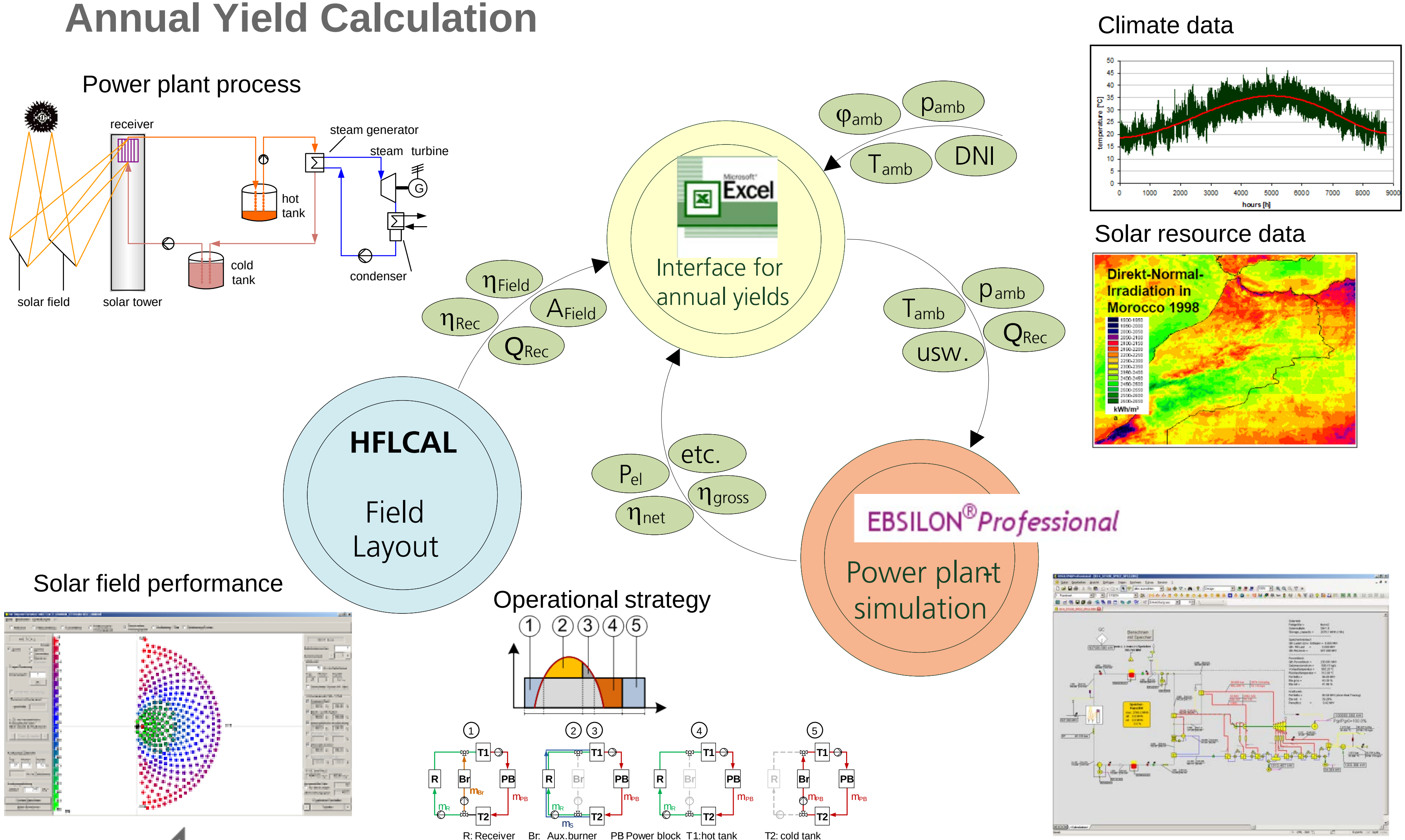
- „All in One" solution for detailed power plant modelling
- for development, acquisition und planning
  of all kinds of power plants and thermodynamic processes
- design and development of single components, subsystems
  and complete systems
- development of new solar library EbsSolar (steag and DLR):
  - 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





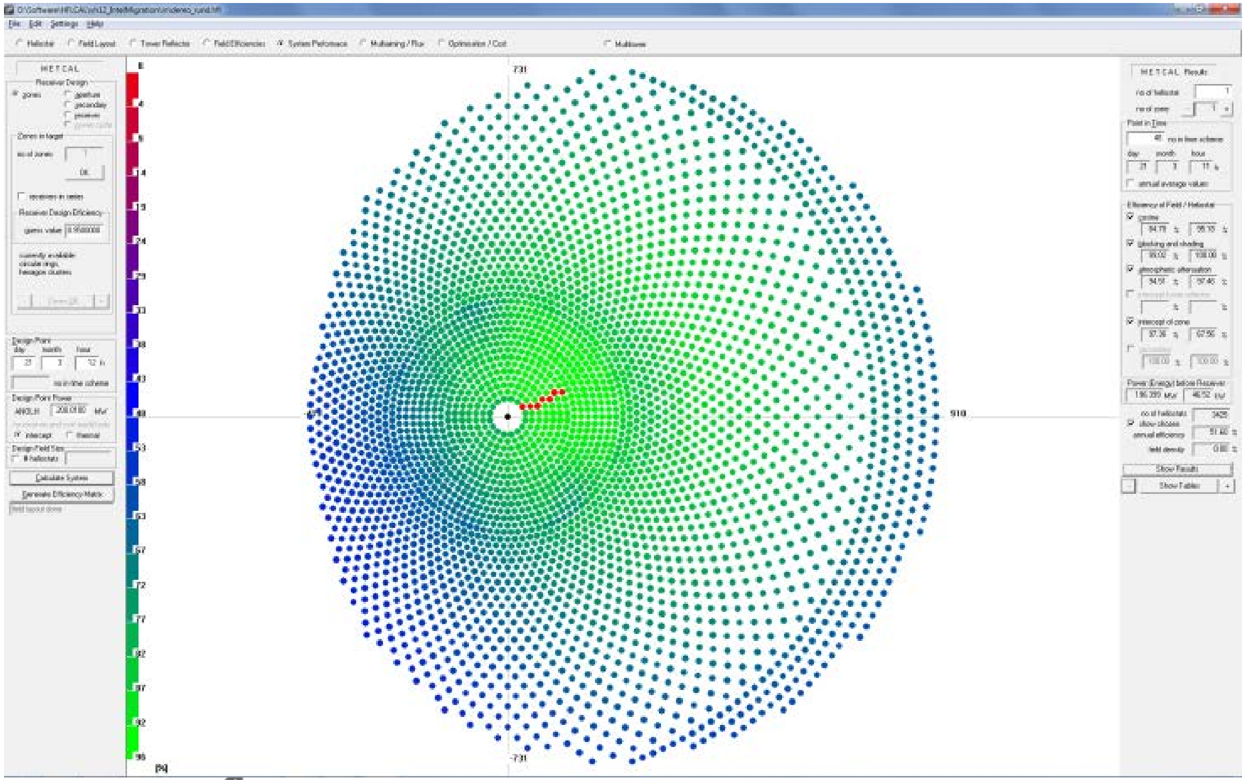
System Simulation: Workflow for Solar Towers

Annual Yield Calculation

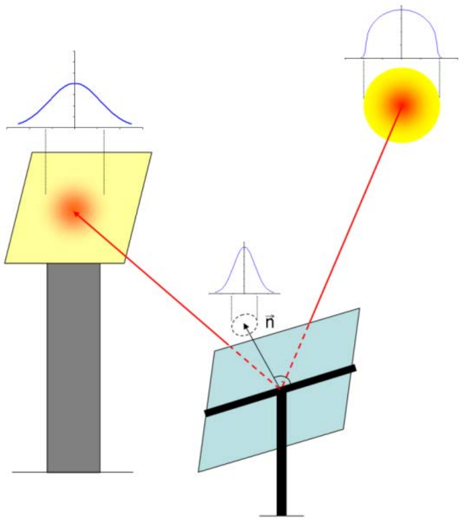


Solar System Layout
Visual HFLCAL: Heliostat Field Layout

- fast optimization of heliostat field, receiver and tower

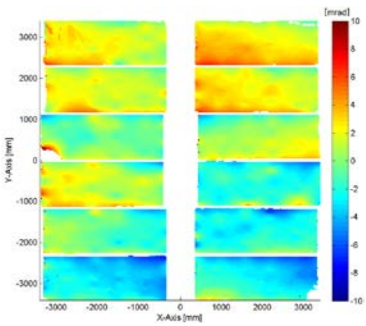


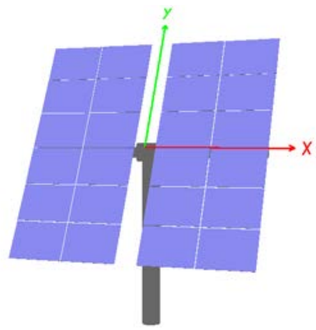
- simplified optical model
- very fast calculation
- optional: use of topography

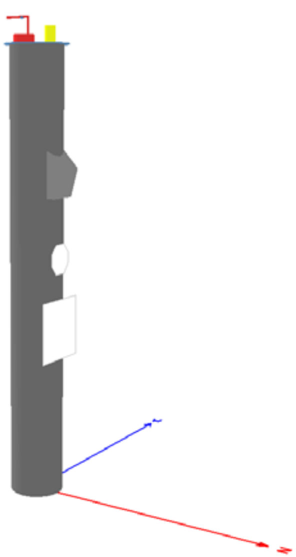


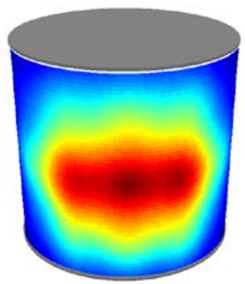
DLR

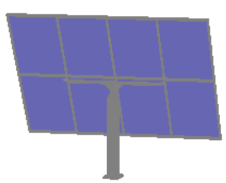
Component Level:
High Precision Ray Tracing (STRAL)



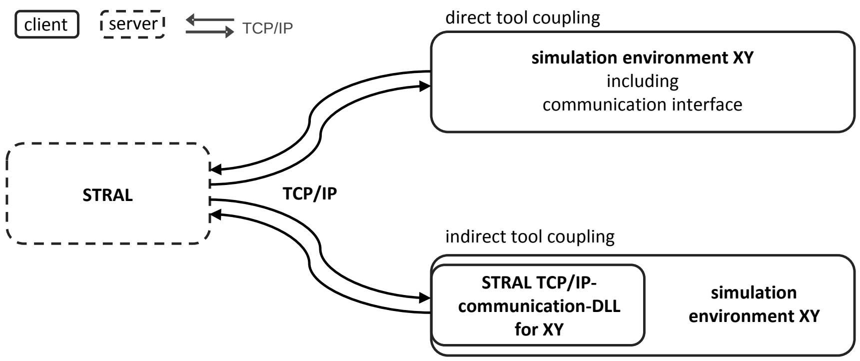




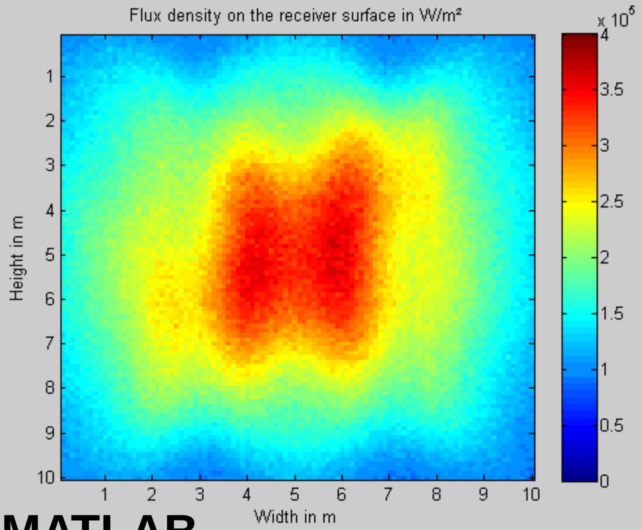




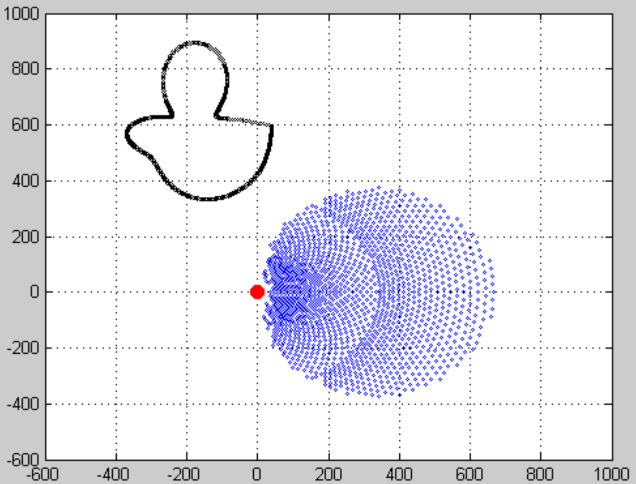
- fast and accurate ray tracing of concentrator systems (tower, trough, ..)
- can use measured heliostat surface data
- aim point optimization
- tool coupling features
  - best simulation environment for specific modeling problems
  - exchange data during co-simulation via network
  - MATLAB® / Simulink®;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

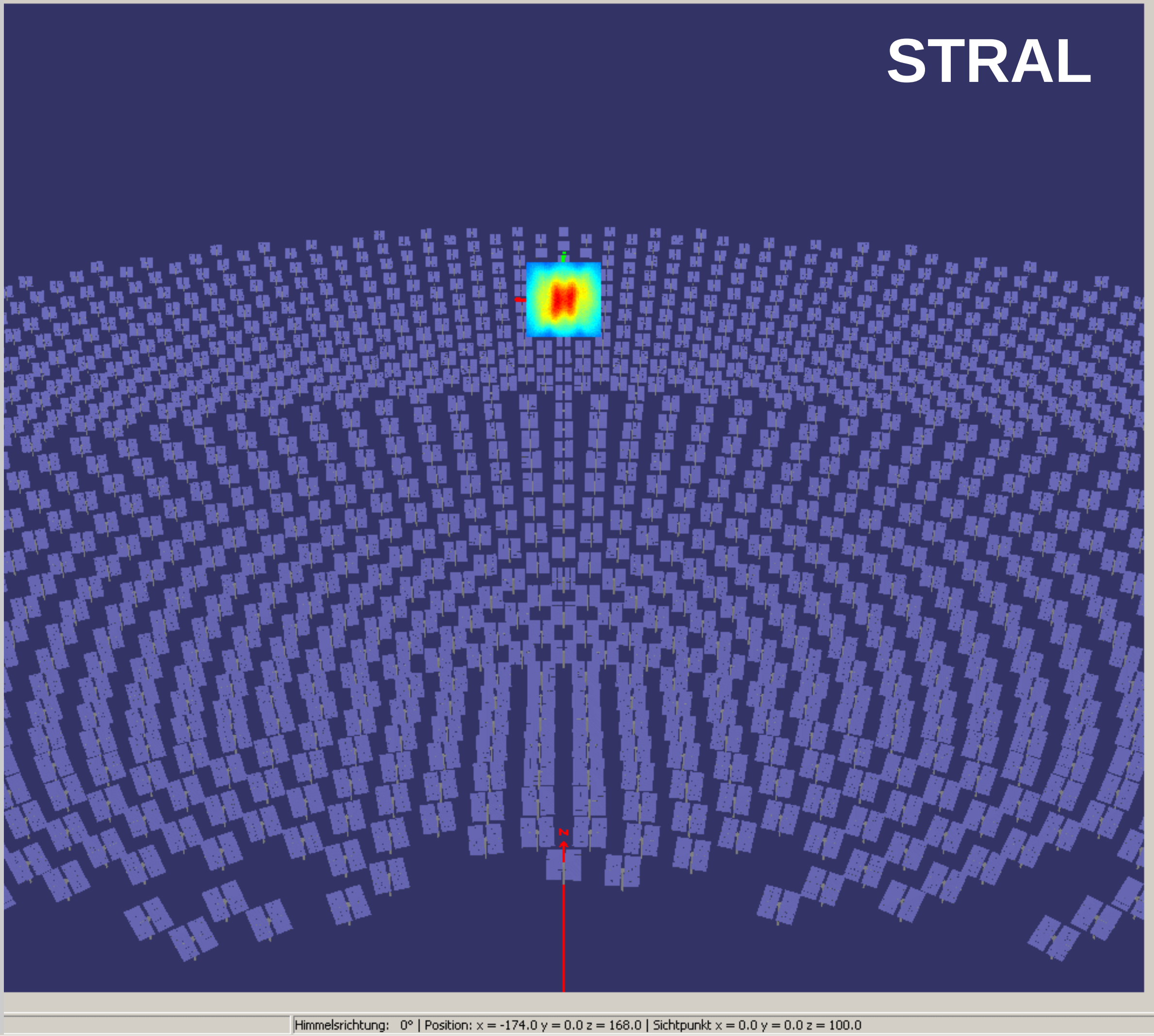


Tool Coupling Example: Cloud Passage



MATLAB



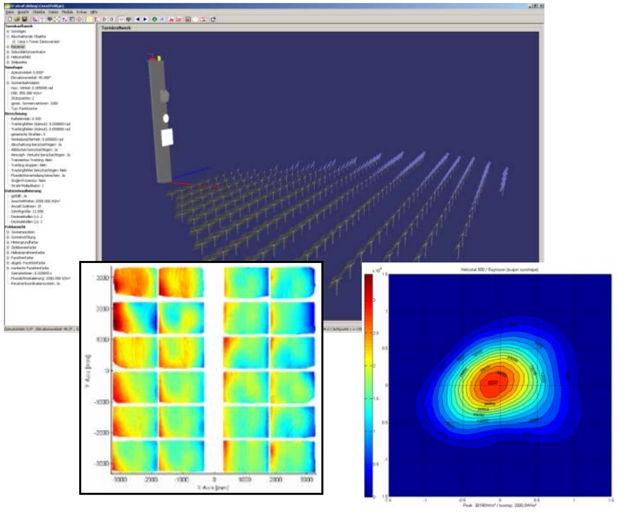


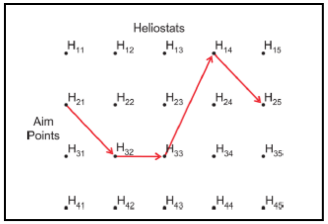
Aim Point Optimization

- 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





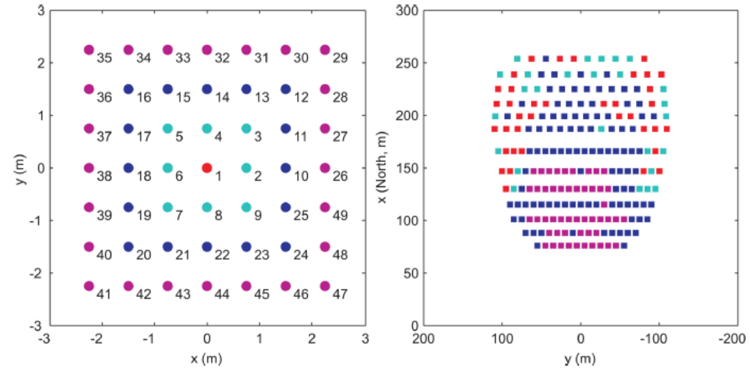
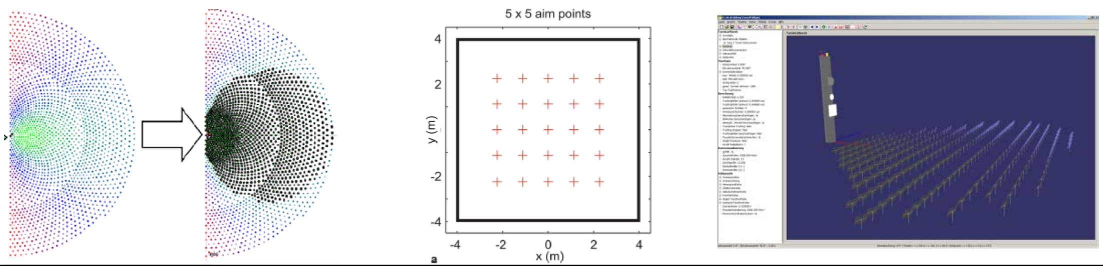


Fig. 7 Optimized aim point configuration on the 7 × 7 raster and the corresponding heliostat positions

Integrated Solar Tower System Layout

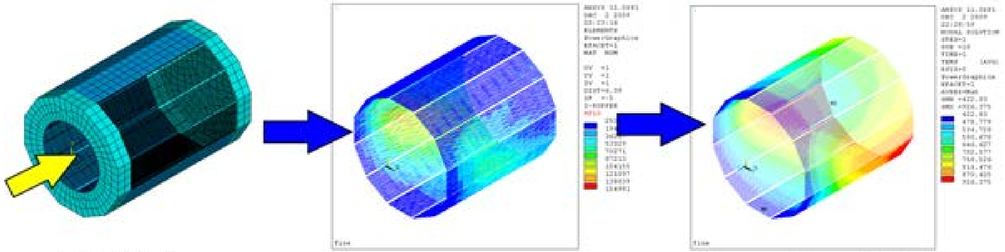
- integrated tool under development: combination of
  - field layout (heliostat positions)
  - aim point distribution
  - receiver design (e.g. FEM stress analysis)



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

FemRay

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



FE- Model

Solar heat fluxes

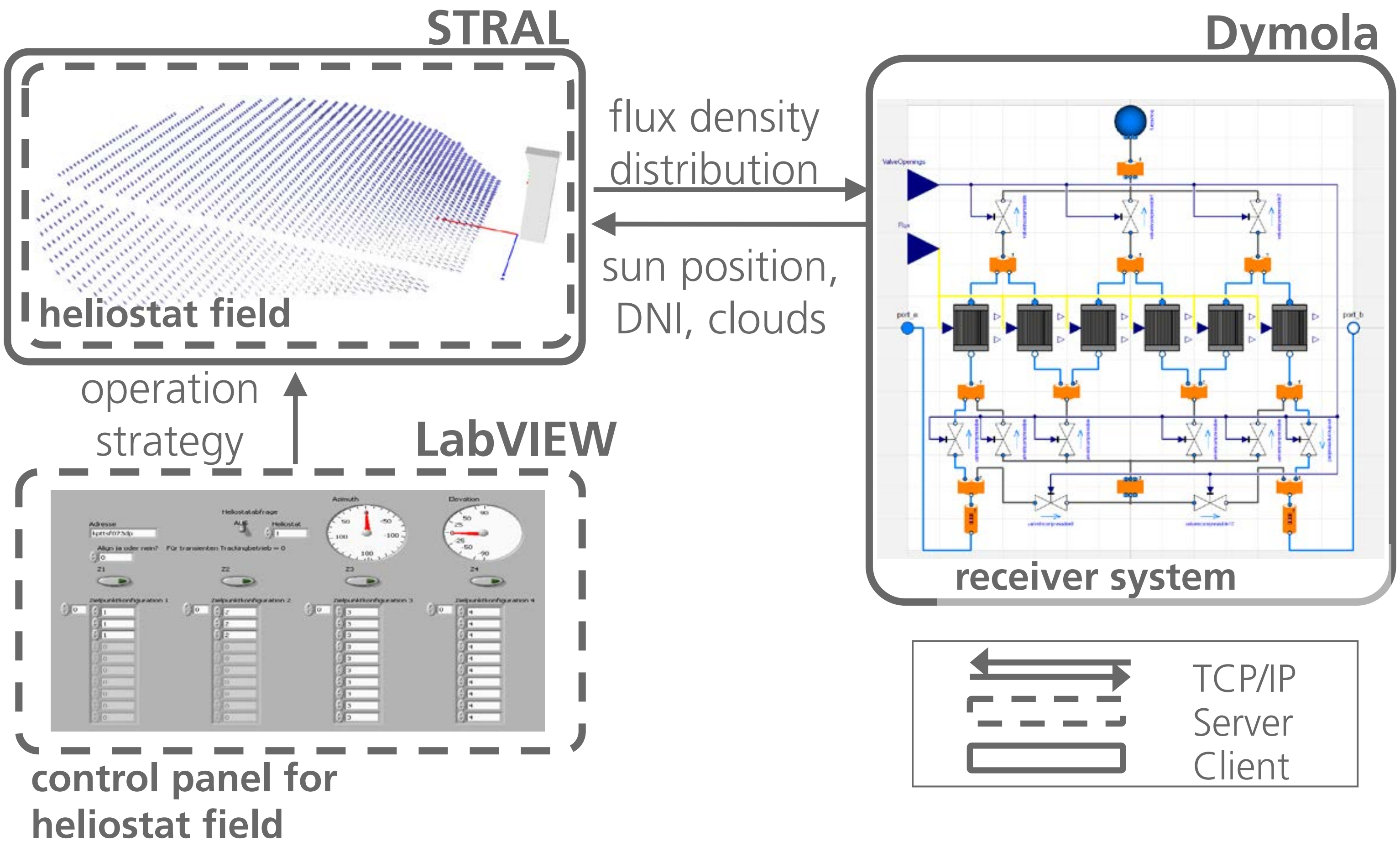
Temperature distribution

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

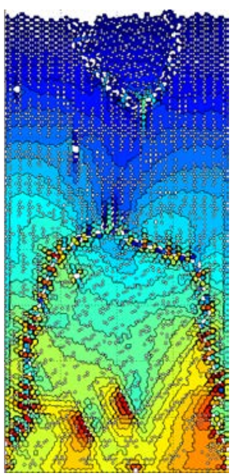
- philosophy: use best suitable simulation tool for each component

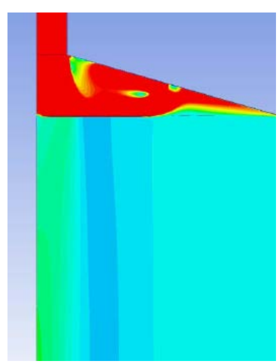


High-temperature storage with solid media

Regenerator storage, Packed bed storage with hot gas HTF

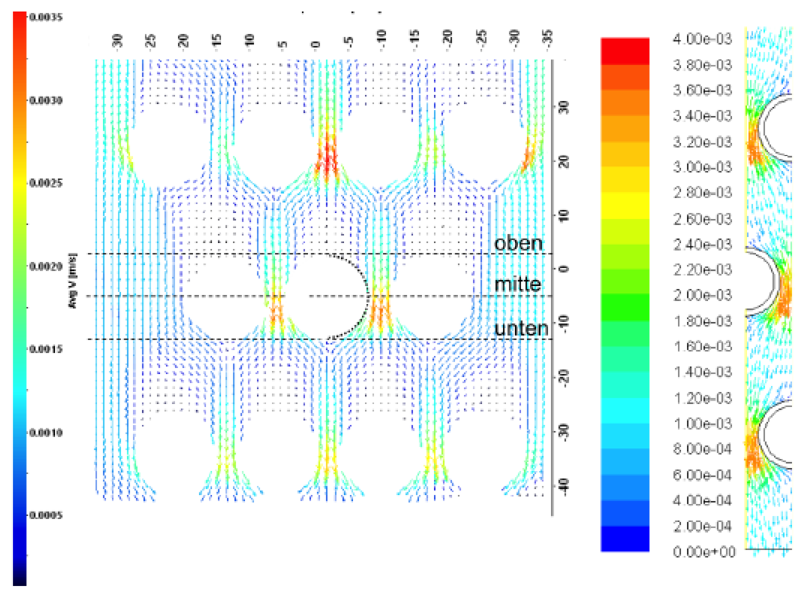
- Thermo-mechanical aspects (thermal ratcheting): particle-discrete models to calculate inter-particle forces
  $\Rightarrow$ design of protective measures
- Uniform flow distribution with “low pressure-loss designs”: CFD-based prediction of pressure loss and flow





Particulate storage and heat exchangers

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



Thank your for your attention!

Contact: reiner.buck@dlr.de