LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

Radiation Cooling of the ILC positron target

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outline

- ILC e+ target
- Radiative cooling
- Basics
- Simple model
- First attempt with more realistic model
  - Temperature distribution
  - Speed of heat transfer
  - Thermal contact between target and radiator
  - Design considerations and mechanical issues
- Summary

ILC positron target (TDR)

- Undulator → photon beam
- Ti alloy wheel
  - **diameter = 1m, Thickness 0.4 X0 (1.4cm)**
  - **Spinning with 2000rpm**
- Average energy deposition 2 - 7 kW depending on E_{cm}
  - **Pulsed, 5Hz**
- peak energy deposition (PEDD) per bunch train:

  Nominal: 67.5 J/g ⇔ ΔT_{max} = 130K
  Lumi upgrade: 101.3 J/g ⇔ ΔT_{max} = 195K
  Fatigue strength in Ti alloy ΔT ~ 425K (240MPa)
- We do not expect thermal shocks
  - **Degradation during irradiation and pulsed heat load should be studied/tested**
- TDR: water cooling
- Alternative solutions:
  - **cooling by radiation**
  - **Sliding cooling**

Radiative cooling

Length of bunch train on target (2000rpm): ~10cm
Same area of 1m-wheel is hit again after ~6s
→ Time sufficient for heat dissipation and removal ?

Stefan-Boltzmann radiation law: $$W = \sigma \varepsilon A G \left(T^4 - T_{cool}^4 \right)$$

σ = Stefan-Boltzmann constant = 5.67 × 10^{-8} W/(m^2K^4)
ε = emissivity (two parallel surfaces: $\varepsilon = (1/\varepsilon_1 + 1/\varepsilon_2 - 1)^{-1}$)
A = surface area
G = geometric form factor

Rough estimate:

W = 5kW
ε = 0.8
T = 250 C
T_{cool} = 20 C
G = 1

→ We need a surface of A > 1.65 m^2

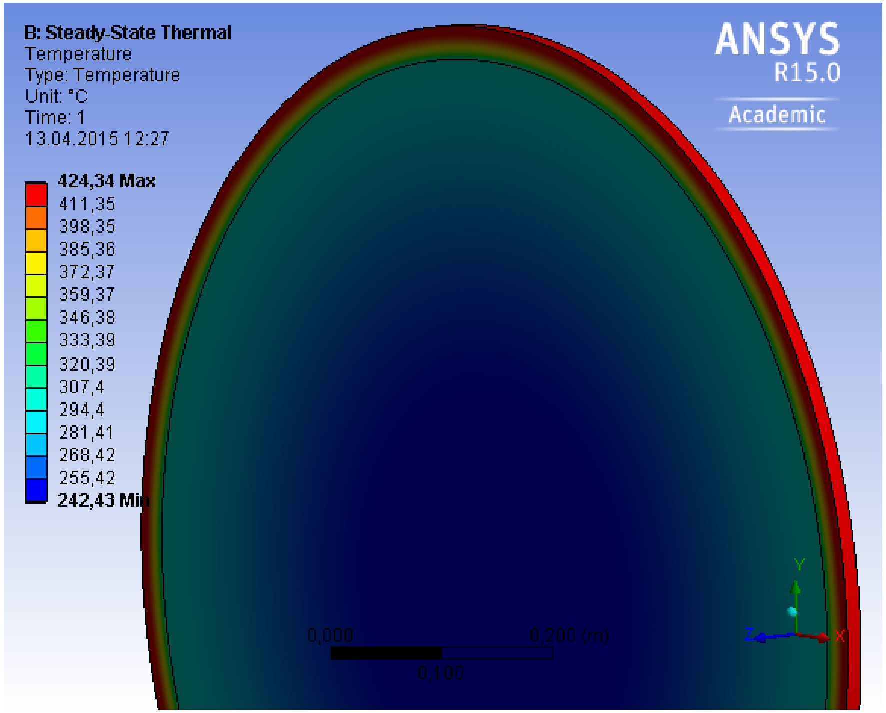
Radiative cooling should be possible

Simple model: Stationary temperature distribution

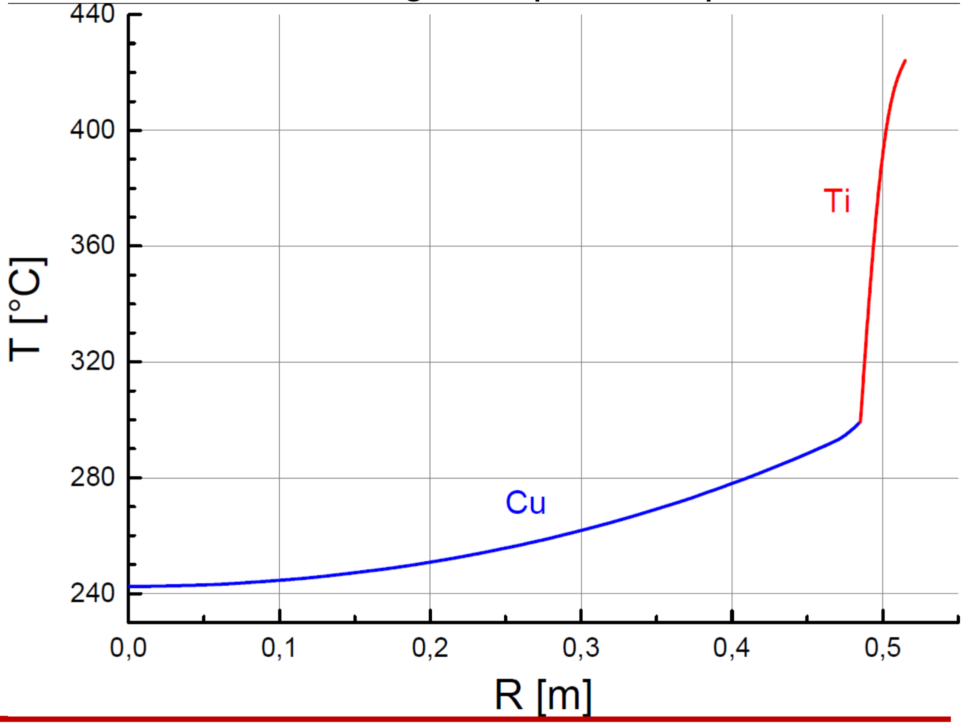
Stationary consideration (energy deposition equally distributed over Ti6Al4V)

- Model: disk of Ti –alloy target + Cu radiator, thickness *1.48cm* (see also A. Ushakov @ POSIPOL14)
- Emissivity of Ti-alloy $\varepsilon_{Ti} = 0.25$
- emissivity of copper alloy $\varepsilon_{Cu} = 0.7$
- P = 5170W
- peak temperature $\approx T_{average} + \Delta T/2 \approx 500°C$

Andriy Ushakov: Radiative cooling of Ti+Cu disk

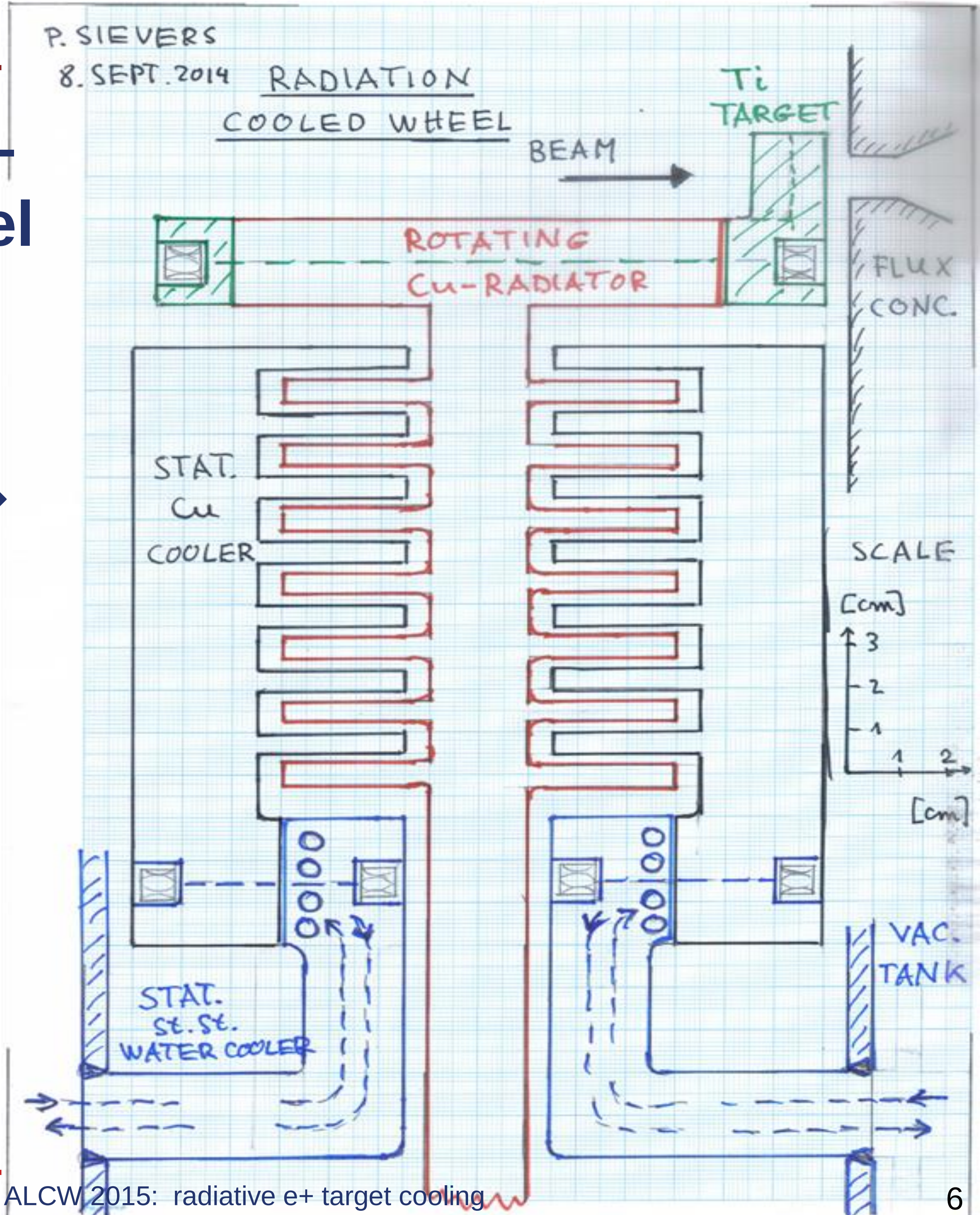


Radial average temperature profile



Radiative cooling – more realistic model

- Heat path:
  - **thermal conduction Ti → solid Cu wheel**
  - **radiation Cu wheel → stationary water cooled coolers**
- Target, radiator and cooler are in vacuum
- Cooling area can be easily increased by additional fins
- thermal contact Ti → Cu is very important



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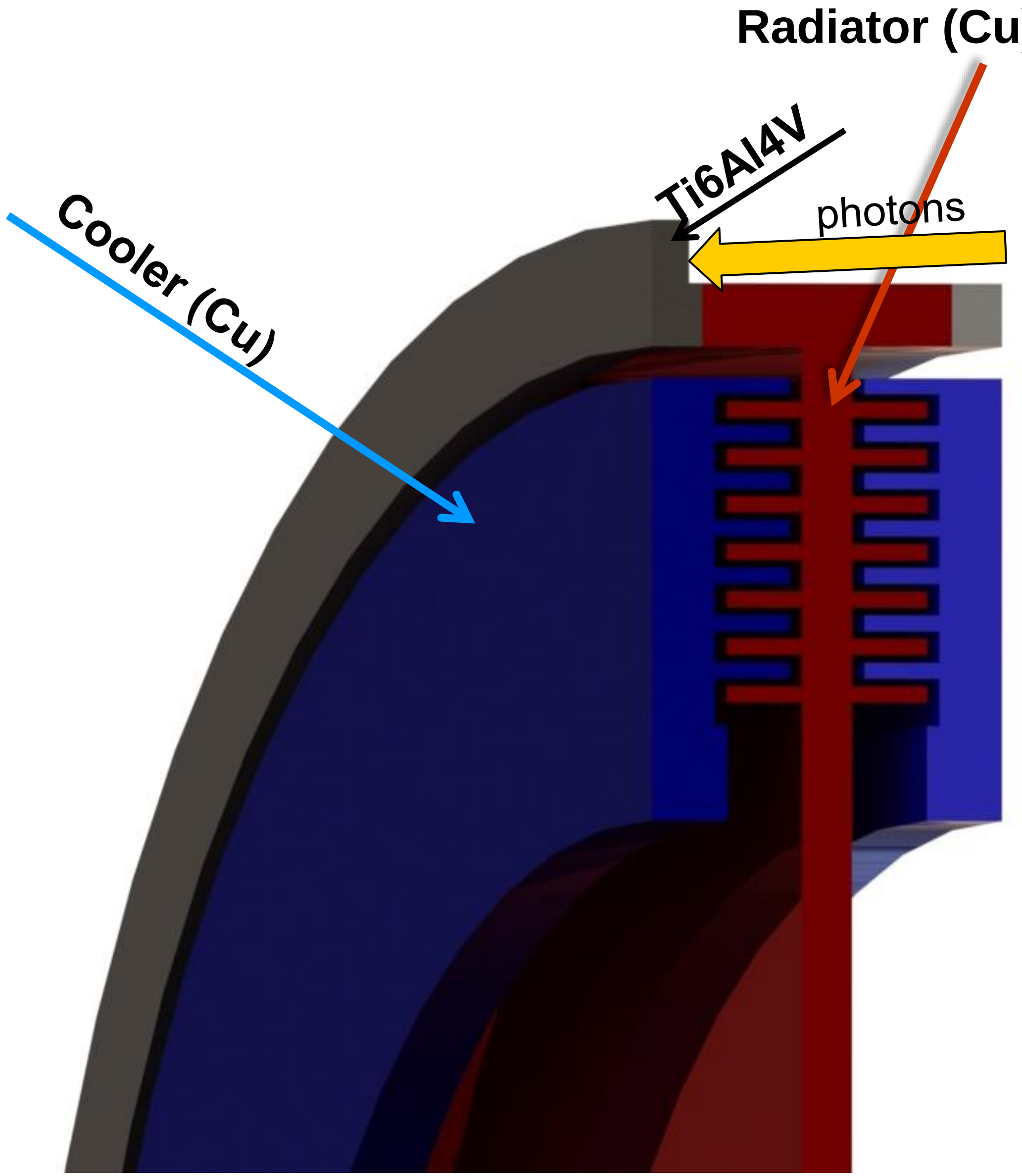
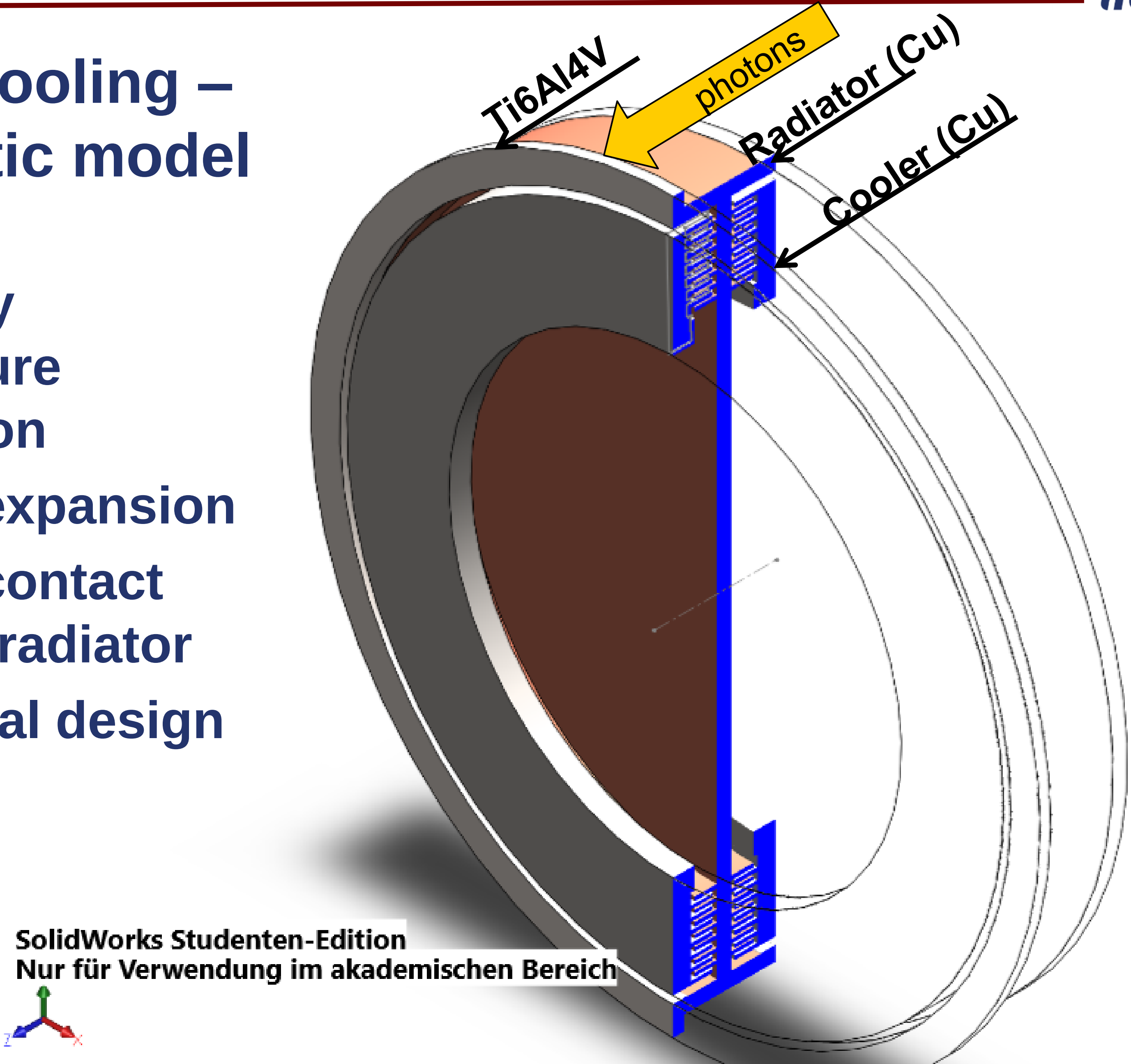


Felix Dietrich

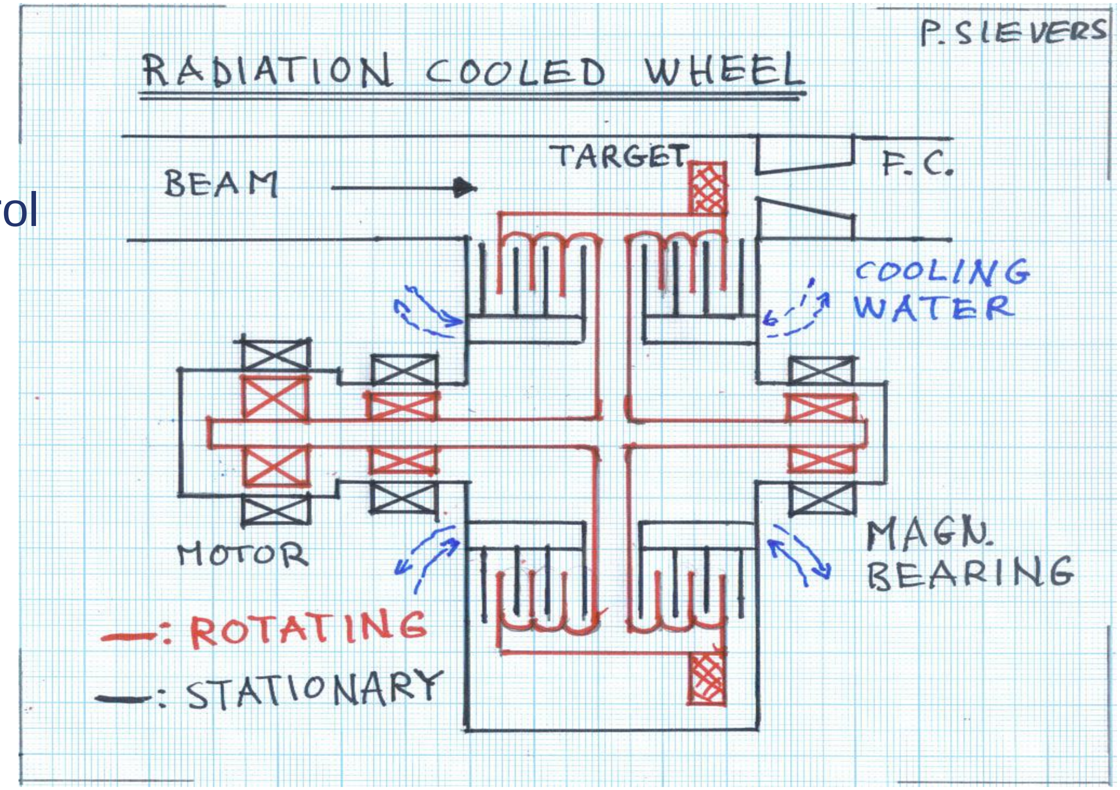
Radiative cooling – more realistic model

- Stationary temperature distribution
- Thermal expansion
- Thermal contact Ti alloy – radiator
- Mechanical design

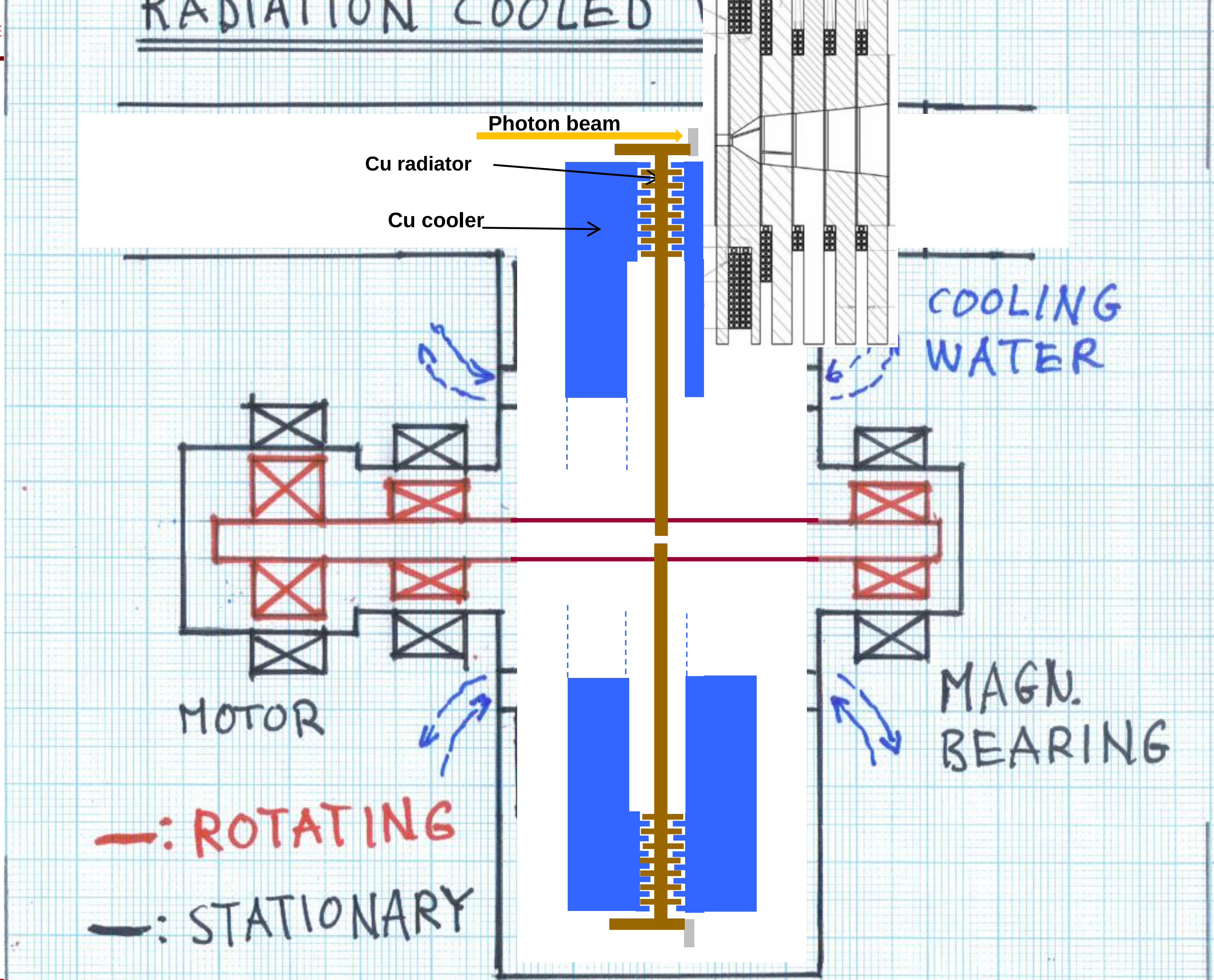


Layout P. Sievers @ POSIPOL 2014

- The motor:
  - rotor inside the vacuum
  - stator outside vaccum
  - Very precise rotation control is possible at well above 2000 rpm.
- Rotating magnetic bearing is inside the vacuum.
- Total unit is sealded inside the vacuum, rotating feed throughs are necessary



- Temperatures up to about 300°C of bearings and rotor can be tolerated.
- Heat removal from these rotating parts under vacuum must be studied, but this is no show stopper.
- Weight of the wheel (~100 kg) can be handled.
- shielding of motor and bearings from radiation damage is feasible
- Differential pumping for adequate vacuum can be arranged

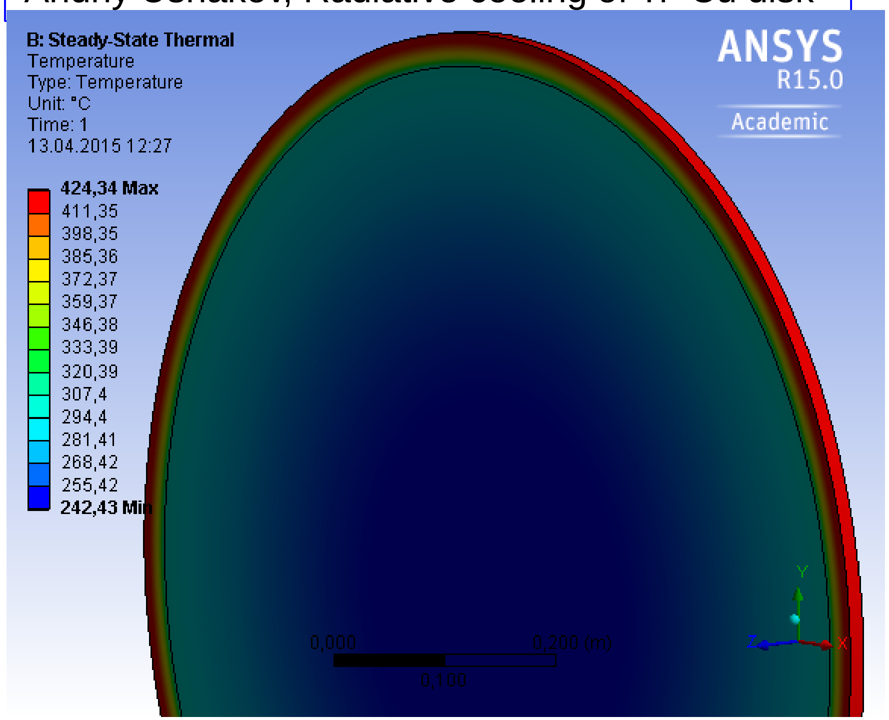

RADIATION COOLED
Photon beam
Cu radiator
Cu cooler
COOLING WATER
MOTOR
MAGN. BEARING
—: ROTATING
—: STATIONARY

Stationary temperature distribution (1)

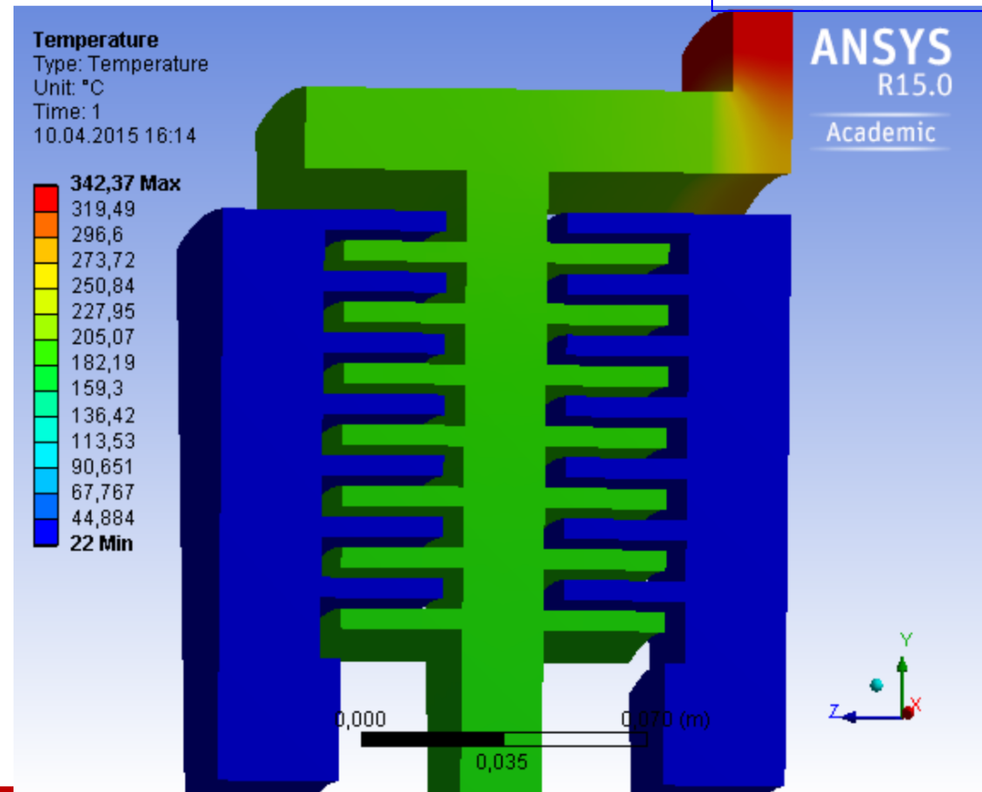
Stationary consideration (energy deposition equally distributed over Ti6Al4V)

- Emissivity of Ti-alloy = 0,25
- emissivity of copper alloy = 0,7
- P = 5170W

Andriy Ushakov, Radiative cooling of Ti+Cu disk



Andriy Ushakov



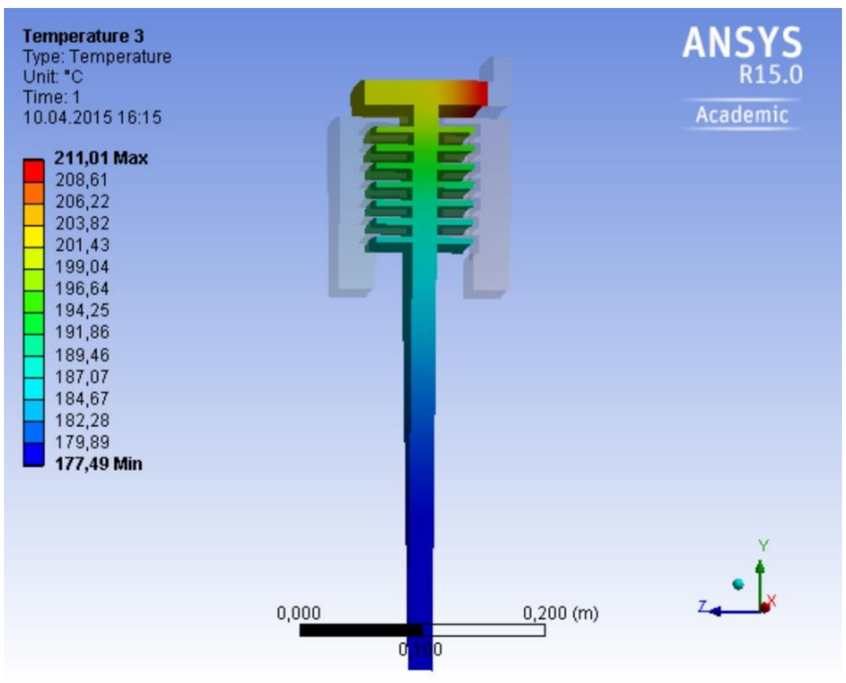
Stationary temperature distribution (2)

ANSYS simulations (A. Ushakov)

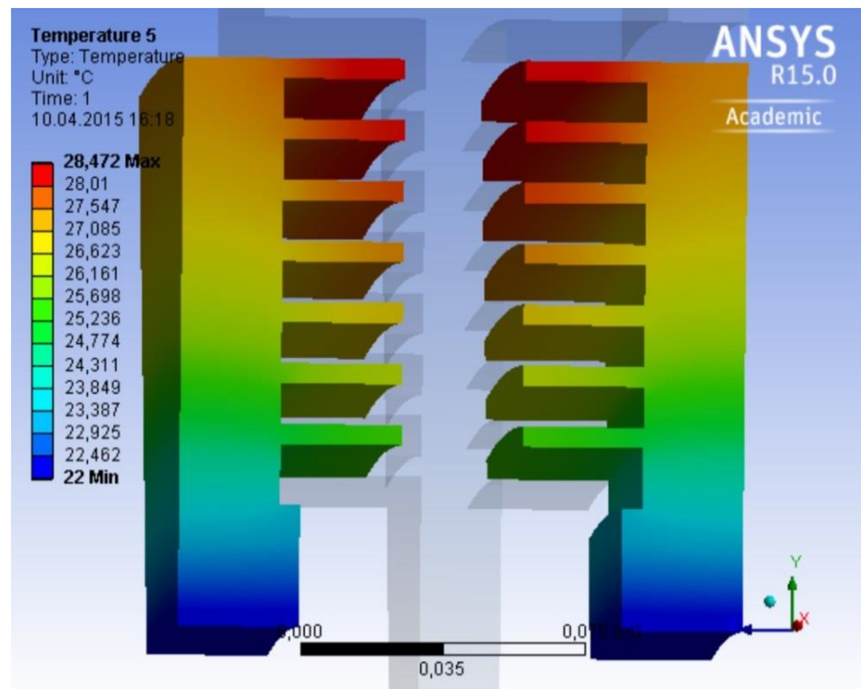
energy deposition of 5.17kW equally distributed over Ti6Al4V)

- emissivity of Ti-alloy = 0.25
- emissivity of copper alloy = 0.7

Cu Radiator



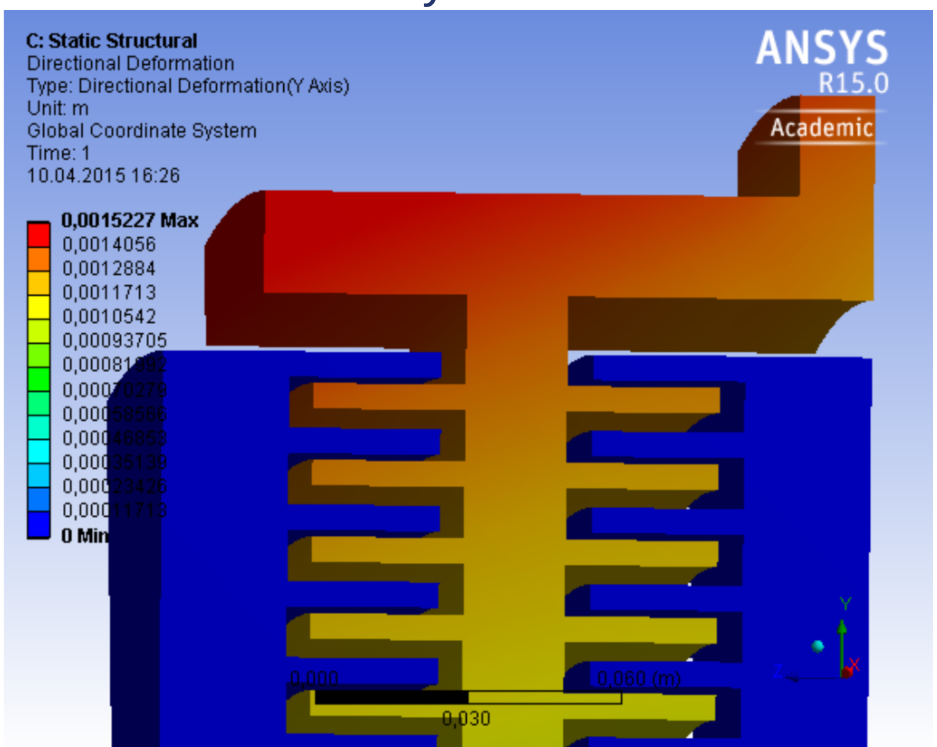
Cu Cooler



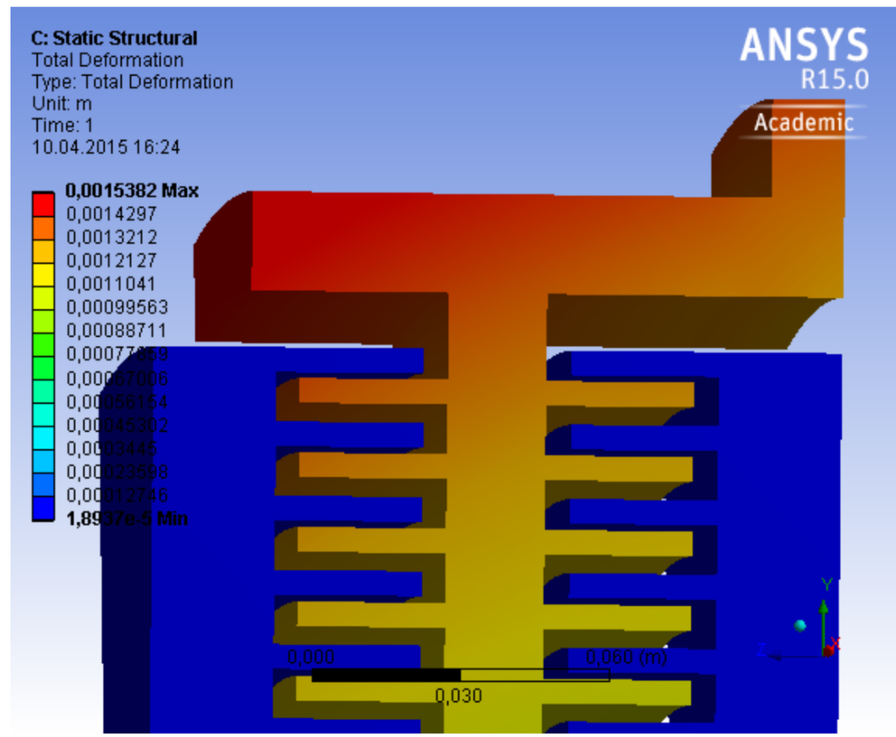
Thermal expansion

- So far, only stationary case considered (A. Ushakov)
  - Deformation in total: wheel radius increased by ~1.5mm
  - → Distance radiator – cooler must be designed carefully

deformation in y-direction

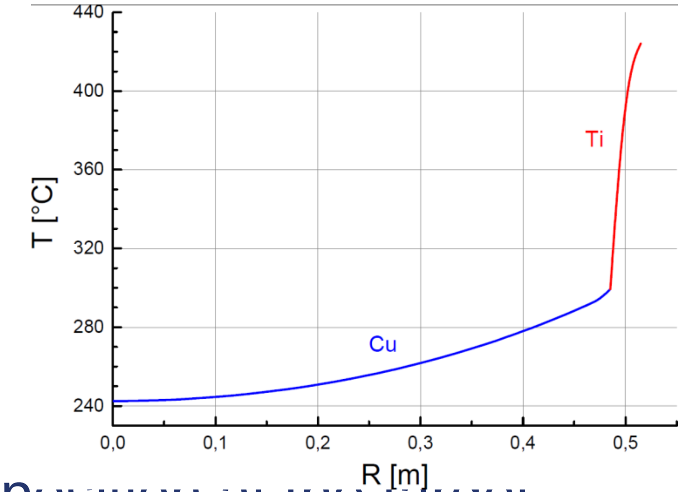


total deformation



Thermal Contact between Ti alloy target and radiator

Speed of heat transfer



- Heat transfer $$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c} \frac{\partial^2 T}{\partial x^2}$$
- Simple ansatz for estimation: $$x = \sqrt{\frac{\lambda t}{\rho c}}$$
- Photon beam hits after ~6-8s the same position at the target
- Thermal diffusion vs time:
  - x_{Ti} = 0.63 cm for 6s; 2cm for 60s
  - x_{Cu} = 2.6 cm for 6s; 8.3cm for 60s
  - 6s are not sufficient to remove the heat, temperature accumulates over O(10) bunch trains

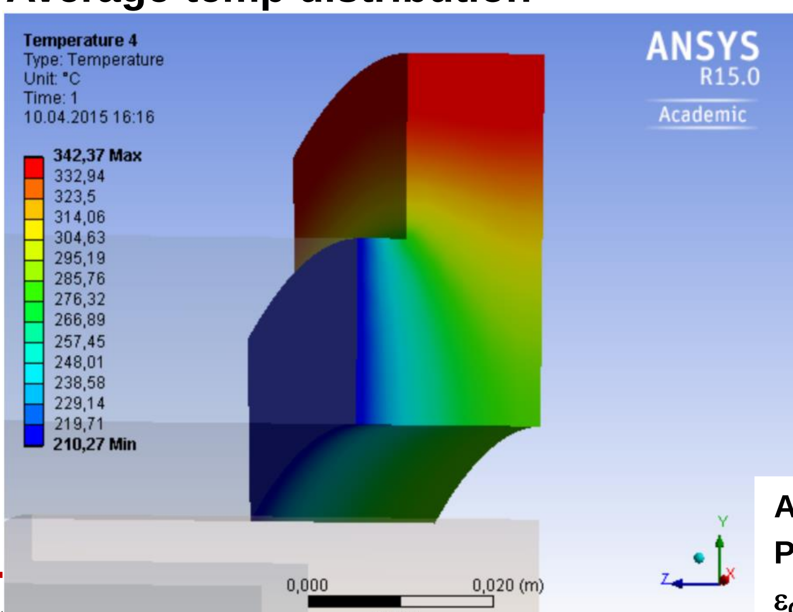
- To avoid too high heat accumulation in the Ti alloy, dimension of target rim should be as small as possible to reduce the time for the heat transfer to the radiator

Thermal Contact between Ti alloy target and radiator

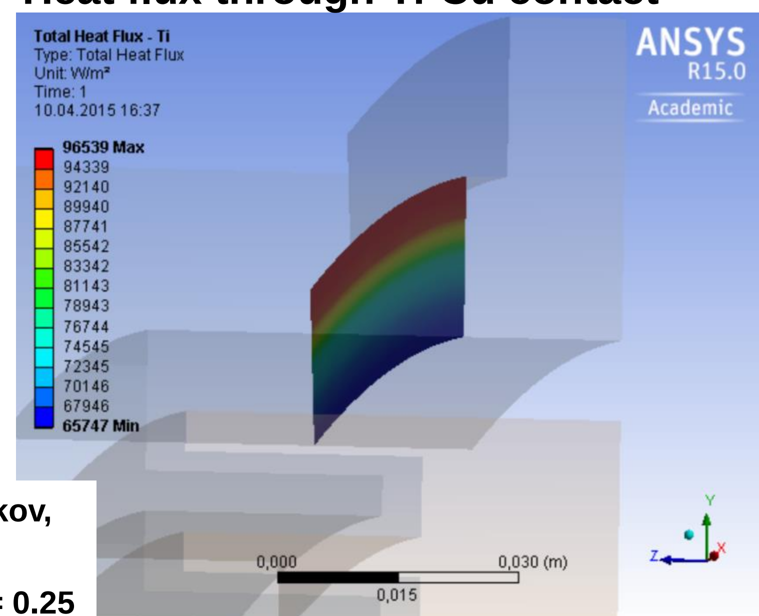
- Depends on surface roughness and contact pressure
- P. Sievers: clamp the Ti rim by spring-loaded bolts to Cu wheel
- Parameter estimate at the contact Ti - Cu radiator:
  - **Consider the area heated by one bunch train (hit every 6s):**
    - Power per bunch train: 7kW/5 = 1.4 kW
    - Surface of thermal contact (assumption): 10cm × 2cm = 20 cm^2

      → average heat transfer density Ti→Cu is 1400W/20cm^2 = 70W/cm^2 = 7000W/m^2
      (influence of thermal resistance not yet studied in detail)

Average temp distribution



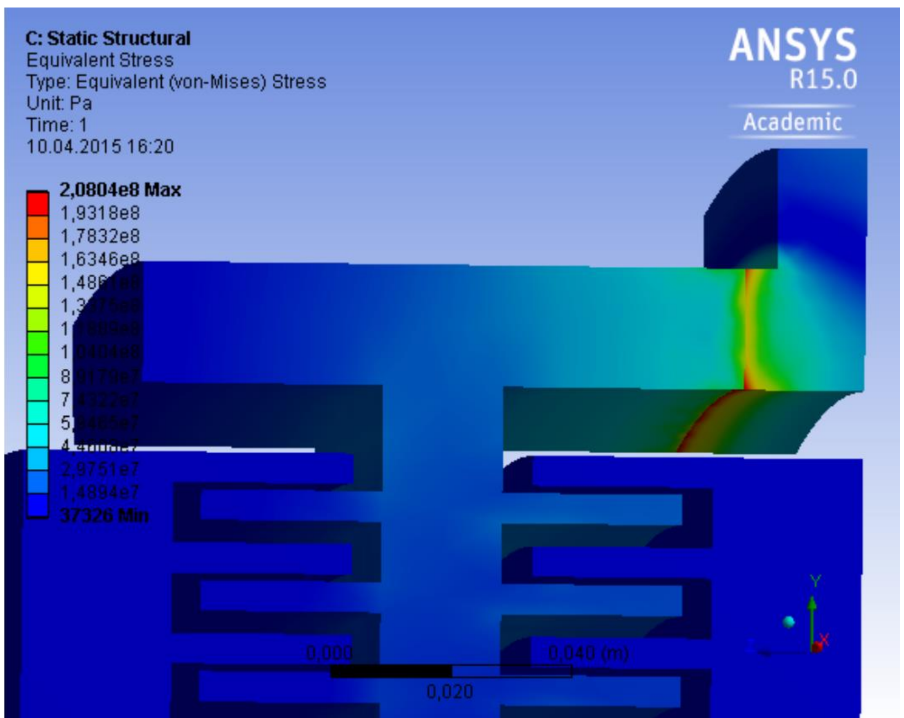
Heat flux through Ti-Cu contact



Andriy Ushakov,
P= 5170W,
ε_{Cu} = 0.7, ε_{Ti} = 0.25

Thermal stress at contact between Ti alloy target and radiator

- Average von Mises stress < 20MPa
  - Thermal contact is important
    - Different thermal expansion
    - Different E modulus, ….
  - Stress at bolted Ti – Cu contact is expected to be smaller than at brazed contacts
    → Tests required
  - Stress due to centrifugal force not considered here

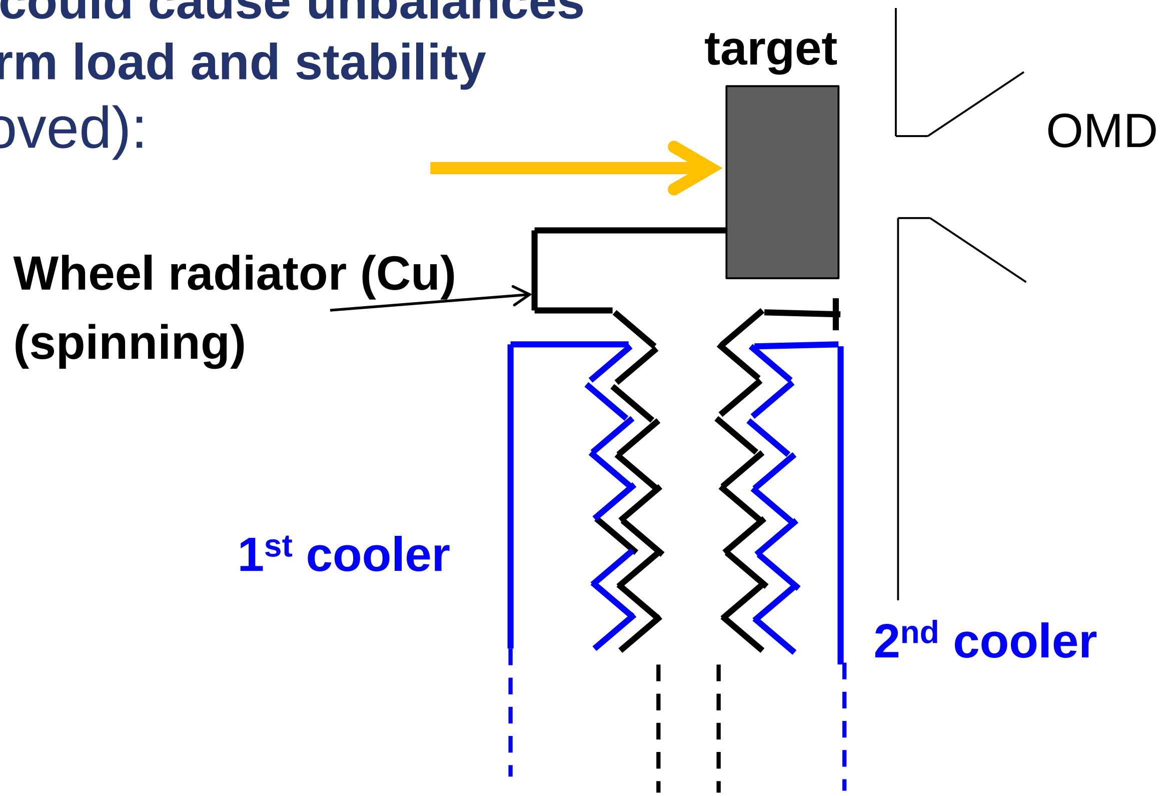


Andriy Ushakov,
P= 5170W,
$\varepsilon_{Cu} = 0.7$, $\varepsilon_{Ti} = 0.25$

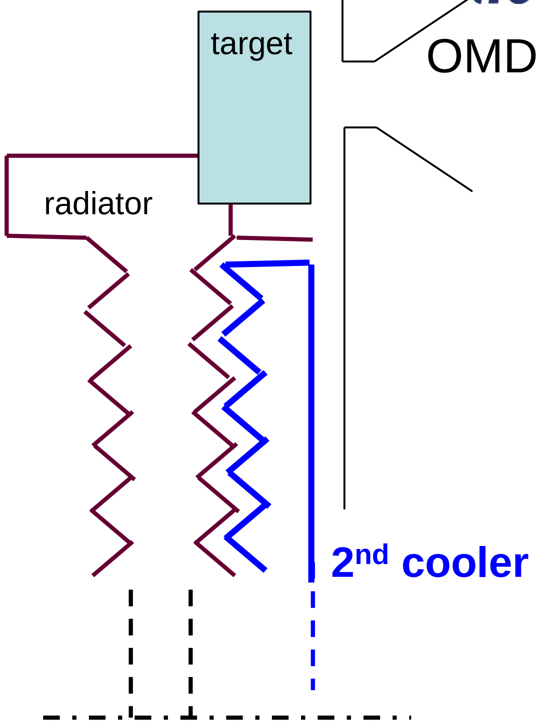
To be studied:
- Thermal and mechanical load
- Stress at the Ti-Cu contact
- degradation of heat contact

Design considerations

- First simulations started with Peter Sievers' design (see slides above)
- Spinning 1m wheel with cooling fins → stress in regions of radiator fins and target holder (heat load + centrifugal force)
  - **Deformations could cause unbalances**
  - **Check long-term load and stability**
- Idea (to be improved):



Mechanical issues



- The special shape causes stress in the region of the target holder (tangential force) → final design will take this into account
- Mass of the wheel (Cu radiator) ~100 kg
- Energy E stored in the wheel: (estimate: I~20kgm²)

$$E = \frac{I\omega^2}{2} \approx 0.5\text{MJ}$$

I = moment of inertia
ω = angular frequency

→ Respect safety rules

- stress (average) due to centrifugal force: $\sigma \approx \frac{1}{0.4} \cdot \frac{E \cdot \rho}{m}$ ~112 MPa

  (1/0.4 = formfactor for shape of flywheels)

- Alternative (lighter) radiator material? Al alloys?
- dimension of target holder along beam-direction determined by
  - **Space for 2nd cooler (in front of OMD) and target distance to OMD**
  - **Symmetry issues to avoid imbalances and too high stress**
  - **Has to be optimized**

Magnetic Bearings

(see POSIPOL14, LCWS14)

- Experience exists over 30 years for the use of magnetic bearings (see Peter Sievers' talk at POSIPOL2014)
- Industrial suppliers are SKF/Gemany/Calgary/Canada and KFZ/Juelich/Germany
- Loads above 100 kg with more than 7000 rpm are possible
- Temperatures of up to 300°C can be accepted by the bearings
- Active vibration control of the axis at the magnetic bearings is available
- Thermal barriers should be arranged to prevent heat flowing into the rotation axis
- Very precise velocity control is standard

Still to do

- Average temperature in target and cooling wheel looks ok

- Temperature evolution in the whole system to be considered
- Temperature distribution and stress at target
  - **Temperature ⇔ peak stress values**
  - **We will use ANSYS for stress simulations**
  - **Experimental test planned to test target material parameters after long-term irradiation load**

    → applied for grant from German Ministry of Science

- Degradation of Ti-target under cyclic thermal load and irradiation must be taken into account
  - **Thermal contact target – radiator after months of target operation**
  - **Heat transfer coefficient after irradiation**

- Stability of spinning wheel (target + radiator)
  - **Thermal expansion**
  - **Centrifugal forces,**
  - **Higher temperatures in the outer regions of the wheel (target, radiator & fins)**

→ Design (with help of engineers)

Vibrations and unbalances (first look)

- Vibrations at shaft and bearings
  - **Force due to unbalance: $F = m_{unbalance} \cdot r \cdot \omega^2$**
    - Unbalance due to deformation from cyclic bunch train is very small
  - **Eddy currents: only short incidence of ~1ms with 5Hz → ignored for the moment**
- 2-sided support of wheel shaft instead cantilever wheel (see Friedrich's talks 2013-14)
- Critical frequencies
  - **In general, eigen-frequency of the system is**

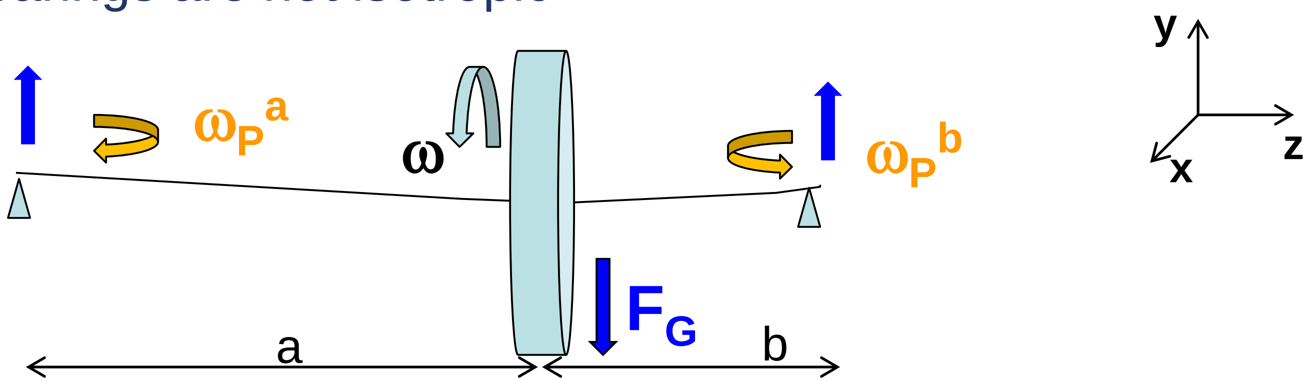
$$\omega = \sqrt{\frac{k}{m}}$$

k = stiffness
m = mass

  - **With increasing mass the eigen-frequency decreases**
  - **Avoid operation at and near eigen-frquencies (damage)**
    - 2000 rpm, ~100kg ⬄ $k \neq 4\times10^6$ N/m
- Forces at bearings are different in x,y,z direction (but coupled) ⬄ $\omega_x, \omega_y, \omega_z$

Forces and reaction forces at bearings

- Forces at bearings are not isotropic



$$\sum F_i = 0$$

- Forces and reaction forces:
  - Torque from spinning wheel: $\tau = I\, d\omega/dt$ (along ~z) ⇔ $\tau=0$ for constant rotation
  - Gravitation → $\tau_G = F_G \times r = mgr$ (along ~y) ⇔ $\tau_G \approx 300N$ (r=0.3m)
  - Precession, $\omega_P = mga / (I\omega)$ (along ~x) ⇔ ≈0.15/s (a=0.3m)
  - Eddy currents

- Forces at bearings and potential sources of unbalances have to be considered in the design phase
  - Studies to be performed with ANSYS

Further issus:

(see P. Sievers, POSIPOL14, LCWS14)

- vacuum
  - **Outgassing must be checked (temperatures of 300°C possible) , and if required, differential pumping should be applied**
  - **Baking procedures are standard**

- monitoring of temperatures
  - **Contactless temperature infrared sensors**
    - Wheel temperature ⇔ sensors placed inside the vacuum close to the rotating wheel
    - Temperature of rotating parts of magnetic bearing and motor

- vibration sensors

Summary

- Radiative cooling is a very promising option, no showstopper identified
- Scheme is under study
  - **Ultimate temperature distribution in the wheel**
  - **Design of the radiator and cooler**
  - **Issues to be looked in detail:**
    - speed of heat transfer
    - Thermal contact Ti alloy → radiator material
    - Overall design for effective cooling ⇔ weight of radiator wheel, stress, imbalances
    - Emissivity of radiator and cooler surface including potential degradation
  - **Alternative target material with higher heat transfer coefficient?**
  - **Alternative radiator material (Al alloy) with lower weight?**
- Desired: design an experimental mock up in real size which could serve as a systems test of the whole unit

  → verification of temperature regime and cooling efficiency

  → optimal target + cooling design
- Resources
  - **Manpower:**
    - Felix Dietrich (master student, until autumn 2016),
    - Andriy Ushakov (contract until June 2015),
    - SR., + Peter Sievers

Resources

First estimates (POSIPOL14)

	k€
Vacuum tank, design + manufacture	170
Wheel design + manufacture	230
Coolers	80
Magn. bearings and motor	170
Instrumentation plus electronics and control	80
Pumps for differential pumping	80
Infrastructure, lab space, safety	70
Dummy run with heaters of rim and water cooling	70
Total	950

Resources (manpower)

Estimate at POSIPOL 2014

	FTE
Initial performance studies (ANSYS, modelling,...)	0.5
Physicist, engineers, designers	3.0
Technicians for assembly, commissioning and test	2.0
total	5.5