LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

Status: Cooling of the ILC e+ target by thermal radiation

LCWS 2015, Whistler, Canada

3rd November 2015

Felix Dietrich (DESY), Sabine Riemann (DESY),
Peter Sievers (CERN), Andriy Ushakov (Hamburg U)

Outline

- Radiative thermal cooling of e+ target
- Status
  - **Target temperature distribution**
  - **Design considerations**
    - mechanical issues
  - **Our next steps**
- Summary

e+ target for E_{cm} = 250 … 500GeV

E_{cm} and luminosity determine energy depsited in target

($P_{e+} \leq 30\%$)

E_{beam} [GeV]		E_{dep} [kW]	ΔT_{max}/pulse [K]	E_{dep} [kW]	ΔT_{max}/pulse [K]
		Nominal luminosity		High luminosity	
120	A. Ushakov, 2015	5.0	66	-	-
175	(ILC EDMS)	3.9	125	-	-
250	(ILC EDMS)	2.0	130	4.1	195
250	A. Ushakov, Update 2015	2.3	85	4.6	165

Target wheel design appropriate for all E_{cm} ?

- radiative surface A sufficient to remove deposited energies W for all E_{cm}?

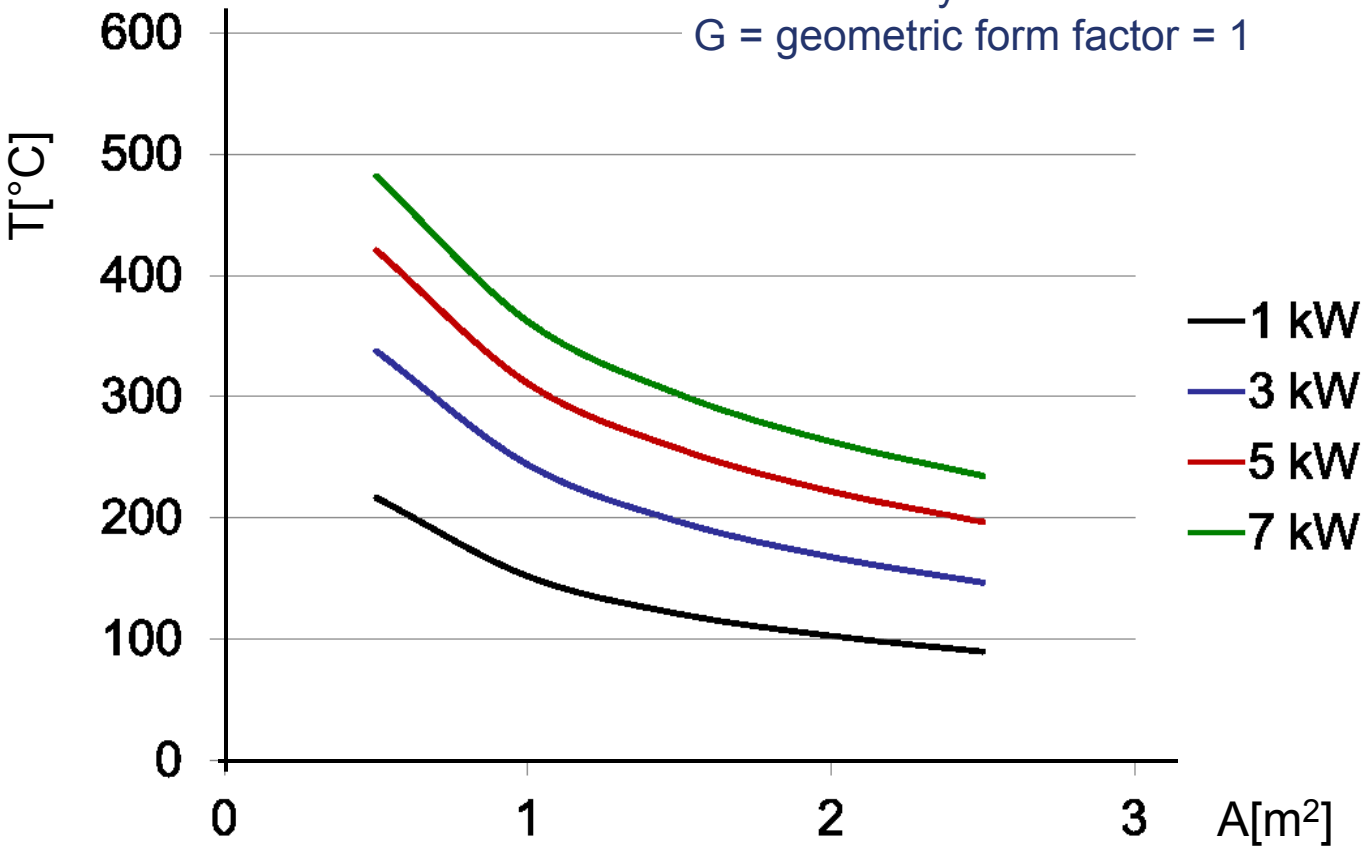
$$P \sim \sigma \varepsilon A \left(T_{radiator}^4 - T_{cool}^4 \right)$$

- Thermal contact Ti-Cu radiator is important

Area A of thermal radiation

$$P = \dot{Q} = \sigma \varepsilon G A \left(T_{radiator}^4 - T_{cool}^4 \right)$$

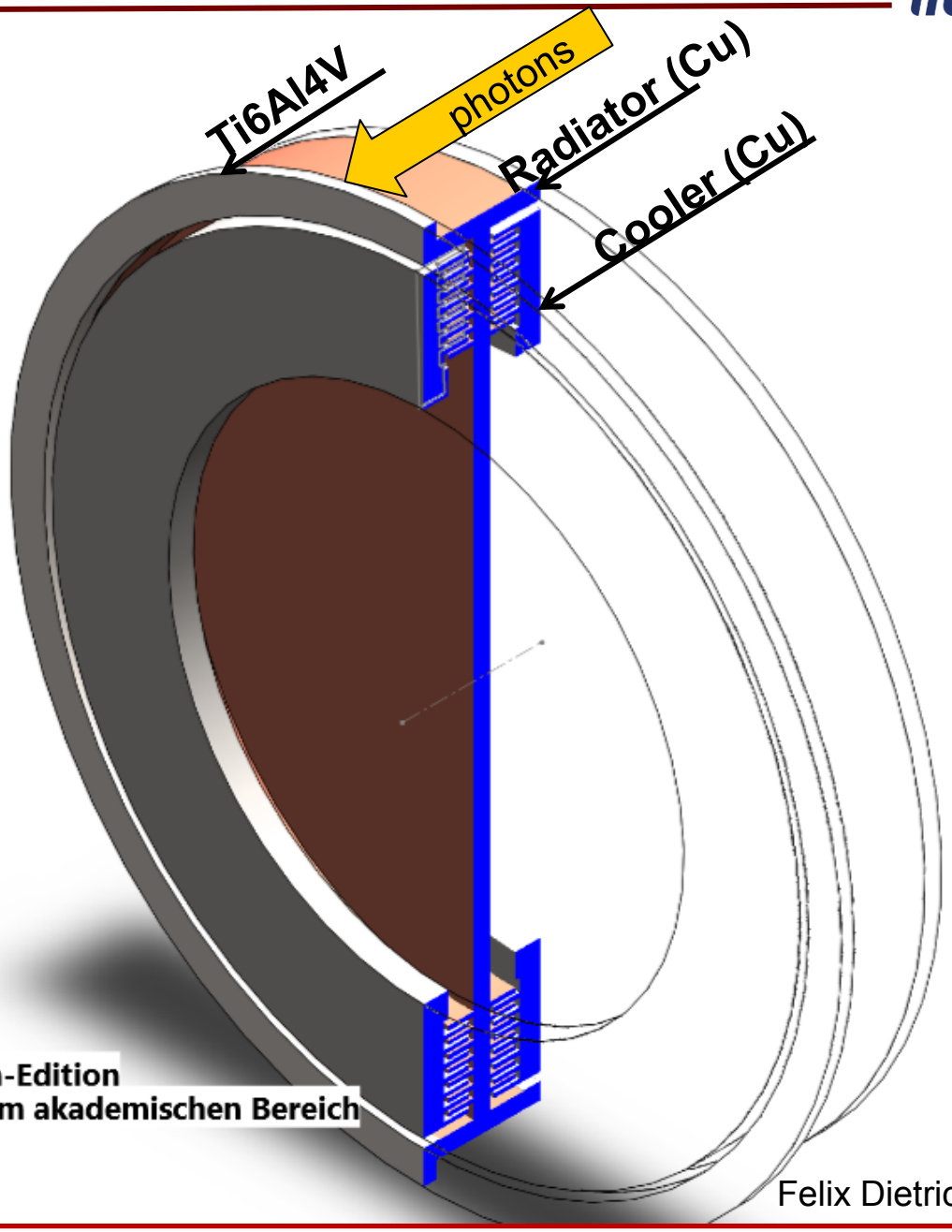
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/(m^{2}K^4)
ε = emissivity = 0.7
G = geometric form factor = 1



Target wheel
r = 0.5m
Simple full disk
→ 1.6m^2

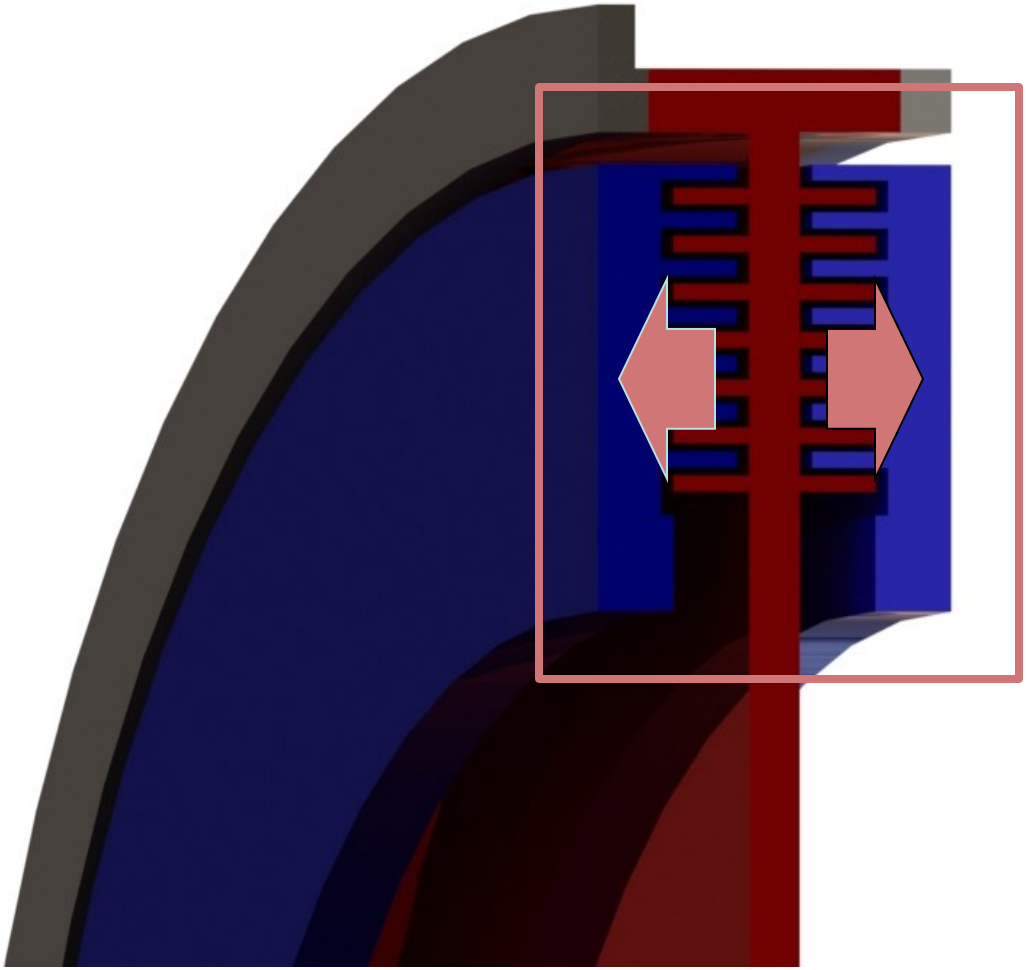
Radiative cooling – considered so far

- e+ target located very close to the optical matching device
- Rotating target wheel consists of Ti rim (e+ target) and Cu (radiator)
- Heat path:
  - **thermal conduction Ti → Cu wheel**
  - **Thermal radiation from Cu to stationary water cooled coolers**
- Target, radiator and cooler are in vacuum
- Cooling area can be easily increased by additional fins
- Target position must be close to OMD



Felix Dietrich

So far, Felix considered a cooling area of 2.8 m^2 near the target created by 2×7 fins (length of fin is 3cm, height 0.5cm)



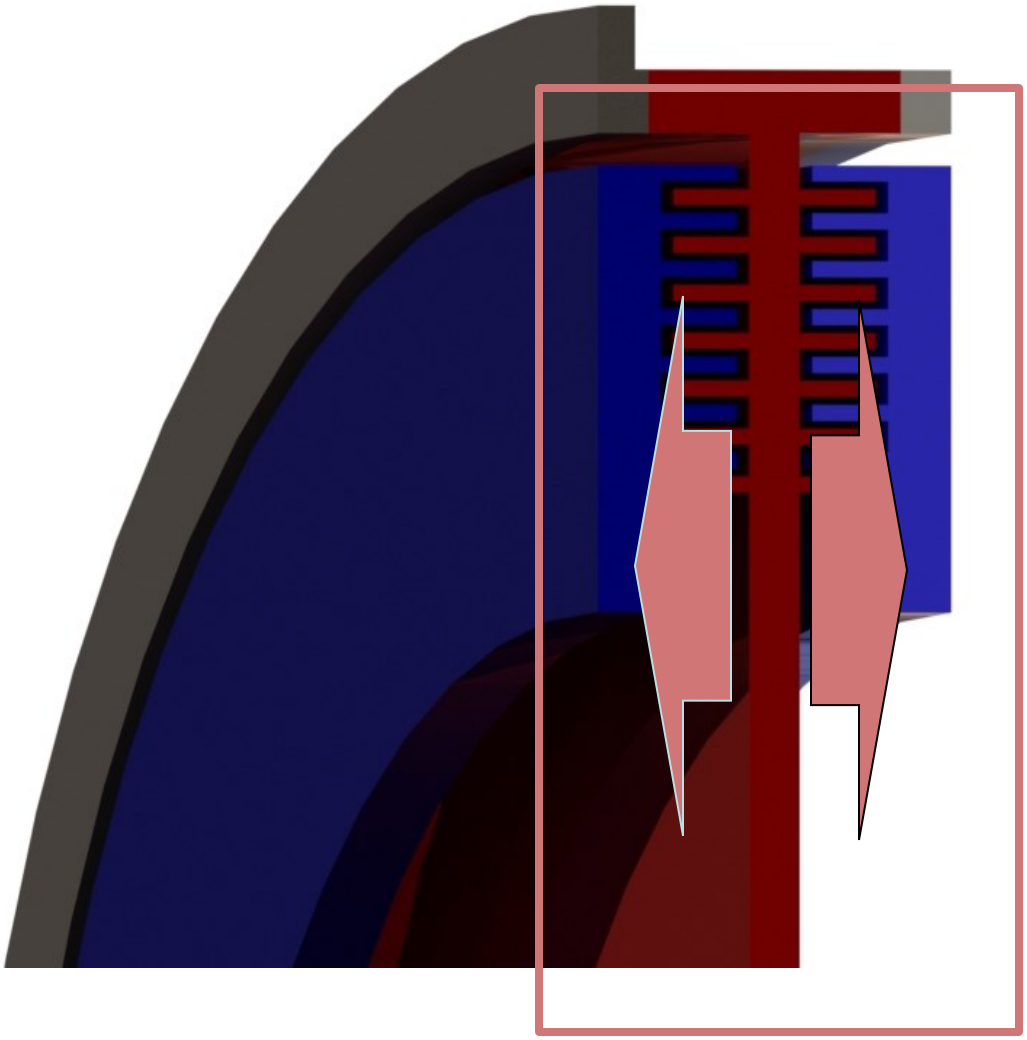
So far, Felix considered a cooling area of 2.8 m^2 near the target created by 2×7 fins (length of fin is 3cm, height 0.5cm)

→ Including almost full disc in radiative cooling, max temperature in target decreases

Max average temperature in target goes down with area:

$$\frac{\Delta T}{T} = \frac{1}{4}\frac{\Delta A}{A}$$

Design (fins) must be optimized to avoid mechanical problems/stress at high rotation speed

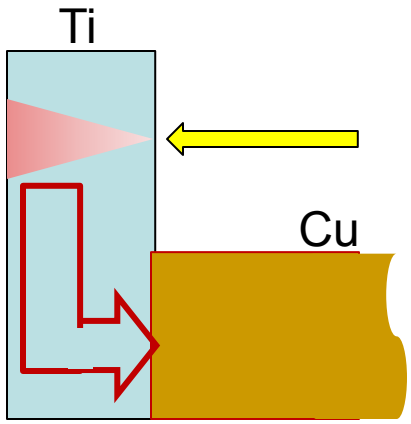


Design issues

- Temperature distrubution
  - **Heat transfer from target to radiator**
    - Titanium has a low heat conductivity
  - **maximum and average temperatures in Ti**
  - **Ti-Cu contact**

- Stress
  - **Stress in Ti target rim**
  - **thermal expansion of Ti, Cu**
  - **Optimum design of radiator**

Heat transfer in the target



Temperature distribution in target depends on
- **deposited energy**
- **Target parameters (material, size,..)**
- **PEDD ⇔ ΔT_{max} = 120K / 200K** (nominal / high lumi)

- Speed of heat transfer
  - **determines**
    - Average temperature in target
    - time until equilibrium temperature is reached
  - **Depends on thermal conductivity λ:** $x = \sqrt{\lambda t / \rho c}$
- Ti target
  - **Photon beam hits after ~7seconds the same position at the target**
  - **Thermal diffusion vs time:**
    - x_{Ti} = 0.68 cm for 7s; 2.2 cm for 70s
    - x_{Cu} = 2.8 cm for 7s; 9.0 cm for 70s
  - **7s are not sufficient to remove the heat from target**
  - **temperature accumulates over many bunch trains up to equilibrium**

→ Temperature gradient from beam path area to contact surface to radiator

Heat flux through Ti-Cu contact

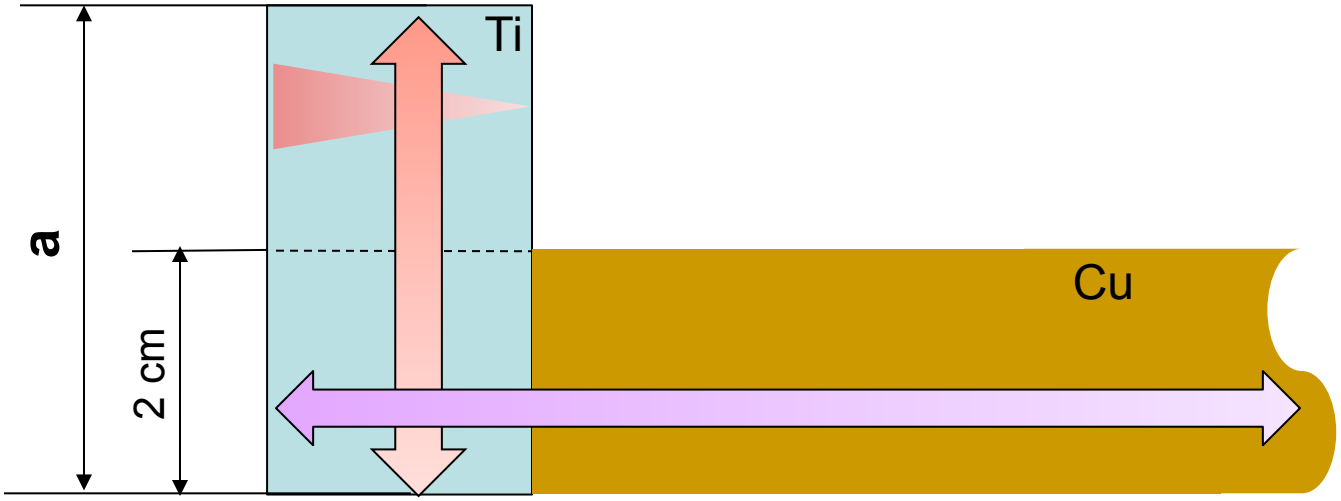
Consider 2 options:

(see also Felix Dietrich's talk at POSIPOL 2015)

1. a = 5cm
2. a = 4cm

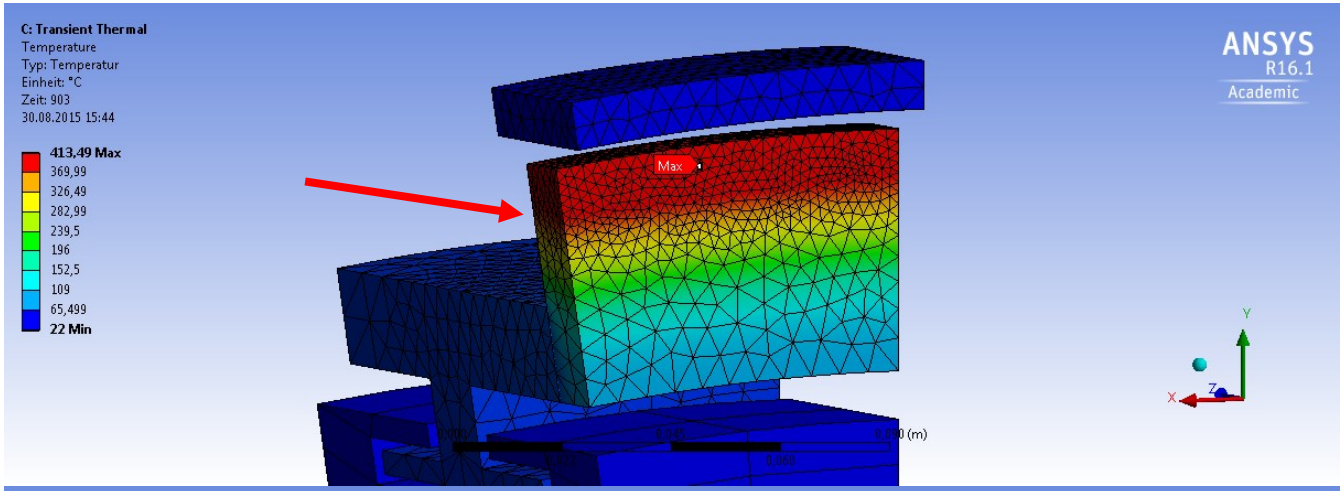
➔ Temperature distribution along the target

➔ Temperature distribution along Ti – Cu contact



Temperature distribution in the target after 903s

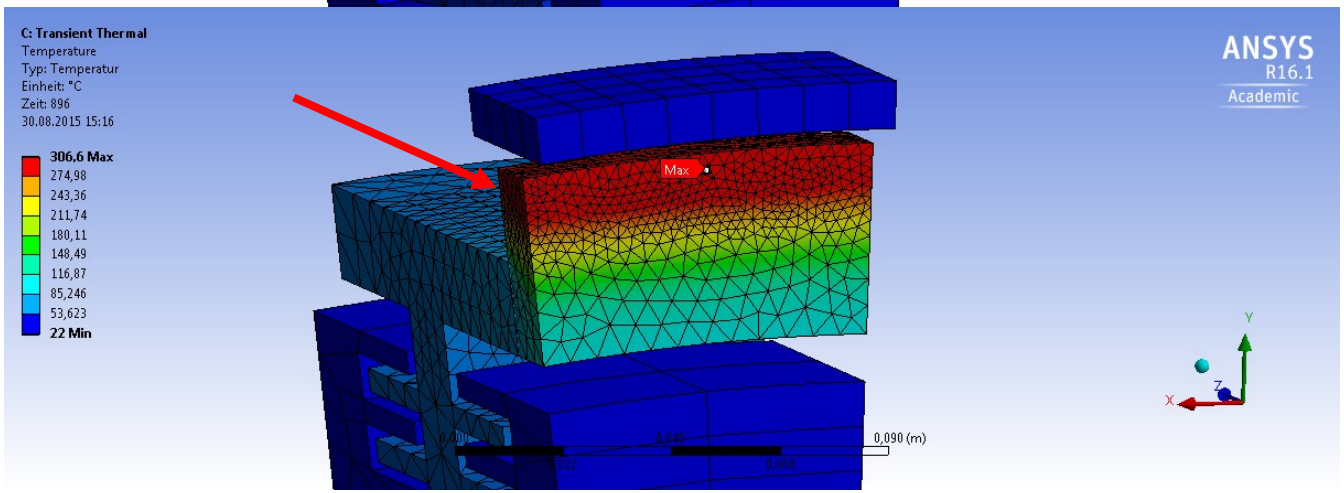
(128 bunch trains hit the same target area, shortly before 129th)



Target height

a = 5cm

T_{max} = 414°C



Target height

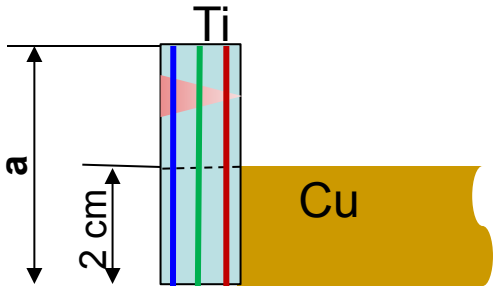
a = 4cm

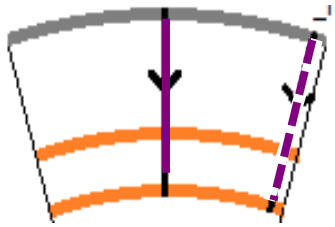
T_{max} = 307°C

Heat distribution in Ti target

Consider 2 options (see also Felix Dietrich's talk at POSIPOL 2015)

1. a = 5cm
2. a = 4cm

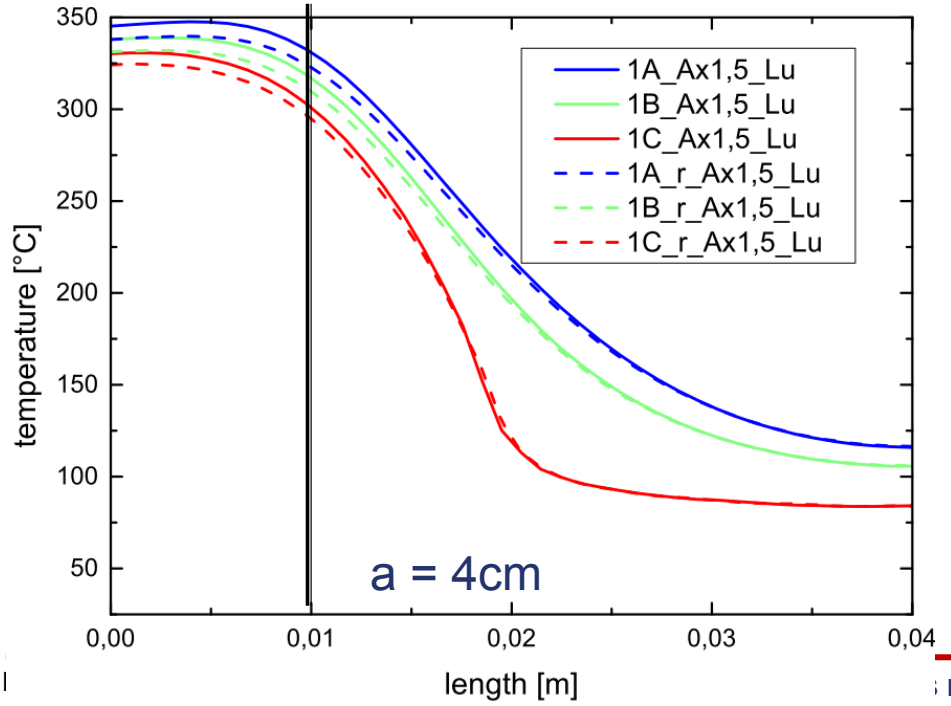


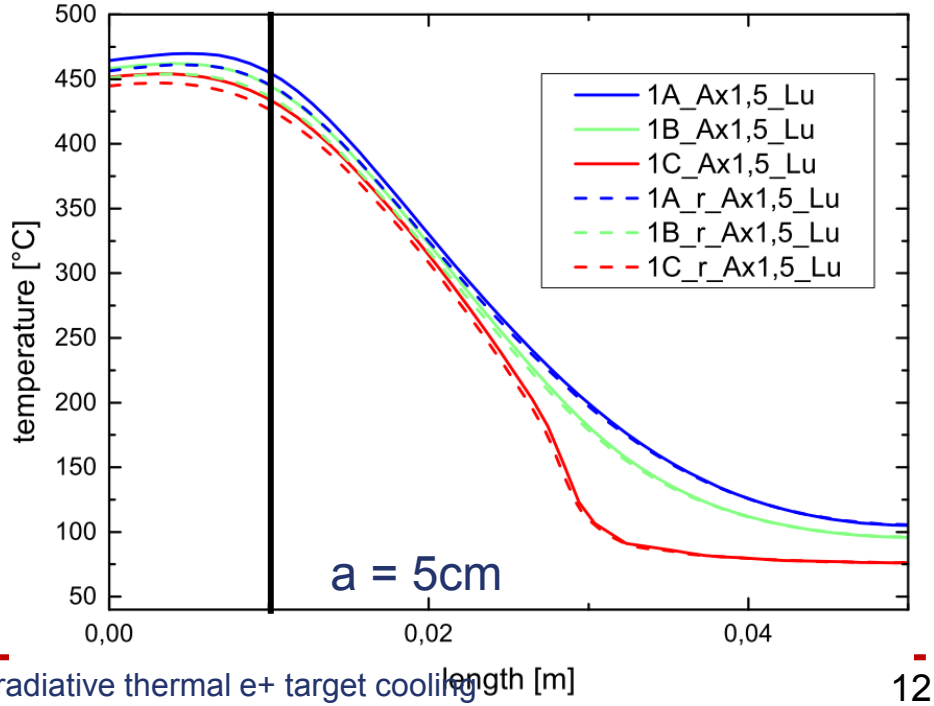


Temp along the target (896s)

128 pulses at same target area

$P = 2.3$ kW, $\varepsilon_{Cu} = \varepsilon_{Ti} = 0.7$

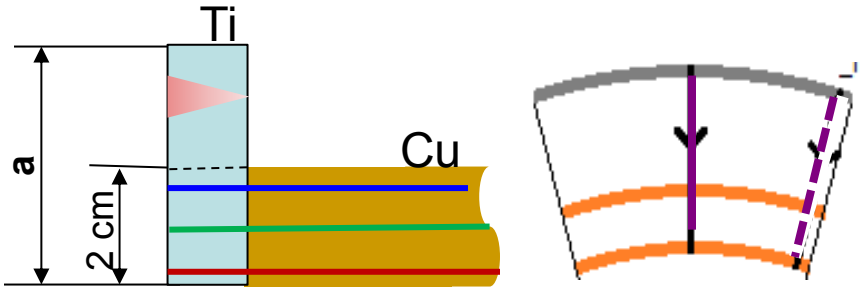




Heat distribution along Ti-Cu contact

Consider 2 options (see also Felix Dietrich's talk at POSIPOL 2015)

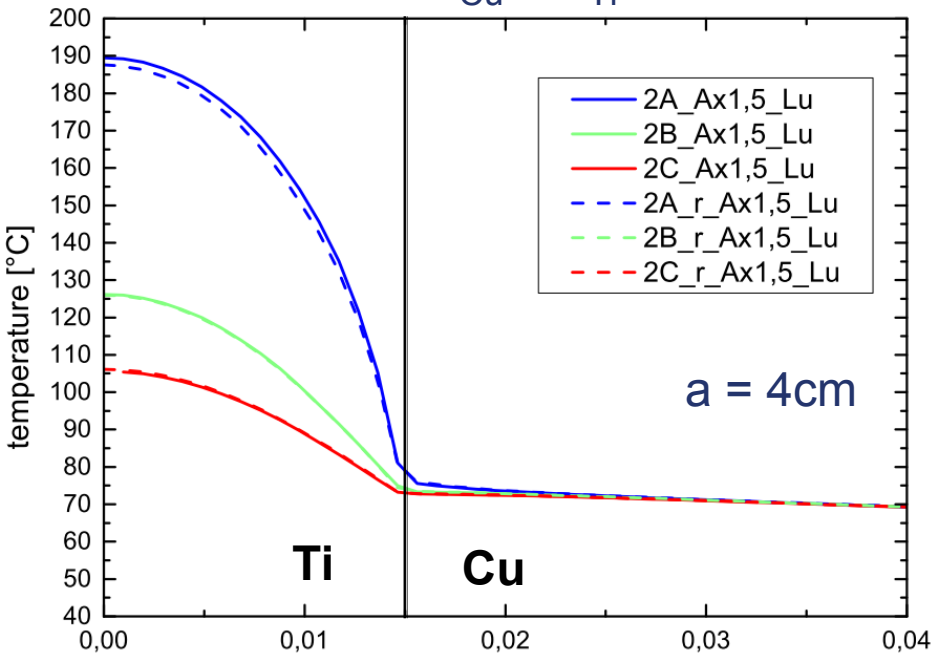
1. a = 5cm
2. a = 4cm

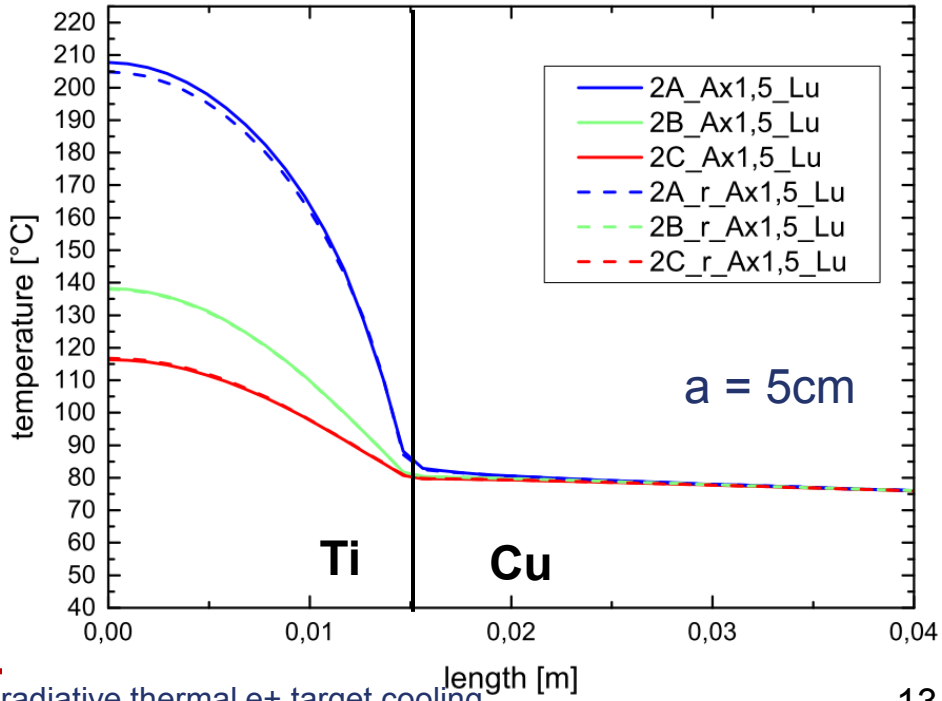


Temp along Ti-Cu contact (896s)

128 pulses at same target area

P = 2.3 kW, $\varepsilon_{Cu} = \varepsilon_{Ti} = 0.7$

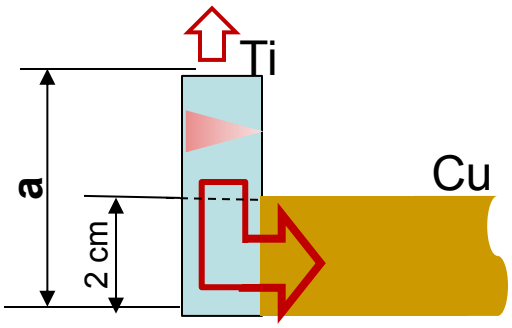




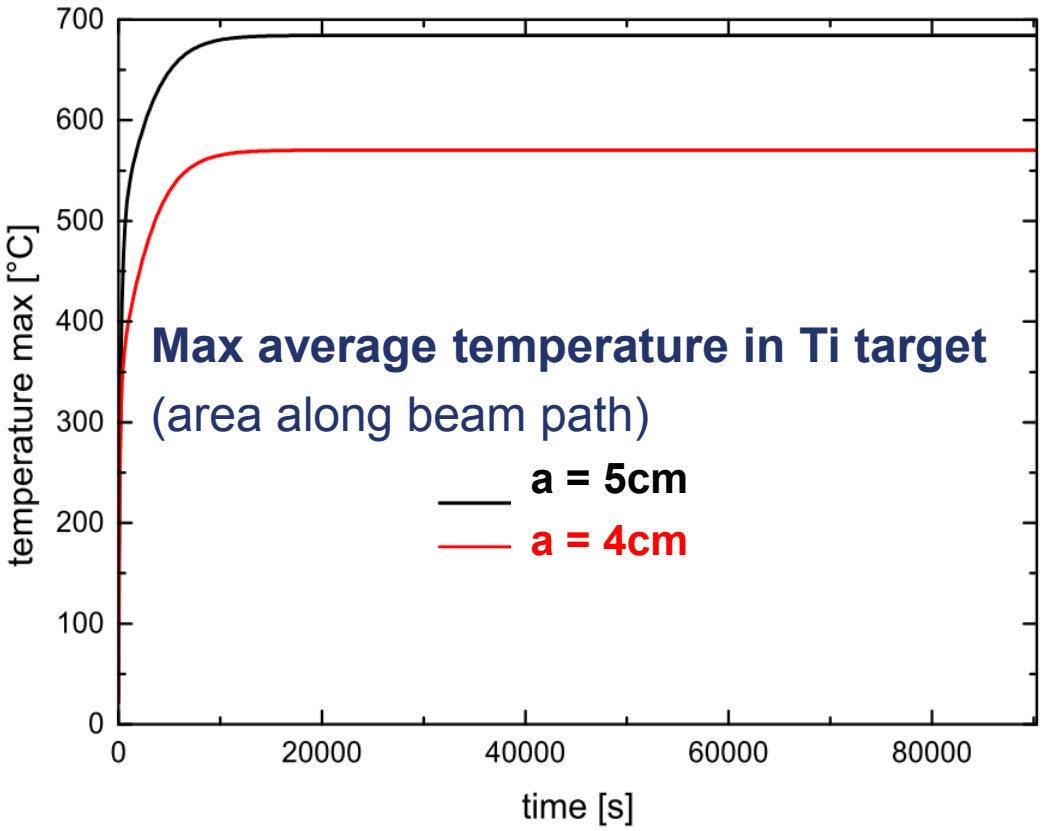
Equilibrium temperature in the target

Temperature evolution over time, ANSYS

- E_{cm} = 500GeV; E_{dep} = 2.3 kW
- Radiator area ~2.8 m^2



Felix Dietrich



- After ~3 hours equilibrium temperature distribution reached
- height a ⇔ max temperature
  - **T_{max} ≈ 680°C (a = 5cm)**
  - **T_{max} ≈ 570°C (a = 4cm)**

→ **Distance beam path to Ti-Cu contact is important**

- Temperature in Cu (near Ti) ≈280°C (a = 5cm), ≈270°C (a = 4cm)

Temperature distribution at the target rim

- adjust revolution frequency to distribute energy deposition almost uniformly over rim
- for example:
  - bunch train occupies angular range θ_{pulse}
  - f_{rev} = 1922rpm instead of 2000rpm

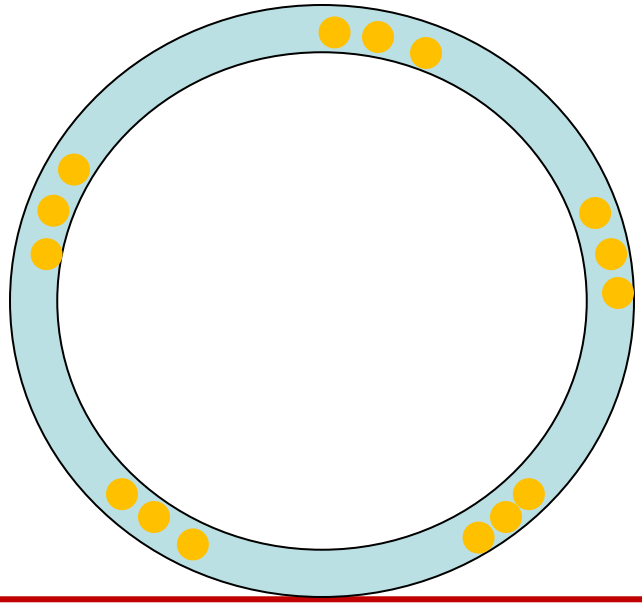
→ pattern: **1st second: 0, 144, 288, 72, 216,**

2nd second: $0 + \theta_{pulse}$ ….,

3rd second: $0 + 2\theta_{pulse}$ ….

→ after ~7s the rim is almost uniformly heated

→ unbalances due to non-uniform heating are avoided



Lower rotation speed?

- F. Staufenbiel et al.: assuming water cooling channels, 1500rpm or even 1000rpm seems possible in case of nominal luminosity @E_{cm}=500GeV
- Radiative cooling is slower due to λ value and longer heat transfer distances → even higher average temperature in the rim for lower rotation speed

→ spinning with about 2000rpm for radiation cooling

- M. Jenkins @ POSIPOL15 considered realistic undulator. Peak intensity of photon beam may be lower; this could help → studies needed

Stress consideration in Ti rim

- Thermal due to energy deposition in Ti rim
  - **Cyclic load from photon beam: $\sigma \sim 250$MPa**
  - **Thermal stress**
    - **ANSYS simulations (A. Ushakov): $\sigma_{thermal} \approx$ 10 - 20MPa**
- Stress due to centrifugal force:
  - **Hoop stress in thin ring: $\sigma_H \approx \rho\, \omega^2\, r^2 = 50$MPa**

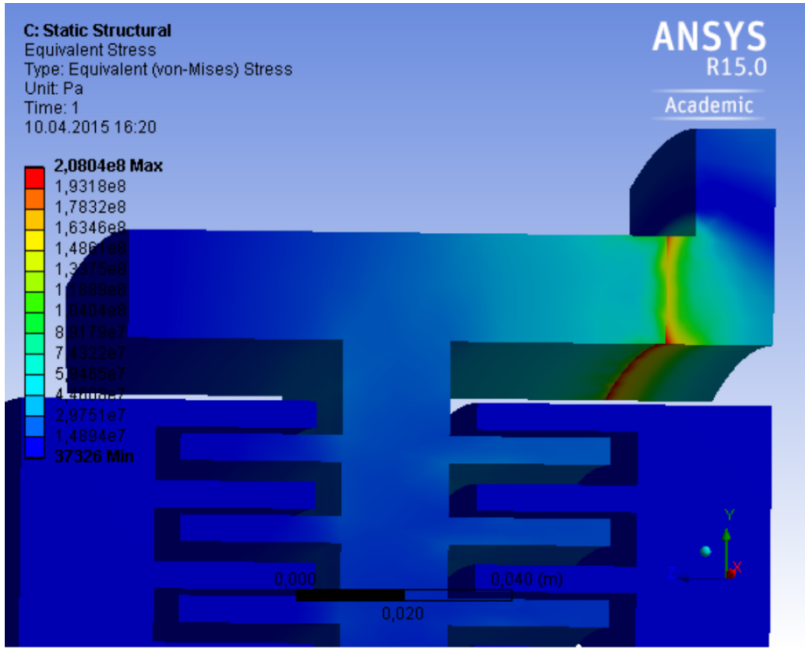
- Properties of Ti alloy:
  - **Tensile yield strength: 880MPa**
  - **Compressive yield strength: 970MPa**
  - **Elongation at break: 14%**
- fatigue strength at 10^7 load cycles: 510MPa (unnotched)
  - **This value is based only mechanical load. Material modification due to irradiation and heating are not taken into account**
  - **Degradation of heated Ti alloy due to cyclic load should be tested**

Stress at Ti-Cu contact

- Thermal expansion and resulting distortion ⇔ stress at the Ti-Cu contact depends on temperature profile in radiator and target

  $\alpha_{Ti} = 8.6 \times 10^{-6}/K$ $\alpha_{Cu} = 16.5 \times 10^{-6}/K$

  - **Max temperature in Ti wheel ~500°C → Δh ~ 0.43% (0.2mm)**
  - **Max temperature in Cu radiator (near Ti-Cu contact) is ~200°C → Δr ~ 0.33% (≤1mm)**



ANSYS simulation (prel.) by A. Ushakov:

assumed brazed Ti-Cu contact

P= 5170W,

$\varepsilon_{Cu} = 0.7$, $\varepsilon_{Ti} = 0.25$ → v.Mises stress < 200MPa

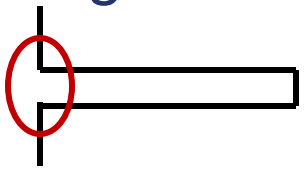
P. Sievers: bolting at 10 MPa could allow frictionless, lateral thermal expansion maintaining the thermal contact

→ bolting is ok, brazing is not ok

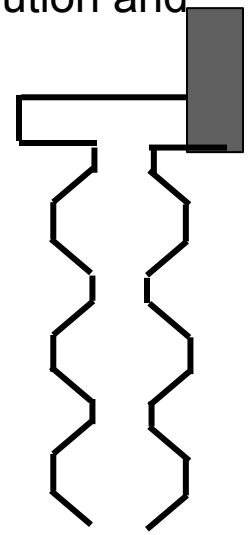
Still to be done: implement 'real' contact in ANSYS simulations.

Radiator: Mechanical aspects and stress

- Mass of the wheel (Cu radiator) ~100 kg
  - **For comparison: 1.5cm thick Ti disk ~55kg**
- Energy E stored in the wheel O(0.5MJ)
- Stress at the (long) radiator fins due to centrifugal force
  - **mass of one fin (3cm long): ≈3kg**
  - **Hoop stress in fins: : $\sigma_H = \rho\,\omega^2\,r^2 \approx 80\text{MPa}$**
  - **Stress at fin – disc connection**
    - Not yet considered: deformation of fins due to thermal distribution and centrifugal force



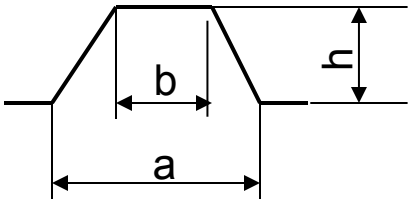
- Under study: fins with trapezoidal shape
  - **Performance concerning cooling parameters**
  - **Stress in radiator**



- Distribution, number and shape of fins is decisive for cooling power
- Design with long outer fins is not the optimum concerning mechanical properties of the spinning wheel
- Example: distribute n fins (trapezoidal shape) on radiator disk

  ⇔ area for radiation cooling,
  mass of all fins
  → temperature distribution in target,
  mech. issues, …

n	Trapez a/b/h [cm]	A [m2]	$M_{all\ Fins}$ [kg]
12	2.15 / 0.42 / 1.5	2.1	30.3
16	1.3 / 0.4 / 1.5	2.6	38.4
18	1.04 / 0.27 / 1.0	2.3	28.5



- In principle, Ti keeps its stability in the temperature range 200 - 635°C (http://form-technik.biz/titan-material-eigenschaften/)
- Stability of Cu decreases with temperature, but this shouldn't be a problem for T ~ 200 and choice of special alloy
  - **Permanent stress due to tangential force ⇔ creeping effects ? → to be checked**
- Thermal expansion ⇔ slightly changed momentum of inertia → wheel slows down slightly if no correction
- Non-uniform average temperatures, deformations around the wheel → unbalances
  - **All unbalances have to be monitored and corrected; has to be discussed with engineers**
- Long term material degradation due to irradiation must be tested experimentally
  - **Target material tests**
    - German Ministry of Science supports work for intense sources; period: July 2015 – 2019 (manpower), collaboration of U HH, U Mainz, U Darmstadt and DESY
    - Simulation of cyclic load at Mainz using e- beam (MAMI, later MESA facility)
    - Collaboration with Mainz U and Darmstadt U

Our next steps @ DESY/ U Hamburg

- Temperature evolution in the whole system (including optimized shape of fins)
- stress at the target + radiator wheel
- optimize system to be flexible for all energies and luminosities
  - **Thermal contact target-radiator**
  - **Aspects important for magnetic bearings (forces, imbalances,…)**
  - **Figure out safety factors for long-term operation**

- Material tests in collaboration with U Mainz

Summary

- Radiative cooling will work, no showstopper identified
  - see also POSIPOL15
- Scheme is under study & optimization
  - **Prototyping:**
    - Desired: design an experimental mock up in real size
    - DESY/Uni HH: no hardware resources
      - Experience of ANL/China R&D is very helpful
  - **Material tests at Mainz (e- beam)**
- Also important and has to be done: polarization issues
  - **Upgrade to higher polarization: photon collimation**
  - **Realistic undulator B field (→ PEDD in target, polarization)**
- Our Resources at DESY and Uni HH are unchanged since POSIPOL15
- Ideas and support are highly welcome

Thank you!