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

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POSIPOL 2016 Workshop

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- Physics Applications of polarized positrons
- High intensity positron sources
- Energy deposition densities in targets : thermal shocks
- Channeling radiation and applications
- Physics applications of X-rays and γ rays

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Outline

- Status
  - Radiative thermal cooling of e+ target
  - temperature distribution
  - Design considerations – update
- Summary

e+ target for E_{cm} = 250 … 500GeV

E_{cm} and luminosity determine energy deposition in target

Ø = 1m; 2000rpm, 0.4X0 Ti6Al4V (P_{e+} ≤30%)

E_{beam} [GeV]	E_{dep} [kW]	ΔT_{max}/pulse [K]	dpa	E_{dep} [kW]	ΔT_{max}/pulse [K]
	Nominal luminosity			High luminosity	
120 **A. Ushakov, 2015**	**5.0**	66	0.035	-	-
175 **(ILC EDMS)**	**3.9**	125	0.06	-	-
250 **(ILC EDMS)**	2.0	130		**4.1**	**195**
250 **A. Ushakov, Update 2015**	2.3	85	0.05	**4.6**	**128**

E_{dep} ≤ 7kW → cooling by thermal radiation is an option

Polarization upgrade:

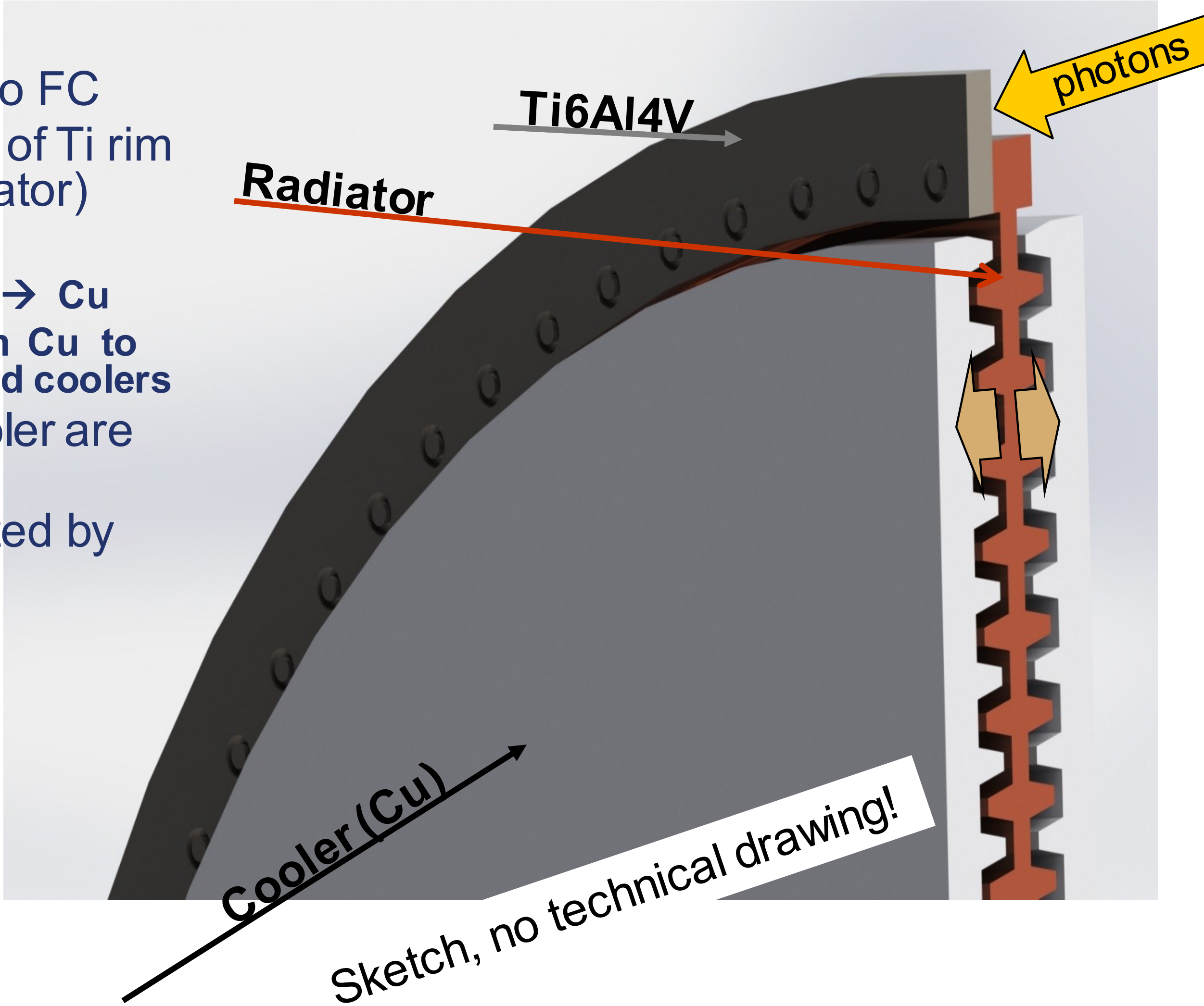
- higher peak load ⇔ higher peak temperatures
- higher average temp in target

Radiative cooling model so far

- e+ target located close to FC
- Rotating wheel consists of Ti rim (e+ target) and Cu (radiator)
- Heat path:
  - **thermal conduction Ti → Cu**
  - **Thermal radiation from Cu to stationary water cooled coolers**
- Target, radiator and cooler are in vacuum
- Radiating area is adjusted by fins

Goal:
keep target temperature below limit for failure of Ti6Al4V

Reliable fatigue limit at elevated temperatures?



Felix Dietrich

Temperature development in target (+radiator)

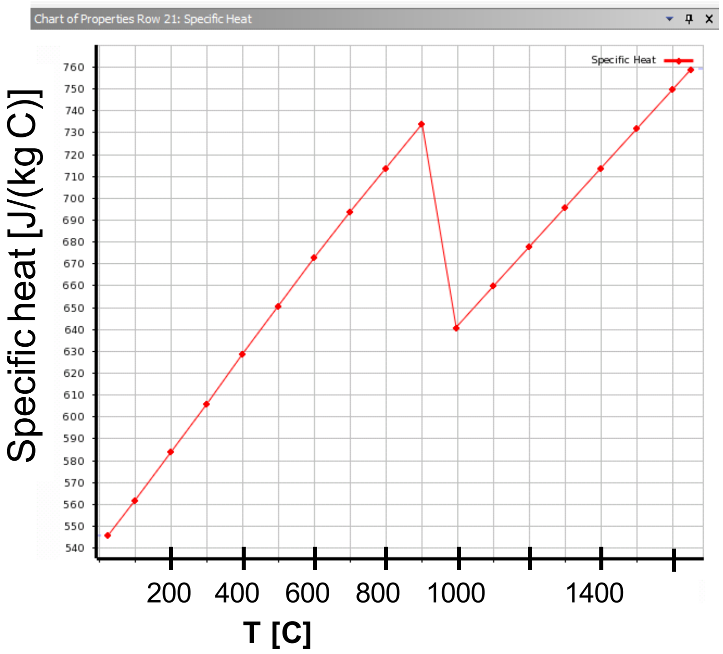
$$\frac{dQ}{dt} = mc\frac{dT}{dt} + \lambda A_{Ti-Cu}\frac{dT}{ds} + \sigma\varepsilon A_{rad}\left(T^4_{target} - T^4_{cool}\right)$$

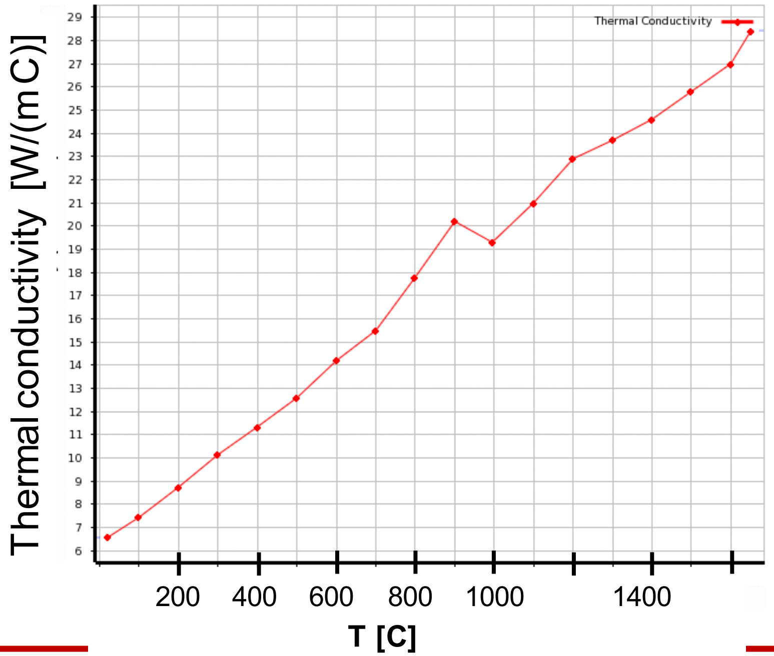
Heating due to energy deposition

Thermal conduction through material

Radiation from surfaces

- FEM to calculate temperature evolution in real model; here ‘estimation by hand’
- Material parameters c, λ, ε depend on temperature and long-term load





K.C. Mills, 2002, Recommended Values of Thermophysical Properties For Selected Commercial Alloys, p. 217, referenced by J. Yang

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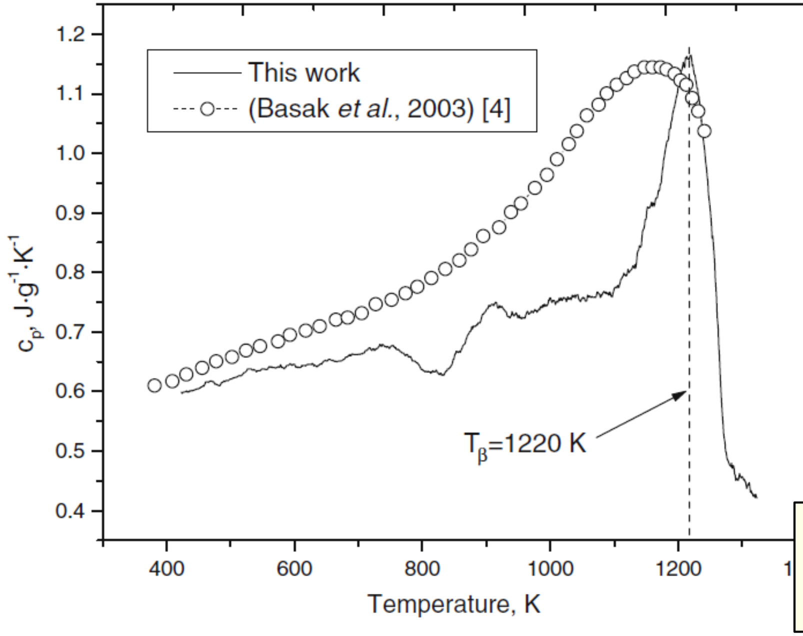


Fig. 7. Specific heat capacity of solid Ti-6Al-4V compared to literature data (Basak et al., 2003) [4].

Boivineau et al., Int. Journ. of Thermophysics, Vol. 27, No.2 March 2006

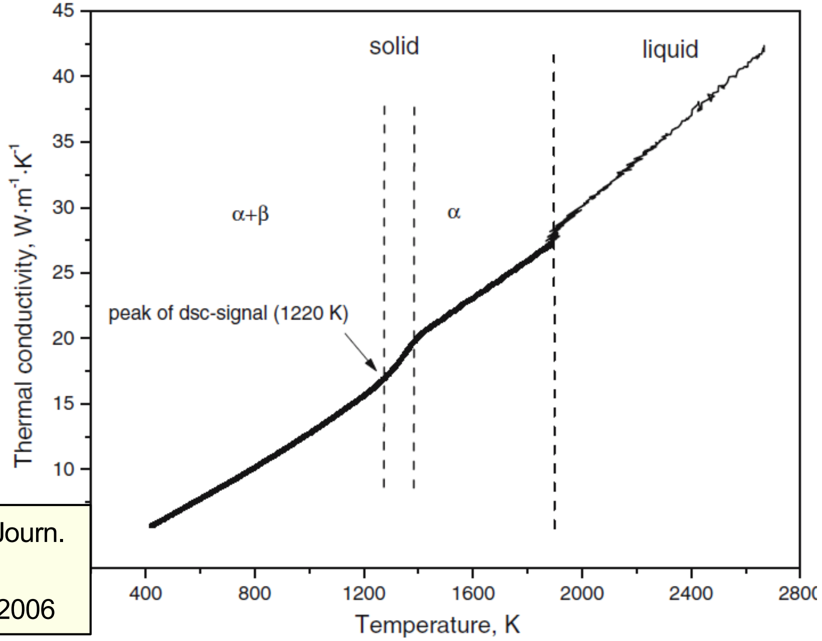


Fig. 13. Thermal conductivity of solid and liquid Ti-6Al-4V versus temperature.

Heating to equilibrium

- Neglect heat conduction and thermal radiation → average T in material increases

$$\boxed{\frac{dQ}{dt} = mc\frac{dT}{dt}}$$

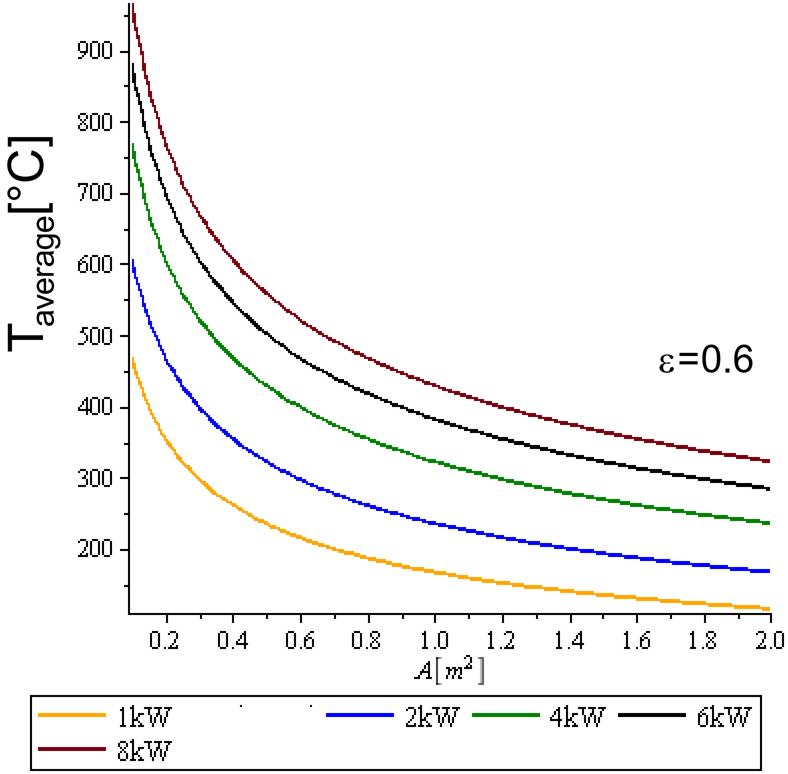
- Assume 2.3kW at target
  - target rim height h = 2cm (4cm)

    $\rightarrow V_{rim} \sim 924\text{cm}^3$ (1.8dm^3)
  - Average rim temperature T_{ave} = 300C (ΔT=270K) reached after

    254sec (~4.2min) for h=2cm;

    497sec (~8.3min) for h=4cm
  - Heating of rim+radiator takes correspondingly longer
- Taking into account thermal radiation and time for heat transfer to radiator, few hours needed to achieve equilibrium (see our talks at POSIPOL14+15 and LCWS15 and Felix’ talk)

Thermal radiation



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

Consider radiation off target rim only,

r = 0.5m, h=2cm, d=1.5cm

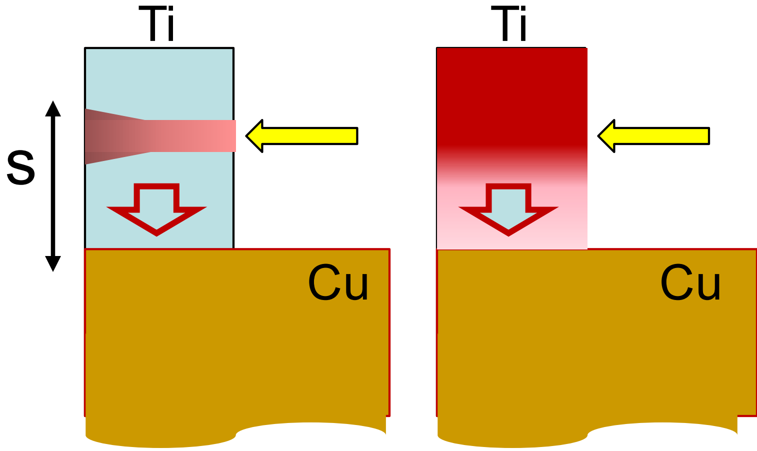
A ~ 0.17m^2, ε = 0.6

2.3kW ⇔ T_{target} (ave)~530C

So far, we concentrated in our T^4 cooling models on radiation from radiator by optimizing the design towards a large area with fins, but there is also substantial thermal radiation off the rim

- low heat conductivity of Ti ⇔ high average temperature of rim
- despite small rim area substantial cooling by thermal radiation off the target rim

Heat transfer target to radiator



- Spinning target⇔ ~6.5s between load cycles
  - Heat moves $\sqrt{\lambda t/\rho c}$ ~ 0.5cm in 6.5sec
  → accumulation of heat in the target
- Temperature flow to radiator depends on s
  - Average heat transfer through rim

$$\frac{dQ}{dt} = \lambda \cdot A_{contact}^{Ti-Cu} \frac{dT}{ds} \sim \lambda/s \cdot A_{contact}^{Ti-Cu} \left(T_{Ti} - T_{Cu}\right)$$

$A_{contact}$~470cm^2, λ~10W/(m K)

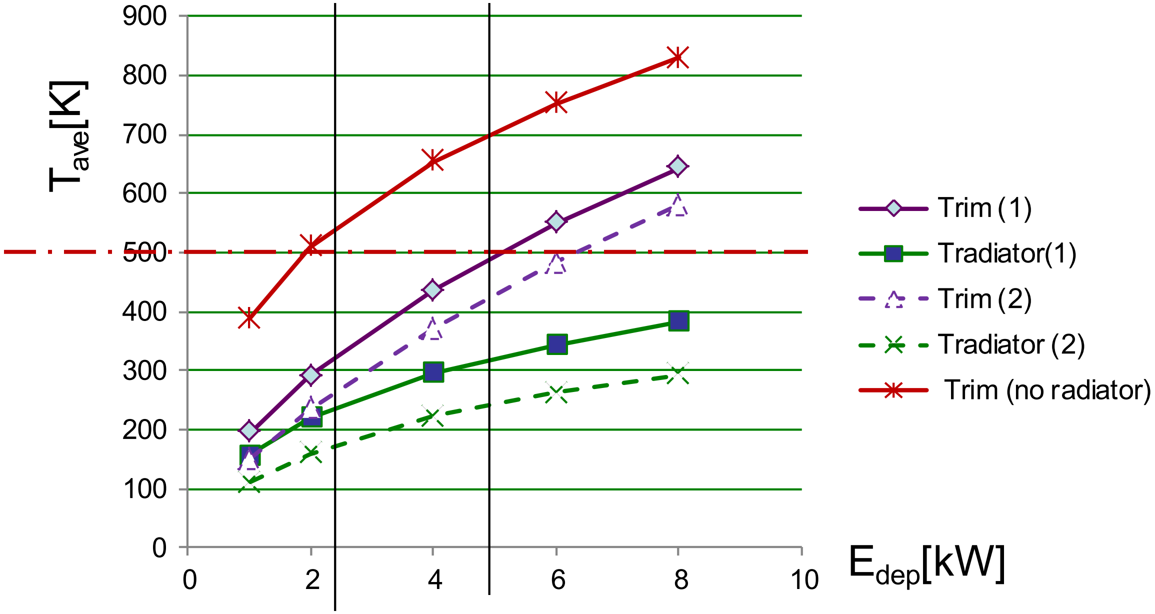
dQ/dt = 2.3kW: $T_{max-ave}$ (Ti) – $T_{contact}$ ~ 100K (s=1.5cm)
~ 150K (s=2.5cm)

  - Additional cyclic temperature rise by pulse (80…200K)
- Cyclic peak temperatures in target can exceed 500˚C, in particular for large s
  → need design with short heat transfer path through Ti rim to keep the average T_{target} as low as possible
  → for high power deposition (⇔ high lumi) even average temperature could be >500C

Estimated average temperature in T rim and Cu radiator

Consider thermal radiation from rim and radiator

- Case (1): rim 0.082m^2 + radiator 1m^2
- Case (2): rim 0.082m^2 + radiator 2m^2
- Case (3): Only rim, 0.16m^2; no radiator
- Emissivity ε=0.6

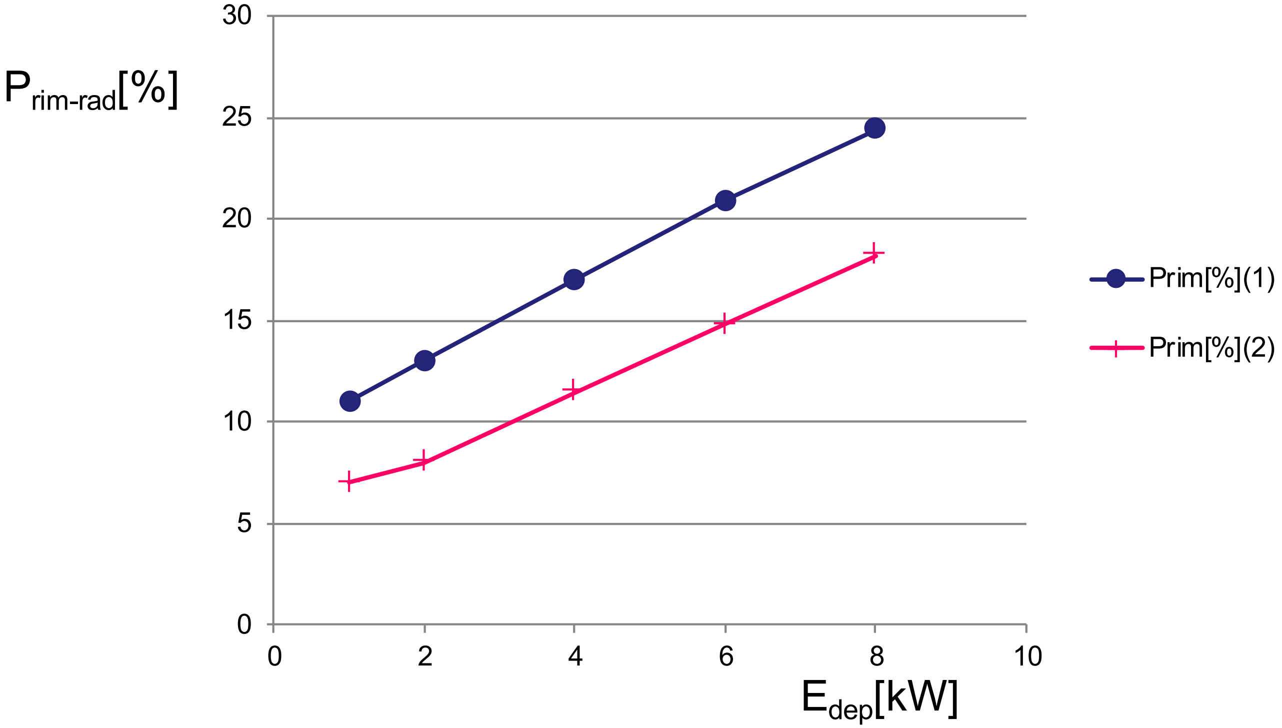


- Estimates give the principal behavior and only approximate temp values. Real temperatures need simulations, they depend on radiator design and Ti-Cu contact

Percentage of power radiated by target rim

- Case (1): rim 0.082m^2 + radiator 1m^2
- Case (2): rim 0.082m^2 + radiator 2m^2

→ Depending on energy deposition, target rim size and radiator area, thermal radiation off the rim is efficient and can reach 35% of E_{dep}



- Due to low thermal conductivity of Ti6Al4V, peak and average temperatures in target are substantially determined by target dimension (height)
- Ti-Cu contact as well as radiator surface are important to remove the heat
- However
  - we need a heavy wheel (>100kg) to provide a radiator area of ~2m^2
  - A lower radiating surface of 1m^2 increases the average temperature in the target by only ~70K.
  - Reduction of # of fins by factor 2 reduces wheel weight by ~20kg
- Idea: Are higher target rim temperatures acceptable?
  - After our first target material tests we feel encouraged to accept higher target temperatures.
  - Similar approach is followed by M. Breidenbach

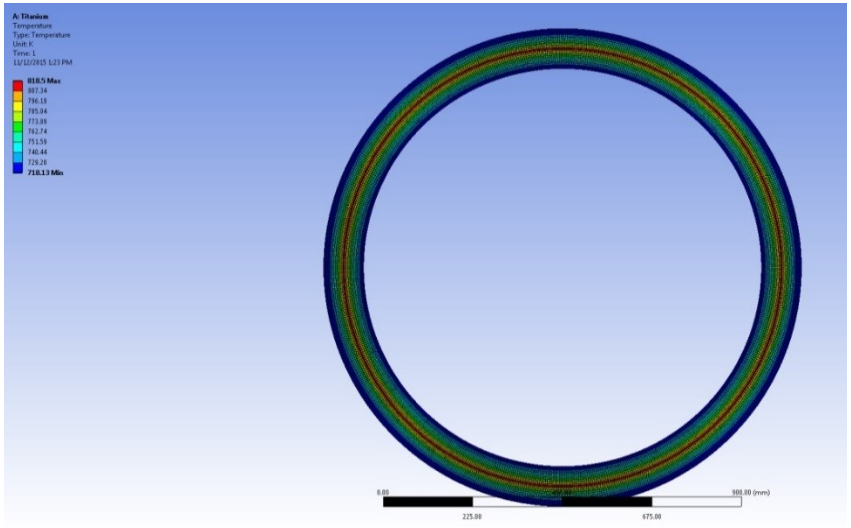
Private communication after LCWS15

Target studies at SLAC (M. Breidenbach, M. Oriunno)

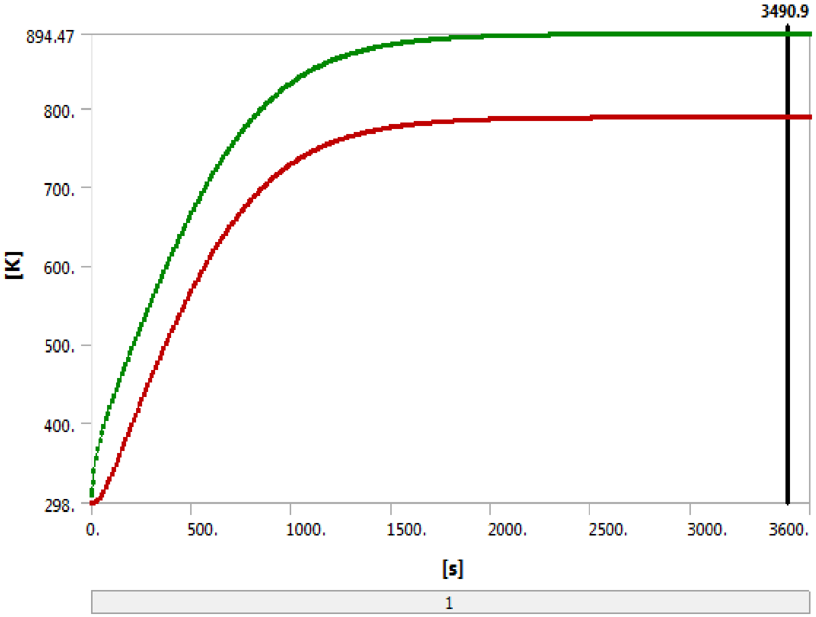
(See also Marty's talk at LCWS15)
Approach:
use high T material Ti-SF61

Study for P = 7.74kW
1312 pulses with 10Hz

λ (W.m-1.K-1)	ε = 0.4	ε = 0.6
21	894 (621)	814 (541)
8	984 (711)	904 (631)



Transient with emissivity 0.4



Stress in target and radiator

- Depends on:
  - design
  - Load by pulse ⇔ Instantaneous and average heating
  - Rotation
  - Eddy current
  - Imbalances (ignored so far)

- **Stress resistivity at elevated temperatures??**
  - Thermal and mechanical stress limits for target and radiator material at high temperatures, under irradiation

Stress due to heating

$$\boxed{\sigma = \frac{E\alpha\Delta T}{1-\nu}}$$

- **Instantaneous heating**
  - Pulse ⇔ ΔT = 80K … 200K
  - Ti rim σ ~ 100…260MPa
  - ILC e+ target: ~2×10^6 loads per year (4000h) ⇔
  - fatigue stress limit for Ti alloy ~600MPa at room temperature but considerably lower at elevated temprature
- **Average heating**
  - Depends on design
  - Heated rim and radiator:
    - Hoop stress in ring: $\sigma_H = E\ \alpha\ \Delta T$ if expansion is prevented
      Ti rim @ 500C → σ_H would be ~420MPa
    - Expansion of rim + radiator is not restricted → increase of rim circumference u,
      Δu = 1.3cm (Δr = 2mm)
  - Spatial expansion V_{rim}(heated) = $\gamma\cdot V_{20^\circ C}\cdot\Delta T$

Ti: ΔV ~ 1.2% for ΔT=500K (~ 2% for 850K)

Cu: ΔV ~ 6.6% for ΔT=200K (~ 11.5% for 350K)

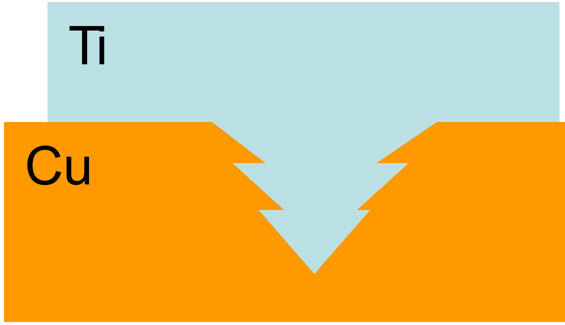
Further stress load

- **Rotation** ⇔ tangential and radial forces
  - thin ring approximation for target rim: $\sigma_t \sim \rho r^2\omega^2 = 50\text{MPa}$
  - Assuming sliced target, (~40 pieces for nominal lumi), height ~2cm (3cm) → $F_c = mr\omega^2$ ~2.2kN (3.3kN)
    With connecting area A~12cm² → σ~2MPa (3MPa)
    → no problem

→ **Sliced target**

- minimizes stress in (non-uniformly heated) target rim and radiator
- Main stress contribution from cyclic energy deposition by photon beam

- **Ti-Cu contact**
  - must work well for all temperatures
  - Calculation of stress at the contact Ti to radiator needs FEM methods
  - Possibilities considered
    - Peter's proposal: use bolts + plate springs
    - Felix' (also Marty Breidenbach's) proposal: use multiple dovetail connection for tight connection between Ti and Cu
    - Status and more details in Felix' talk



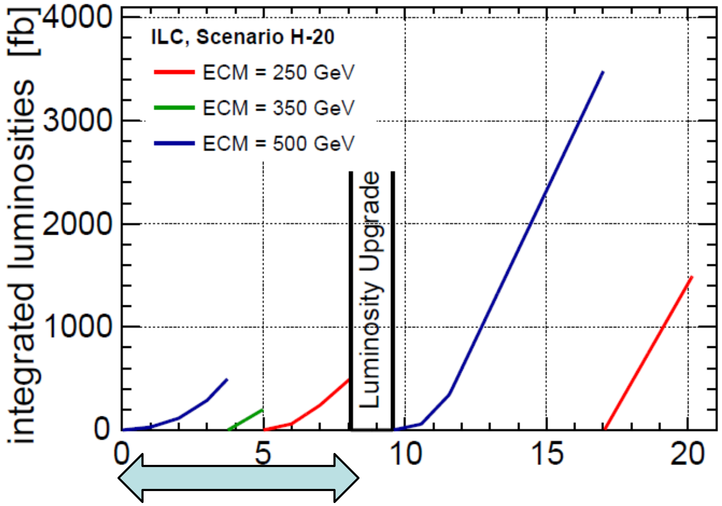
- Eddy currents
  - See talks at ALCW15, POSIPOl15
  - no problem for 5Hz, τ_{pulse}~1ms, and 0.5T at target
  - Pulsed braking power ⇔ intermittent force on the target shaft and bearings (P. Sievers: ~100N in 1ms)

    → tight control of the wheel velocity, motor torque

    → vibrations have to be studied

Expected target load in the first years

- Running scenarioH-20 start with E_{cm}=500GeV (500fb^{-1}), followed by E_{cm}=350GeV (200fb^{-1}); and 250GeV (500fb^{-1}); 1326 bunches per pulse during the first years.



- Average E deposition: 2.3kW (500GeV), 3.9kW (350GeV), 5kW (250GeV)
  → **Estimated peak temperatures for 2m^2 (1m^2) radiator area:**
    ~400C (500C) at 500GeV
    ~450C (550C) at 350GeV
    ~470C (570C) at 200GeV, 5Hz, 230m undulator length
- Cyclic load stress due to γ beam ≤200MPa (nominal L, no e+ pol upgrade)
- Beam test studies at microtron in Mainz show that Ti6Al4V should stand this

Ti alloy parameters at high temperatures

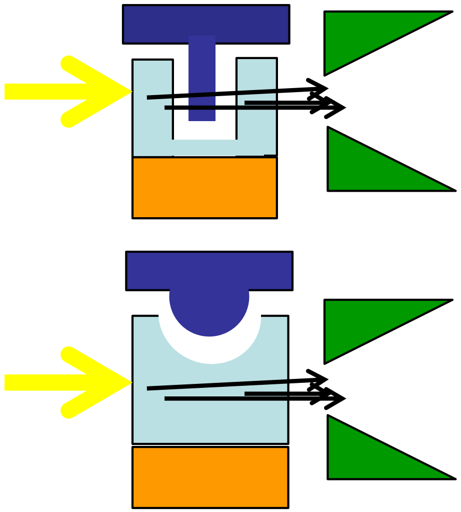
- Ti6Al4V (http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP642)
- Ti-SF61(Ti-5.9Al-2.7Sn-4Zr-0.45Mo-0.35Si-0.22Y), see also http://amt-advanced-materials-technology.com/materials/titanium-high-temperature/ :

  "This Titanium alloy could be used up to 620°C for long service times. …highest creep resistance … The fatigue strength is very high up to 820°C…"

	ρ [g/cm^3]	λ [W/mK]	α [10^{-6}/K]	T_{melt} [C]	E [GPa]	UTS [MPa]	YS [MPa]	Elong [%]	Fatigue [MPa, 10^7]	β-trans. [C]
						RoomTemp				
Ti-SF61	4.56	6.7	8.3	1650	120	1068	1050	11	195@760C	
						600C				
						752	655	16		
						Room temp				
Ti6Al4V	4.43	8		1604	113.4	950	880	14	510 unn. 240n.	980

Thoughts for improvements

- Assuming radiator surface of 1m^2,
  - at least 20-40% of the deposited power are radiated from the target rim
  - average target temperature increases less than 100K in comparison to 2m^2 radiator area
- Ti6Al4V seems stable up to T~700C average temperatures (see our material tests at MAMI, Alexandr's talk)
- Use Ti alloy developed for high temperature applications ? (M. Breidenbach: Ti-SF61)
- High temperature Ti alloy + lower radiator area → Optimization of target shape? Increase radiating target area by factor 2 or ~1.5



(Rough sketches, no technical drawings!)

1. Split target in 2 parts and add a stationary cooler fin between them outside the beam area

   → Lower e+ yield due to larger effective distance to FC (but this could help to increase e+ polarization)

   A. Ushakov estimate: Yield reduction by ~10% for 10mm gap between target parts

2. Do not touch beam path region but increase outer target surface

Summary

- Radiative cooling will work
  - Under study:
    - Efficient contact between target rim and radiator
    - Optimize target+radiator surface + material
    - Mechanical issues
- Polarized positrons
  - Realistic undulator spectrum (see Khaled's and Ian's talks)
  - Polarization upgrade
    - PEDD and target design
    - photon collimation?
    - Polarization measurement at the e+source
- Cyclic load tests at MAMI (see also Alexandr's talk)
  - Check target material properties at high temperatures and high load
    - Target and exit window material
- Photon dump
  - … was not subject of this talk
  - 'Extrapolation' of photon collimator studies (see http://arxiv.org/abs/1412.2498) show that a graphite dump is possible, but should be either moved (as the dump window) or consist of cooled rods

Thank you!

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: **1^{st} second: 0, 144, 288, 72, 216,**

2^{nd} second: $0 + \theta_{pulse}$ ….,

3^{rd} second: $0 + 2\theta_{pulse}$ ….

→ after ~7s the rim is almost uniformly heated

→ unbalances due to non-uniform heating are avoided