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# Status of the target for the undulator-based positron source

POSIPOL 2018, Geneva Switzerland
September 3rd, 2018

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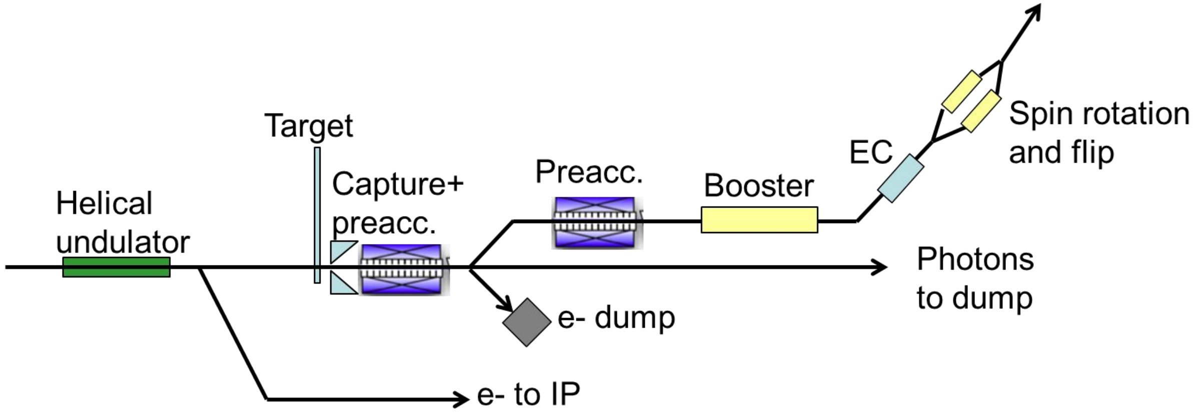
# Basic e+ source parameters

| **Electron beam energy** | **125 GeV…250GeV** |
|---|---|
| Number of particles per bunch | $2\times10^{10}$ |
| Number of bunches per pulse | 1312 (Upgr. 2625) |
| Repetition rate | 5 Hz |
| Positrons per second at IP | $1.3\times10^{14}$ $(2.6\times10^{14})$ |

for comparison: SLC 2.4x$10^{12}$/s ⬄ factor ~50 (100)

Required positron yield: Y = 1.5e+/e- at damping ring

# Outline



Focus: ILC250

- Superconducting helical undulator → circ pol photons → polarized e+
- **Target design**
  - **Cooling by thermal radiation**
  - **Discussion of issues for the engineering design**
- Capture system
- Dump of photon beam ("critical issue")
- **Summary and realistic plans**

Status for the undulator-based e+ source for ILC250 are documented in the [Positron Source Working Group Report]

# ILC250: parameters of undulator and photon beam

Undulator Prototype → **$K_{max}$ = 0.92 and $\lambda_u$ = 11.5mm is "fixed"**

- Parameter optimization to achieve Y = 1.5e+/e-
  - efficiency of e+ generation depends on photon energy

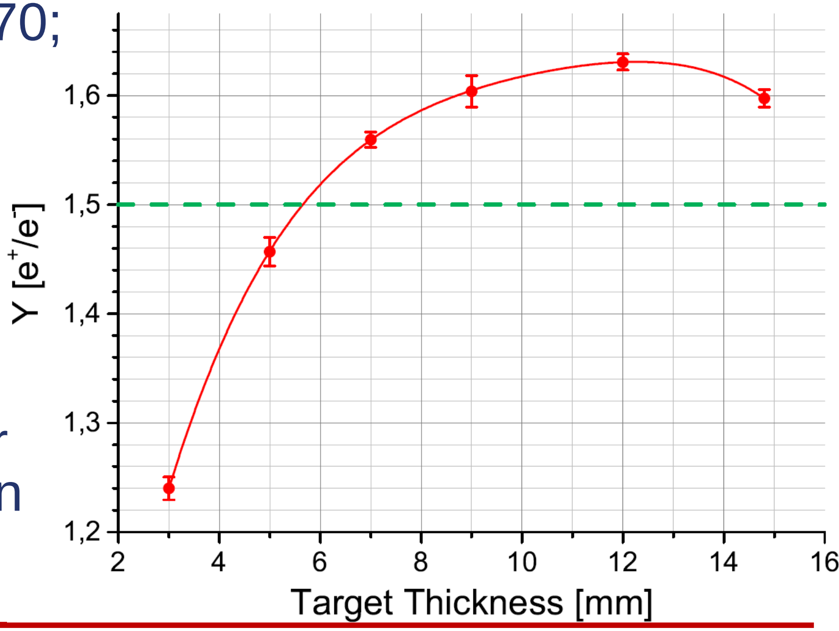
    first harmonic: $E_{1\gamma} \sim \frac{E_e}{\lambda_u(1+K^2)}$ → low K increases photon energy
  - Number of photons $N_\gamma \sim \mathbf{L} \cdot \frac{K^2}{\lambda_u}$ → low K gives less photons
- 125GeV e- beam requires high K and maximum active undulator length
- Opening angle of photon beam ~1/γ →Spot size on target is small

| | | |
|---|---|---|
| Electron beam energy | GeV | 126,5 |
| Active undulator length $L_{und}$ | m | 231 |
| Undulator K | | 0.85 |
| Photon energy (1st harmonic) | MeV | 7.7 |
| Average photon beam power | kW | 62.6 |
| Distance target – middle undulator | m | 401 |
| Photon beam spot size on target (σ) | mm | 1.2 |

1312 bunches/pulse

# The positron target

- Wheel of 1m diameter, spinning in vacuum  with 2000rpm (100m/s tangential speed)
- Target material Ti6Al4V, thickness 0.4 X0 = 1.48cm for ILC500
- lesson from prototyping for target wheel at LLNL
  - water-cooling of the wheel will be extremely difficult (vacuum seals, bearing) → use radiative cooling
  - see Gronberg et al., arXive1203.0070; Gronberg et al., POSIPOL2013
- ILC250:
  - Photon energy is lower, ~7.7 MeV
  - Reduction of target thickness from 14.8mm (TDR) to 7mm  maintains Y=1.5e+/e-  and reduces  the power deposition in the target by more than a factor 2 to ~2kW



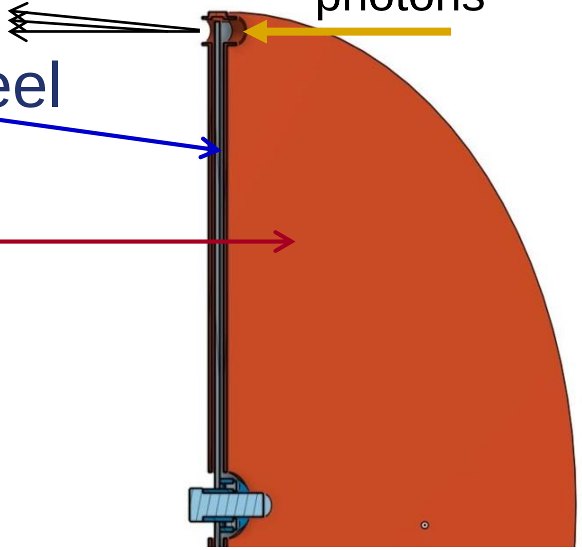
# Positron target parameters - ILC250

| | | |
|---|---|---|
| Electron beam energy | GeV | 126.5 |
| Active undulator length | m | 231 |
| Undulator K | | 0.85 |
| Photon energy (1st harmonic) | MeV | 7.7 |
| Average photon beam power | kW | 62.6 |
| Distance target – middle undulator | M | 401 |
| Photon beam spot size on target (σ) | mm | 1.2 |
| Target (Ti6Al4V)thickness | mm | 7 |
| **Average power deposition in target** | **kW** | **1.94** |
| **Peak Energy Deposition Density (PEDD) in spinning target per pulse** | **J/g** | **61.0** |
| **Polarization of captured positrons** | **%** | **29.5** |

1312 bunches/pulse

Only ~3% of photon beam power are deposited in target, the photon beam is dumped

# Cooling by thermal radiation



- heat is radiated from spinning target wheel which radiates to a stationary water-cooled cooler

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

ε = effective emissivity

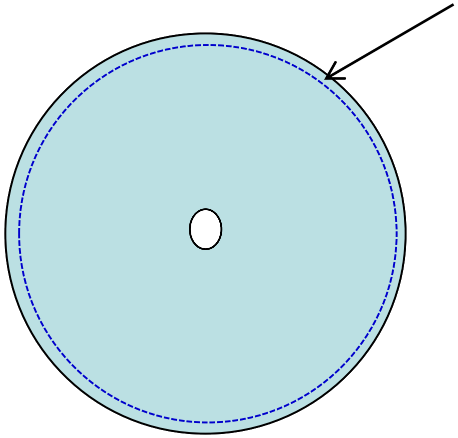
  - Rough estimate: for 2kW power deposition about 0.6 m^2 are needed to keep material at 400C average temperature (ε = 0.3)

- low thermal conductivity of Ti alloys (λ = 0.06 – 0.15 K/cm/s)
  - heat dissipation ~ 0.5cm in 7sec

  → heat accumulates in the rim near to beam path

**What is the load on target, and can the material stand it ?**

- Consider target wheel designed as disc consisting of Ti6Al4V
- Thickness 7mm
- Load on target (1312 bunches/pulse)
  - About 2kW, i.e. the 400W per pulse are smeared over ~7.5cm due to wheel rotation
  - Every ~7-8sec load at same target position → in 5000h roughly 2.5 × $10^6$ load cycles at same target area



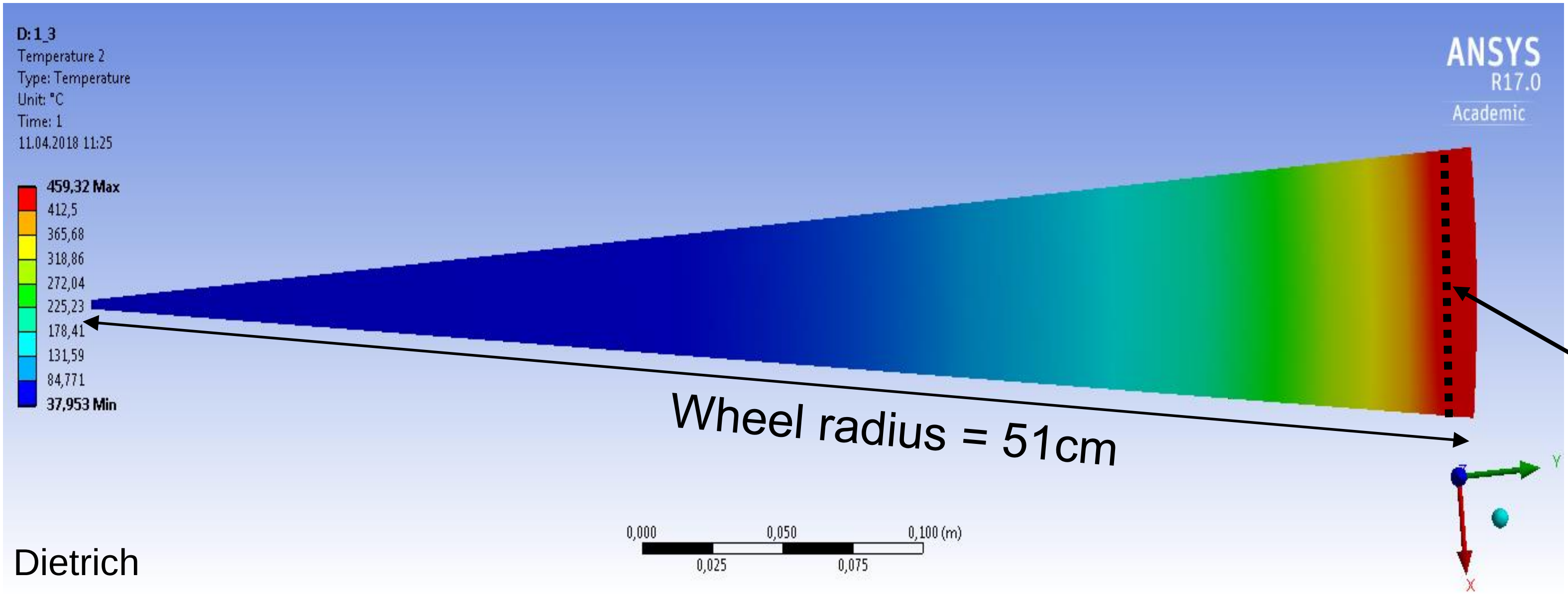
Photon beam path on spinnig target wheel

# Temperature distribution in target wheel

- Average energy deposition in target ~2kW (ILC250, ILC500)
- ANSYS simulations for radiative cooling of target wheel
  - Efficiency of cooling depends on emissivity of surfaces of wheel and cooler ($\varepsilon_{Ti}$ and $\varepsilon_{Cu}$)

Temperature distribution in target piece corresponding to 1 pulse length; ILC250

($\varepsilon_{eff}$= 0.33; $\varepsilon_{Ti} = \varepsilon_{Cu}$=0.5)

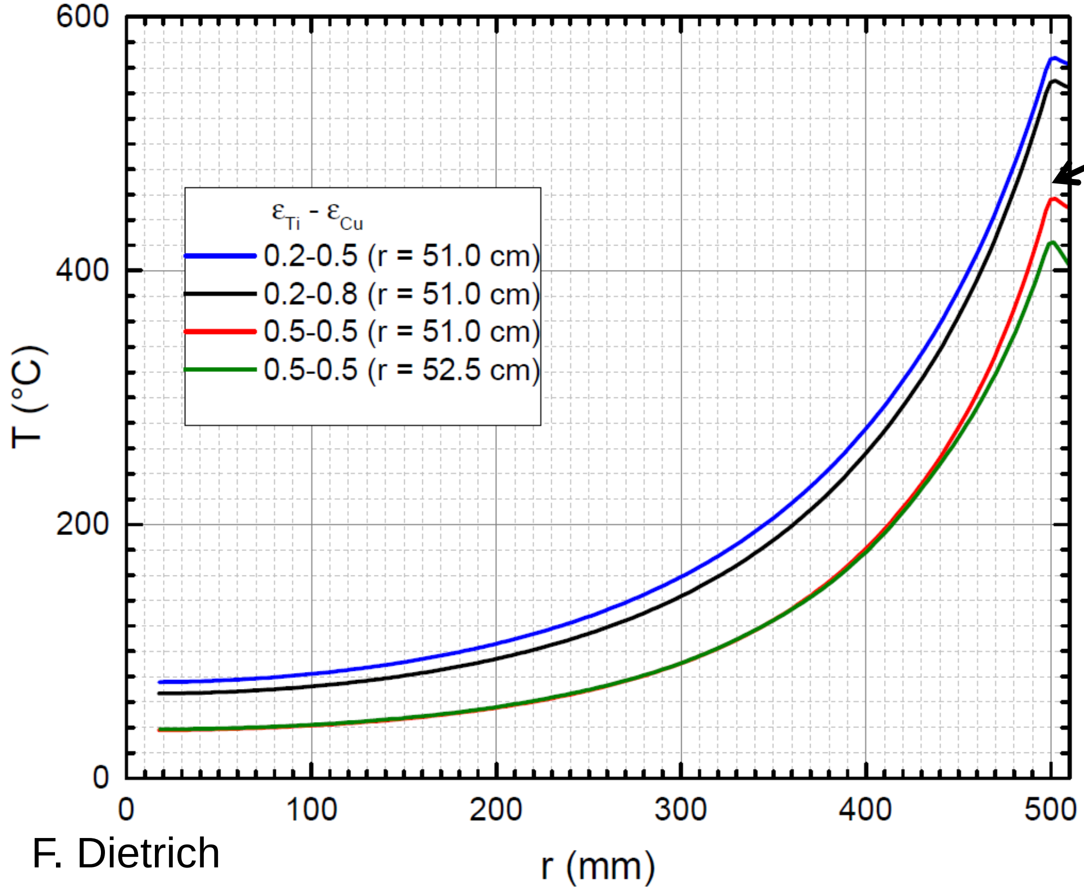


Photon beam pulse

F. Dietrich

# Temperature on target, ILC250

Average temperature in wheel as function of radius r for different surface emissivities of target and cooler (Cu)



Photon beam impact always at r=50cm

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$\varepsilon_{eff}$= 0.33 for $\varepsilon_{Ti}$ = $\varepsilon_{Cu}$=0.5

Deposited E = 2kW

$T_{ave} \leq 460^{\circ}C$

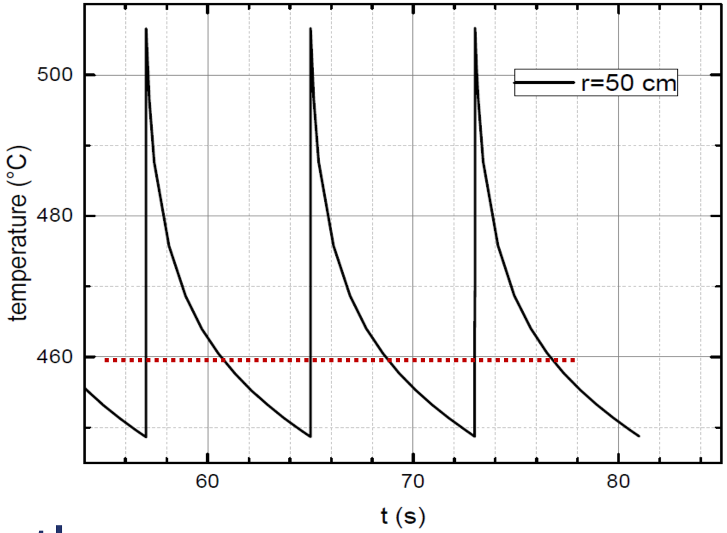
We checked different wheel radii, r = 51…52.5cm

→ max temperatures can be slightly decreased for larger wheel radius

# Cyclic load at the target - peak temperature

- Max temperature evolution along rim
  - if wheel has equilibrium temperature distribution reached, pulse increases temperature up to ~510C

    (2kW, $\varepsilon_{eff}$= 0.33 for $\varepsilon_{Ti}$ =$\varepsilon_{Cu}$=0.5)



- for ILC250, nominal luminosity; the average temperature as well as cyclic peak temperature are below the limits that Ti6Al4V accepts (see talk of Andriy Ushakov)

# Upgrade to higher energies

## No problem for nominal luminosity: PEDD and max temperatures do not exceed limit, target thickness could be optimized

| Electron beam energy | GeV | 126,5 | 175 | 250 |
|---|---|---|---|---|
| Active undulator length | m | 231 | 147 | |
| Undulator K | | 0.85 | 0.66 | 0.45 |
| Photon yield | $\gamma$/e- | 393 | 157 | 76.1 |
| Photon energy (1st harmonic) | MeV | 7.7 | 17.6 | 42.9 |
| Average photon beam power | kW | 62.6 | 45.2 | 42.9 |
| Distance target – middle undulator | m | 401 | 500 | |
| Target (Ti6Al4V)thickness | mm | **7** | 14.8 | |
| **Average power deposition in target** | **kW** | **1.94** | **3.3** | **2.3** |
| Photon beam spot size on target ($\sigma$) | mm | 1.2 | 0.89 | 0.5 |
| **Peak Energy Deposition Density (PEDD) in spinning target per pulse** | **J/g** | **61.0** | **42.4** | **45.8** |
| Polarization of captured positrons | % | 29.5 | 30.8 | 24.9 |

# Upgrade to high luminosity (2625 bunches/pulse)

- Doubled energy deposition in target
- PEDD and temperature rise
  - Pulse length: 0.727ms (1312 b/pulse) → 0.961ms (2625 b/pulse)
    → Increased temperature amplitude DT per pulse by factor 1.5
    i.e. ~ 60-80K (1312 b/pulse) → 90–120K (2625 b/pulse)
    - $\Delta$T depends on average T in target since specific cheat depends on T
- Average temperature
  - simple scaling: max $T_{ave}$ [K] rises by $\sim 2^{1/4}$ in comparison to nominal lumi
    i.e. 460 C → about 600 C for our ILC target parameters ($\varepsilon_{eff} = 0.3$)
  - Larger temperature rise per pulse and low thermal conductivity complicate this simple scaling;
  - ANSYS sim (Felix Dietrich): . max $T_{ave} \approx 650$ C $\varepsilon_{eff} = 0.3$)
- peak temperature values increase to ~750C

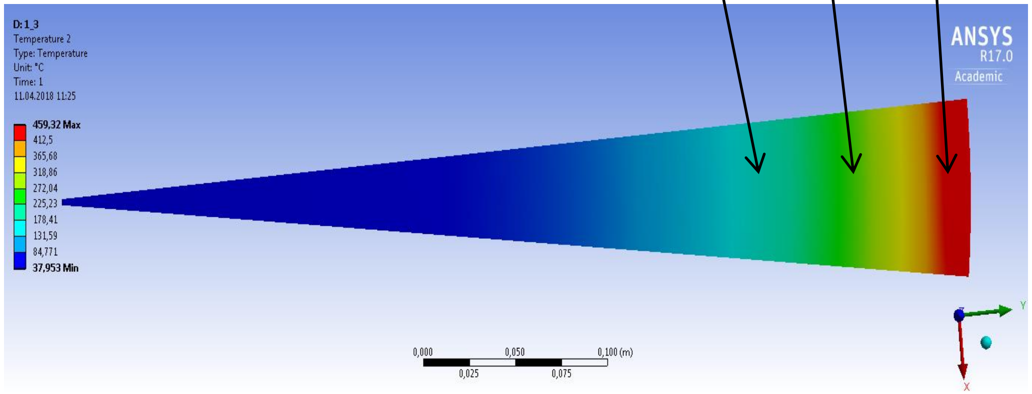
- for ILC250, high luminosity; the average temperature as well as cyclic peak temperature seem acceptable but are close to edge (see talk of Andriy Ushakov)

# Stress in the target disk

$T_{ave}$ ~ 180C
r = 40cm

$T_{ave}$ ~ 280C
r = 45cm

$T_{ave}$ ~ 460C
r = 50cm



Large temperature gradient creates stress within disk, in particular in outer region (circumferential)

Thermal expansion along z is possible, but target material is restrained along x,y.

$\Delta T$ for r = 45…50cm: 180K

→ Stress along rim, $\sigma = E \alpha \Delta T/(1-\nu)$

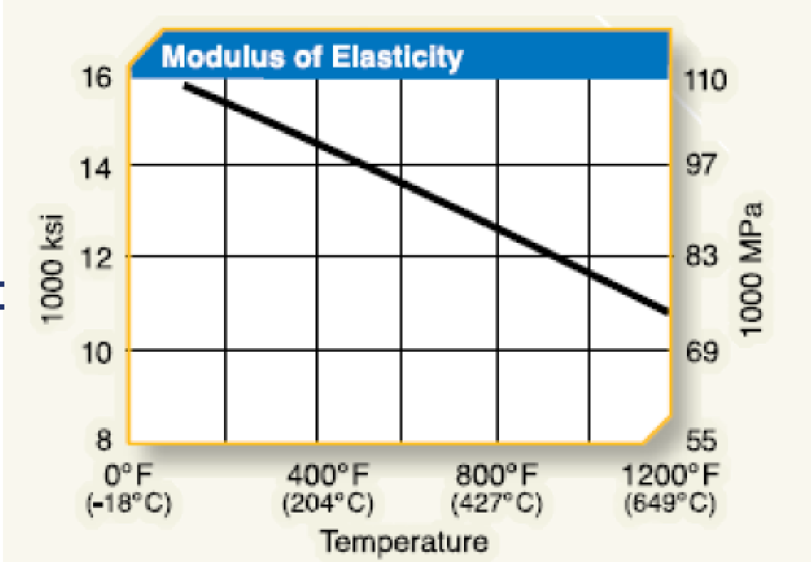
# Temperature dependence of Ti6Al4V parameters

Important for the simulation of target load: all parameters depend strongly on temperature

→ Modulus of elasticity, E, varies on the target disk corresponding to the temperature

  - Material parameters given in data sheets depend slightly on vendor

- modulus of elasticity; E(T)
  - E is important for stress evaluation:
    Stress ~ E $\alpha$ $\Delta T$
  - At ~500C E≈83GPa
    about 75% of E(RT)
  - Material response (stress) at higher T seems smaller – but also the load limits go down with increasing temperature
  - In addition: long-term operation ⇔ fatigue degradation



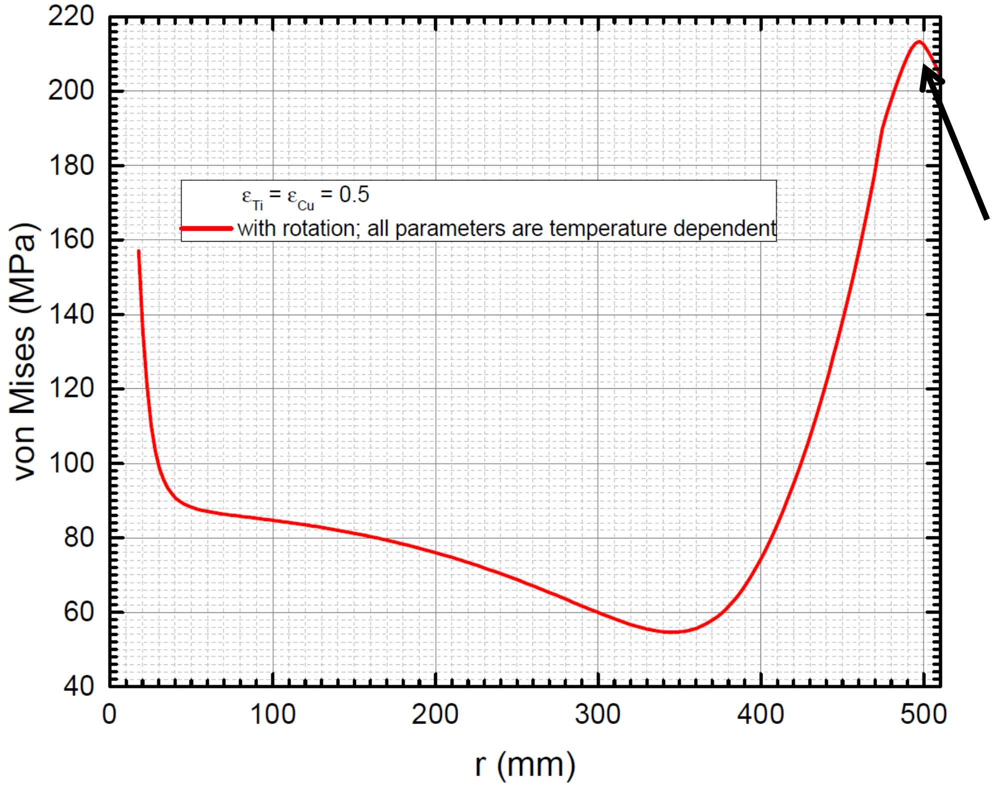
Taken from
ATI data sheet
Ti Grade 5

# Average stress in target, ILC250, 1312b/pulse

ANSYS simulations: Consider spinning target disc, thickness 7mm, $r_{out}$= 51cm ,beam hits target at r=50cm

- Material expansion ⇔ high thermal stress in beam impact region
- Stress due to rotation (hoop and radial) is <50MPa, in the rim region <10MPa

Average von Mises stress
along wheel radius r
$\sigma_{vM} < 220$MPa



Photon beam
impact
at r=50cm

F. Dietrich

# Dynamic stress at radius r

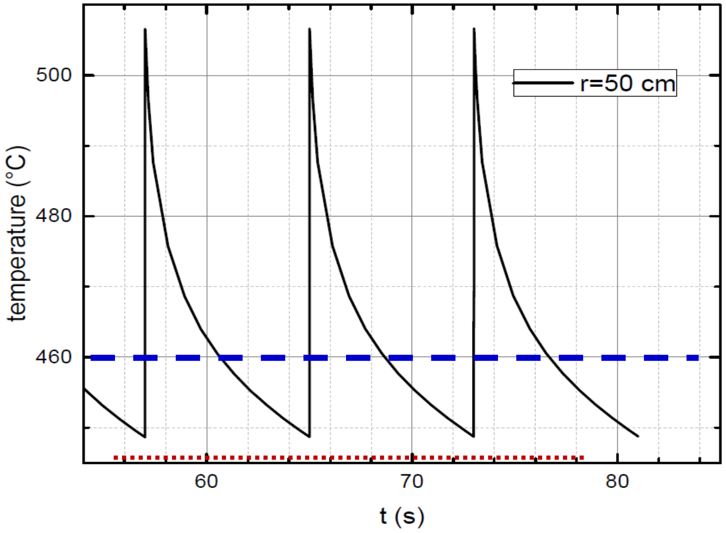
$$\begin{aligned}\sigma_{\mathrm{H}} &= \frac{3+\nu}{8}\rho\omega^2\left(1-\frac{r^2}{r_o^2}\right)\left(1-\frac{r_i^2}{r^2}\right)\\ \sigma_{\mathrm{r}} &= \frac{3+\nu}{8}\rho\omega^2\left(1+\frac{r_i^2}{r_o^2}+\frac{r_i^2}{r^2}-\frac{1+3\nu}{3+\nu}\frac{r^2}{r_o^2}\right)\end{aligned}$$

$r_o$ = outer wheel radius, $r_i$ = inner radius at shaft

- Max radial stress is located at $\sqrt{r_o r_i}$, i.e. more in the inner region where the T is low (assuming full disc)
- Hoop stress from rotation at the beam path (maximum temperature) is low, ~ 9MPa
- ANSYS calculations for detailed stress evaluation required

# Cyclic load at the target - peak temperature

- Max temperature evolution along rim
  - if wheel has equilibrium temperature distribution reached, photon pulse increases temperature up to ~510C (2kW, $\varepsilon_{eff}$= 0.33 for $\varepsilon_{Ti}$ =$\varepsilon_{Cu}$=0.5)



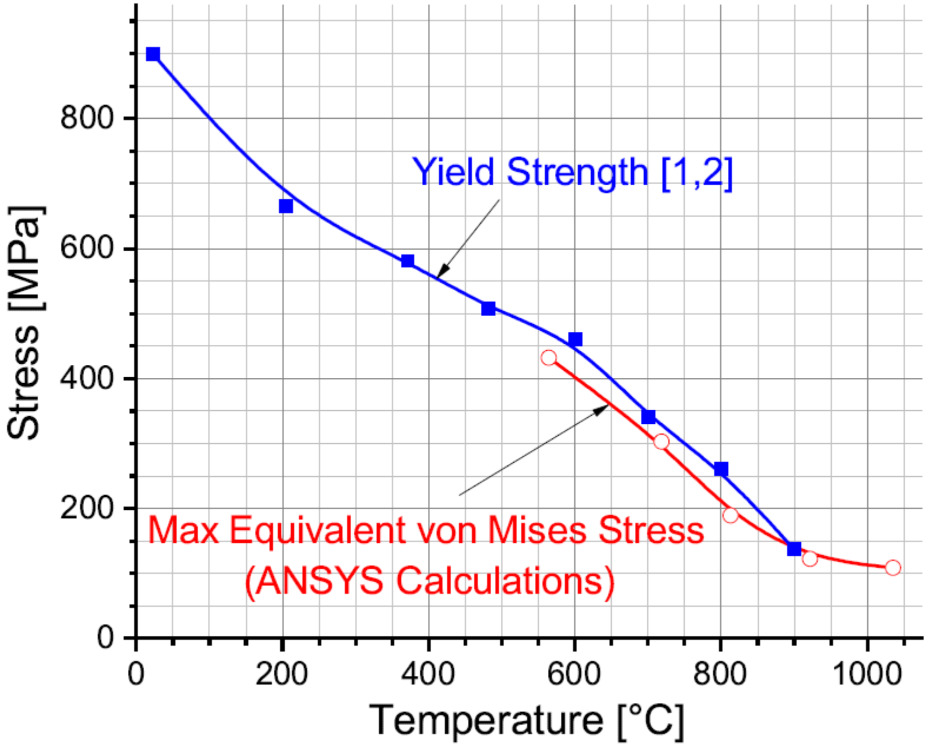
- **Resulting peak stress at beam path**
  - Time of energy deposition is too slow, intensity too small to create shock waves, thermal expansion along z is possible, restricted along r
  - Estimate stress by pulse: $\sigma_{peak} = E\,\alpha\,\Delta T / (1-\nu)$

    $\sigma_{peak} \approx 75$ MPa (ILC250, 1312b/pulse)
  - In total:

    $\sigma_{peak} <$ 220MPa (ave) + 75MPa (pulse) ≈ 300MPa (full target disk)
  - The stress is compressive

Following the tests at MAMI and Andriy’s studies (see his talk), we are safe with the von Mises stress of 300 MPa for ILC250 (nom.Lumi)

Lumi upgrade → Peak stress values could exceed limits



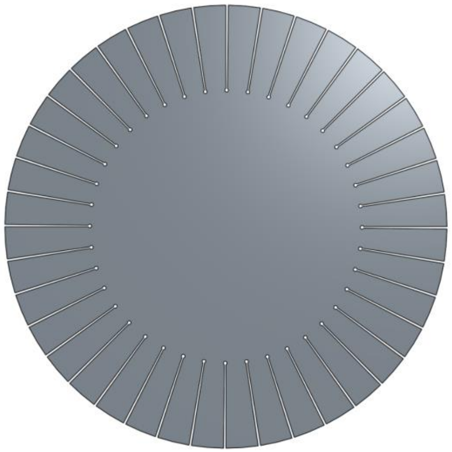
Stress reduction is possible with expansion slots

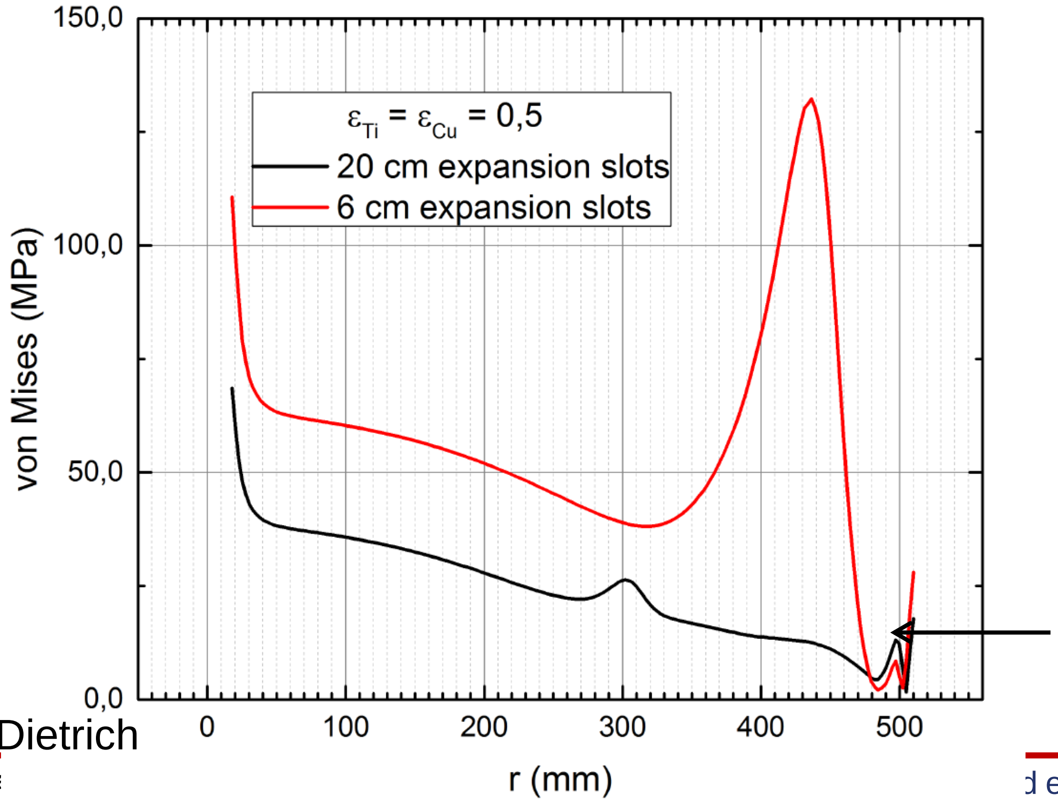
# Average stress in target, ILC250, 1312 b/pulse

ANSYS simulations: Consider consider target disc, thickness 7mm, $r_{out}$= 51cm, beam hits target at r=50cm

- Expansion slots (6cm and 20cm long)

→ stress substantially reduced, $\sigma_{vM} \leq$ 20MPa in rim region





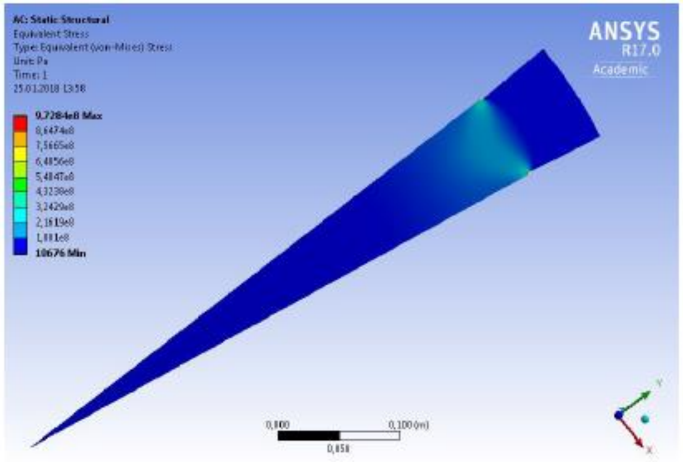
Photon beam impact at r=50cm

Expansion slots require synchronization with beam e- pulses ⇔ timing constraints!

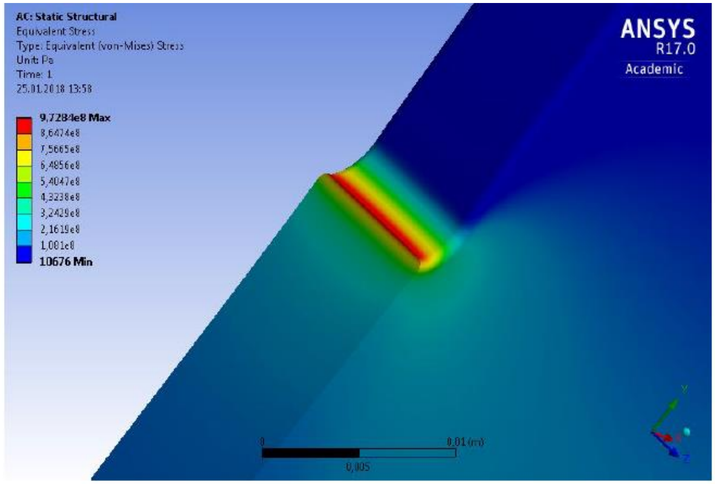
F. Dietrich

# Expansion slots

- stress around the bore of the expansion slots;
    - Stress can be reduced with optimized bore shape
- Results on this page are still with E(RT), see 1801.10565



cm long

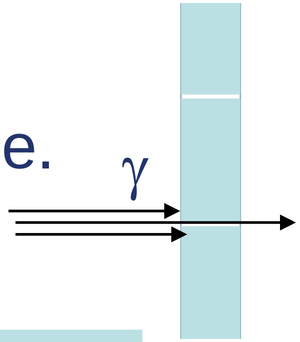


| | full disc | expansion slots | |
|---|---|---|---|
| | | 20 cm | 6 cm |
| von Mises [MPa] | | | |
| r = 50 cm | 348 | 7.39 | 2.71 |
| r = 45 cm | 192 | 4.43 | 125 |
| r = 30 cm | 67.66 | 47.4 | 44.5 |

# Expansion slots & synchronization (1)

Without synchronization:

- Ignore the gaps ⇔ lumi is not constant over pulse.
- Rim temperatures of 750C expand the material by ~2.3 cm → slots



| Slot width [mm] | #of slots | Distance between slots at | |
|---|---|---|---|
| | | r=50cm [mm] | r=40cm [mm] |
| 0.5 | 46 | 68 | 28 |
| 0.25 | 90 | 35 | 14 |
| 0.1 | 230 | 13.8 | 5.5 |

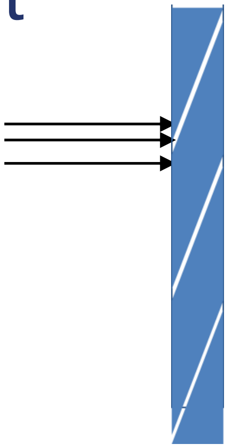
- smaller beam spot size at higher energies → less e+

| | | ILC250 | ILC350 | ILC500 |
|---|---|---|---|---|
| Spot size, σ | mm | 1.2 | 0.89 | 0.5 |
| Max e+ loss per bunch, 0.25mm slots | % | 13 | 18 | 31 |
| Max e+ loss per bunch, 0.1mm slots | % | 5 | 7 | 12 |

# Expansion slots & synchronization (2)

At IL250, the loss of e+ seems acceptable. But at higher energies and higher lumi ?

- What is acceptable for the machine feedback systems?
- Stability of wheel with many slots?
- Insert slots that provide the required target thickness without missing e+
  - Inclined gaps → photons pass always roughly the same target thickness
  - Potential yield fluctuations as well as engineering aspects still to be studied



# High-temperature stress in target

- For ILC high lumi, stress could exceed limits, at least, the safety margin is small
- Possible material degradation: plastic deformation, creep
- Creep:
  - Slow deformation under influence of mechanical stresses.
  - It can be result of long-term exposure to high stress levels which are below the yield strengths; in the worst case it could cause failure
  - Creep deformation depends on material's properties, exposure temperature and the applied structural load.
  - Creep deformation is time-dependent it does not occur suddenly. The strain accumulates as a result of long-term stress
  - For temperatures > 0.4 $T_{melt}$ [K] the possibility of creep effects should be taken into account, in particular if the exposure is over a long time (Ti6l4V: 0.4 $T_{melt} \approx 750K$ )
- The operational conditions for the target wheel differ from that for creep and load tests. Are creep effects important for wheel operation?

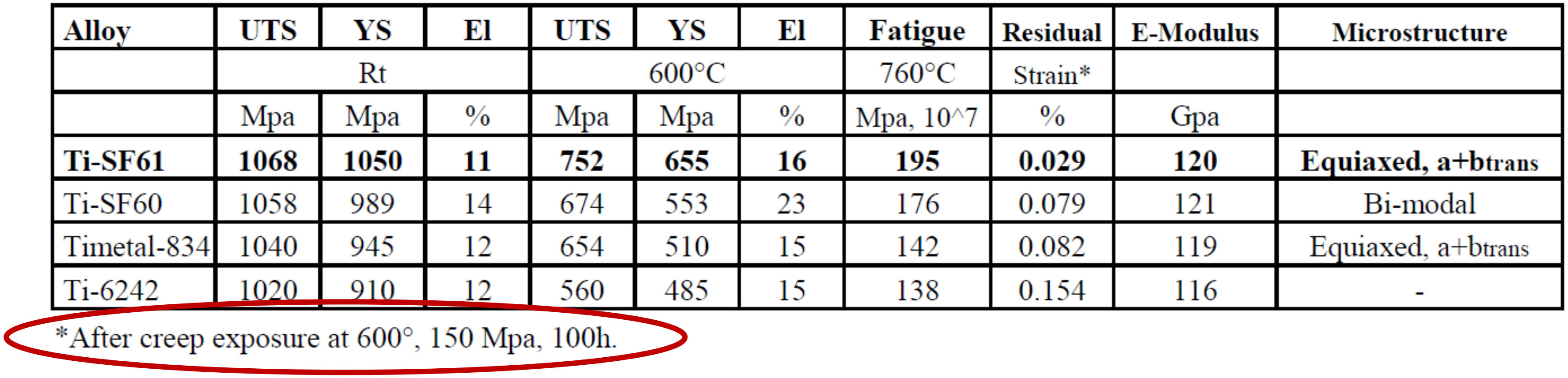
# Data sheet for high temperature and high strength **Ti alloy SF61**

https://www.amt-advanced-materials-technology.com/materials/titanium-high-temperature/

**Material composition**

Chemical Composition: Ti-5.9Al-2.7Sn-4Zr-0.45Mo-0.35Si-0.22Y

**Mechanical properties**



| Alloy | UTS | YS | El | UTS | YS | El | Fatigue | Residual | E-Modulus | Microstructure |
|---|---|---|---|---|---|---|---|---|---|---|
| | Rt | | | 600°C | | | 760°C | Strain* | | |
| | Mpa | Mpa | % | Mpa | Mpa | % | Mpa, 10^7 | % | Gpa | |
| **Ti-SF61** | **1068** | **1050** | **11** | **752** | **655** | **16** | **195** | **0.029** | **120** | **Equiaxed, a+btrans** |
| Ti-SF60 | 1058 | 989 | 14 | 674 | 553 | 23 | 176 | 0.079 | 121 | Bi-modal |
| Timetal-834 | 1040 | 945 | 12 | 654 | 510 | 15 | 142 | 0.082 | 119 | Equiaxed, a+btrans |
| Ti-6242 | 1020 | 910 | 12 | 560 | 485 | 15 | 138 | 0.154 | 116 | - |

*After creep exposure at 600°, 150 Mpa, 100h.

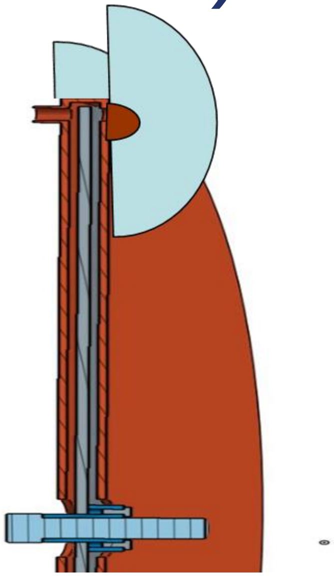
## Preliminary conclusion concerning high-T stress effects:

- further studies necessary; contact/support from material experts
- Ignore creep?
  - Creep models: Larger grains ⇔ less creep
    - MAMI: high T and long irradiation increases grains,
    - MAMI: irradiation time is hours up to day, not weeks

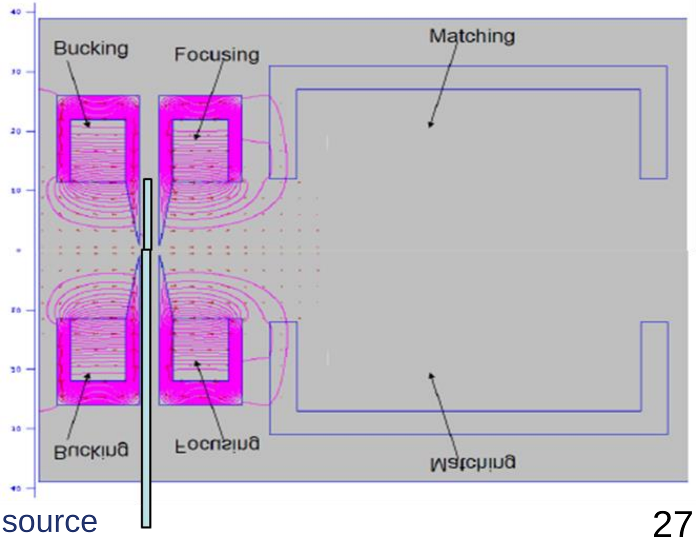
# Remark on fins to increase radiative cooling surface

- In the past we considered cooling fins made of material with high thermal conductivity (Cu), connected to the target rim
- Lower average and peak temperature in the target
- Engineering design with fins is still missing; first performance considerations are available (P. Sievers and DESY/Uni HH group)
- However (personal view): With QWT, cooling fins are more difficult:
  - QWT occupies a large part of the target front and exit surface
  - The fins need a short distance to the hot target rim region
  - The distance cooler fins to target fins should not too large

# Target + optical matching device (OMD)



- The OMD occupies part of the radiating surface
  → surface for effective cooling is reduced up to
  ~25% for the QWT (~13% for the FC)
- In reality, the OMD acts a ‘cooler’
- I guess it is not easy to insert the target with cooling fins into the QWT setup
  - Taking the temperature profile, fins should be as close as possible t the hot target region



If fins are desired, further studies are needed

# Summary and plans

- The roadmap towards the undulator target wheel is clear
- To be done
  - Finalize the parameter list for the undulator based source
  - Finalize the engineering specifications for a target wheel
  - Test in the lab the cooling efficiencies by thermal radiation for a target piece
    - Including mechanical load tests ?
  - Develop a full-size mock-up for the target to test the target rotation in vacuum
    - this includes the full set-up of the target including motor, bearings
    - full-size wheel
  - Photon dump design
- Our problem: resources (→ slow progress for target design)
  - Third-party funding and DESY support material studies. Prototyping is not in the budget.
  - The current manpower situation at DESY/Uni HH does not guarantee that the feasibility will firmly verified in the time of design finalization