Target for the Undulator e^+ source

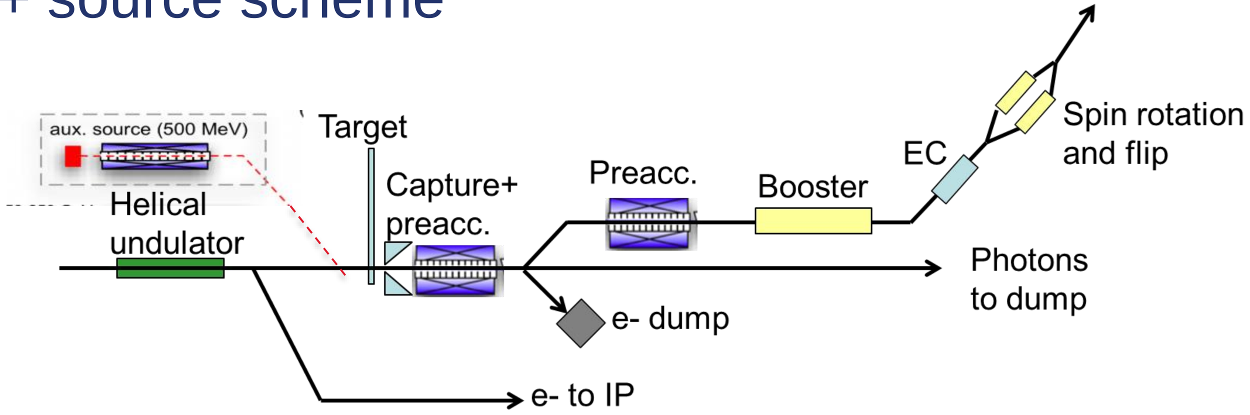
S. Riemann, G. Moortgat-Pick, P. Sievers

Outline

- Undulator
- Target cooling
- Material test
- Design of Rotating Wheel system
- Summary

TDR baseline layout of the e+ source

- The polarized e+ source scheme

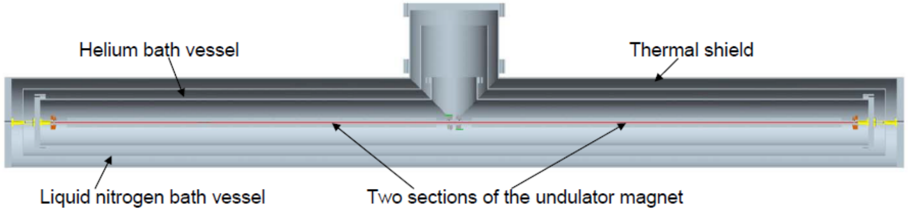


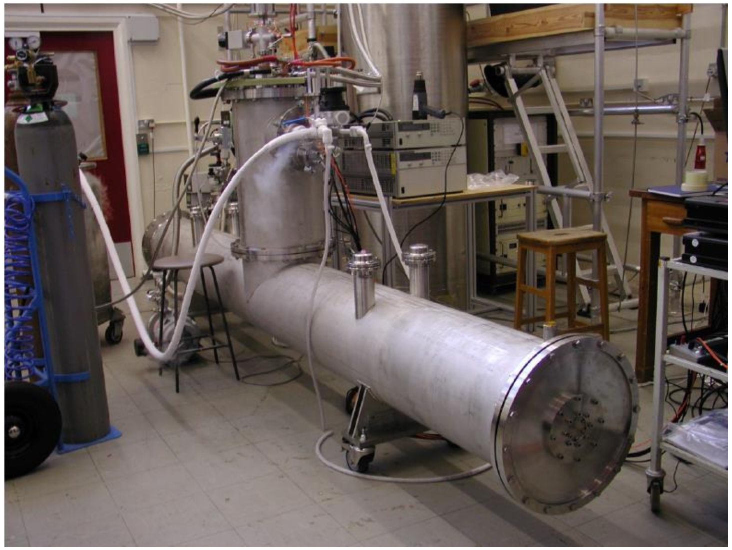
- Required positron yield: Y = 1.5e+/e-   at damping ring
- **To be done until e+ source decision:**
  - Undulator: Simulation (field,errors, alignment)
  - target system design
  - Design of the magnetic focusing system

Superconducting helical undulator

- Helical undulator
  - period, λ_U =11.5mm
  - strength K ≤ 0.92 (B ≤ 0.86T); $K \sim B\cdot\lambda_U$
  - aperture 5.85mm
- 4m prototype built and tested (UK)
  - Cryomodule, contains 2 undulator modules of 1.75m length each

D.Scott et al.,Phys. Rev. Lett. 107, 174803 (2011)





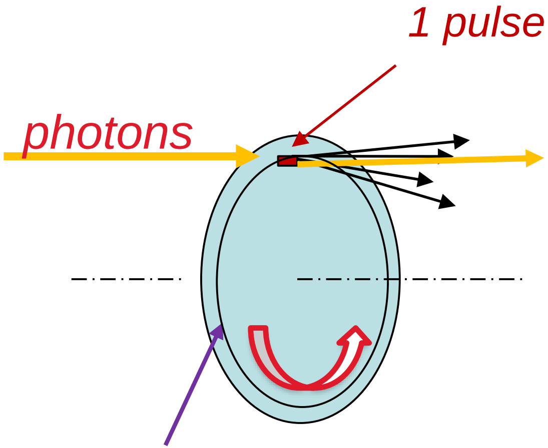
- ILC TDR:
  - Max 231m active undulator length (132 undulator modules in 66 cryomodules]
  - Quadrupoles every 3 cryomodules → total length of undulator system is 320m
- Narrow photon beam ($\theta \sim 1/\gamma$), few 10^{16} γ/sec, ~60-70kW

The conversion target

- Located ~240m downstream the undulator exit
- Only few % of the photon beam power is deposited in the target

- Target: Ti6Al4V
  - Wheel (~1m diameter) spinning in vacuum with 2000rpm (100m/s tangential speed) to distribute heat load

- Target thickness:
  - ILC250
    - Av. photon energy is O(7.5 MeV);
    - target thickness of 7mm ($0.2X_0$)
    - Power deposition ~2kW (nominal Lumi)
  - ILC500:
    - Av. photon energy is O(27 MeV);
    - target thickness of 14.8mm ($0.4X_0$)
    - Power deposition ~2kW (nominal L)



Photon beam path on spinning target wheel

- Photon beam hits wheel at r=0.5m
  - One pulse with1312 bunches occupies ~7cm (2625 bunches ~10cm)
  - Every ~7-8sec load at same target position
  - in 5000h roughly 2.5×10^6 load cycles at same spot

e+ source parameters

		ILC250	
Electron beam energy	GeV	126.5	
Active (total) undulator length L_{und}	m	231 (320)	
Undulator K		0.85 (FC)	0.92 (QWT)
Photon energy (1st harmonic)	MeV	7.7	7.2
Average photon beam power	kW	63	72
Distance target – middle undulator	m	401	
Photon beam spot size on target (σ)	mm	1.2	1.45
Average power deposited in target (1312 bunches/pulse)	kW	1.94	2.20
Peak energy deposition density in rotating target (1312 b/pulse)	J/g	61.2	59.8
Positron polarization	%	~30	

- so far, e+ source simulations assumed ideal undulator
- yield with QWT below 1e+/e- ➔ alternatives see P. Sievers’ talk

Cooling of the target wheel

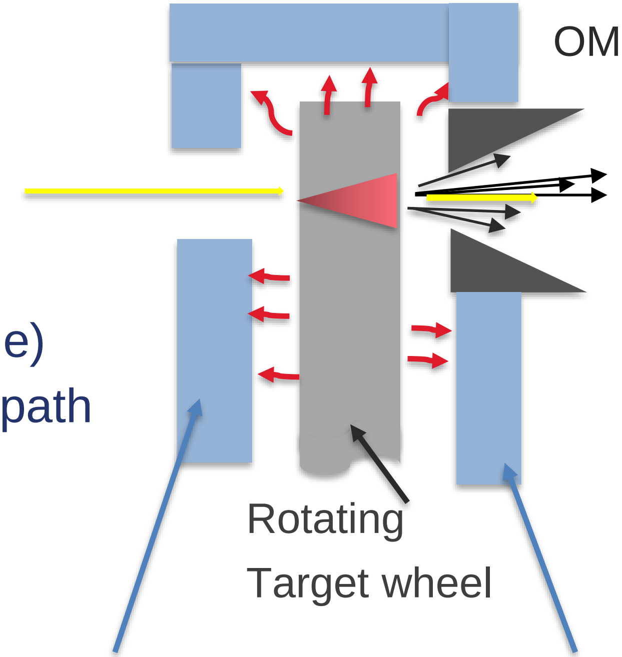
- Water cooling (TDR) does not work
- Few kW heat deposition can be removed with thermal radiation:
  - heat radiates from spinning target to a stationary water-cooled cooler

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

ε = effective emissivity

- Ti alloys have low thermal conductivity
  (λ = 0.06 – 0.15 K/cm/s)
  - heat propagation ~ 0.5cm in 7sec (load cycle)
  - heat accumulates in the rim near to beam path

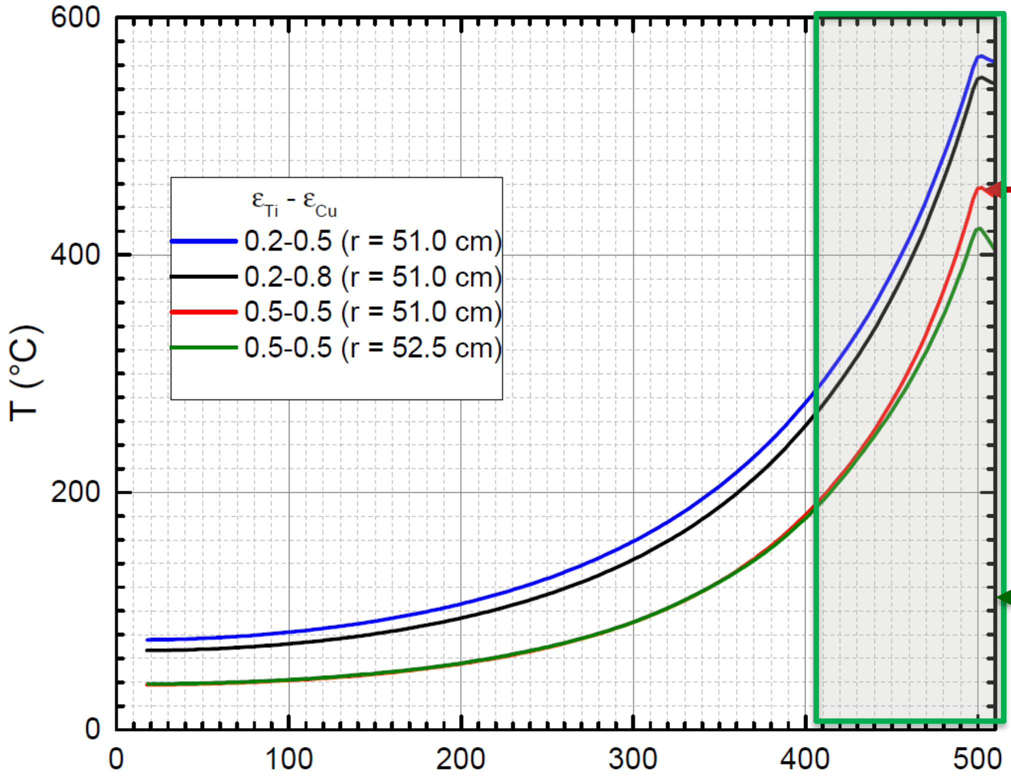
Side view cutout e+ target



stationary water-cooled cooler, T_{cool}

Temperature distribution in target

Average temperature in Ti6Al4V wheel as function of radius r for different surface emissivity of target and cooler (Cu); Target wheel assumed as disk



Photon beam impact at r=50cm

Deposited power = 2kW

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

$T_{ave} \leq 460$˚C

max average temperatures can be decreased for larger wheel radius

Main cooling power from area with r_0 ±5cm

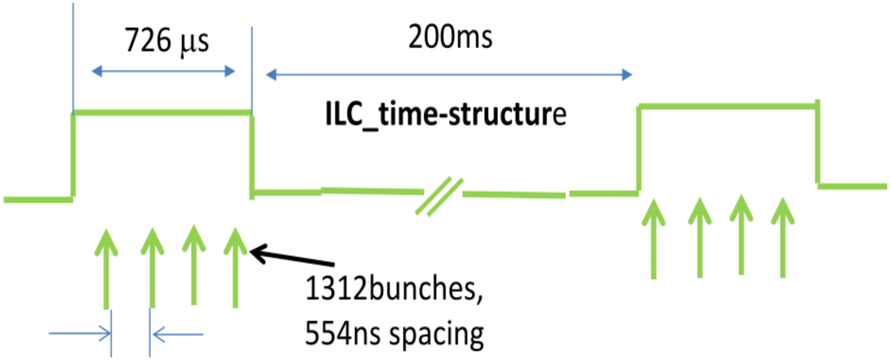
F. Dietrich

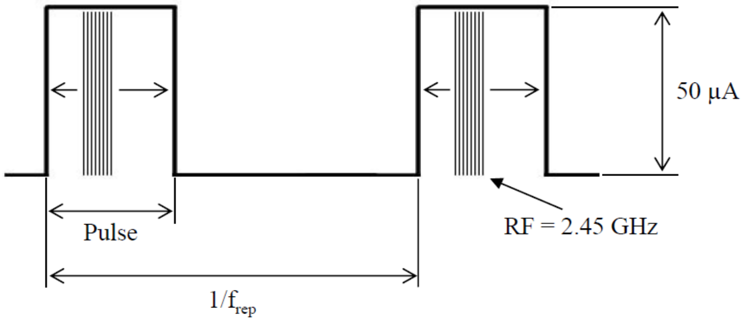
Studies (FLUKA, ANSYS) show that such spinning disk stands heat and stress load

Material Tests

	ILC e+ target	MAMI	
Beam particles	photons	electrons	
Average energy	7.5…40MeV	14MeV, 3.5MeV,	180MeV(plan)
ΔT_{max} /pulse	60-120K	50-350K	
Max energy deposition density	~60J/g	~50-200J/g *	
Eff. pulse length on material	25-55μs	1-5ms	O(50μs)
Eff. pulse rep rate on material	0.17 Hz	1Hz …120Hz	
Displacement per atom (dpa)	~0.3-0.5 per year	~0.33/24h (14MeV) ~0.22/24h (4MeV)	

* Load adjusted by beam spot size,





Tests performed for Ti6Al5V (choice)

year	thickness [mm]	Pulse length [ms]	Rep. rate [Hz]	ΔT/pulse [K]	T_{ave} @ spot [C]	# load cycles
2016	1	2.0	100	~60-80	≥630	6.8×10^6
	2	2.0	100	~60-80	710…~1000	5.2×10^6
2017	0.2	2	100	455	40	6.2×10^6
2018	0.2	1.5	10	350	98	54,000
2018	0.2	1.5	20	335	155	48,000
	0.2	1.0	100	240	365	100,000
	0.25	1.0	120	230	425	324,000
	0.25	0.5	140	170	300	336,000
	0.5	1.00	100	230	435	240,000
	0.5	0.5	100	170	280	240,000
	0.5	0.5	140	160	345	336,000

Plan: use the e- beam with 180MeV

- Tests with shorter pulse length (ms → ~50 microsec)
- use samples of ~5mm thickness
- Test also alternative high temperature Ti alloys, e.g. Ti SF61

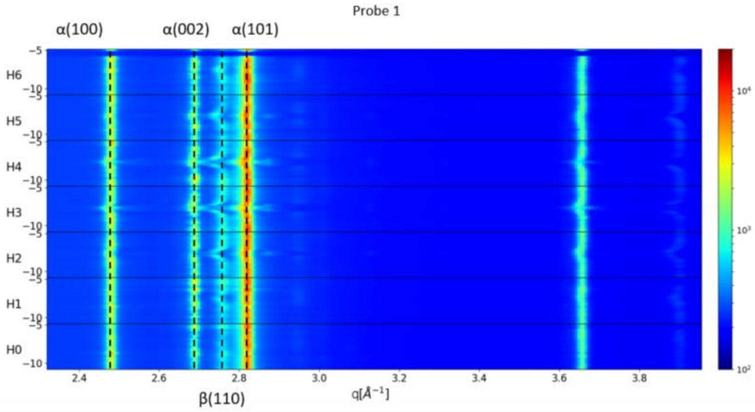
Analyses of irradiated samples

- Surface inspection by laser scanning
- Scanning electron microscope
- synchrotron diffraction methods performed
  - Used in transmission as well as in reflection geometry
  - Phase transitions between α- and β-phase in Ti-alloy observed in case of heavy overloading
  - Overloading yields grain growth in Ti alloy
  - Thin foils of Ti and Ti alloys stand high PEDD
- Target material will stand the load by photon beam

A. Ushakov et al.

TUPAB002 IPAC2017

See also Bachelor Thesis of T. Lengler



Upgrades (E, L)

Ecm	GeV	250	350	500
Active undulator length	m	231	147	
Undulator K		0.85	0.66	0.45
Photon yield	γ/e-	393	157	76.1
Photon energy (1st harmonic)	MeV	7.7	17.6	42.8
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 (σ)	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

Luminosity upgrade

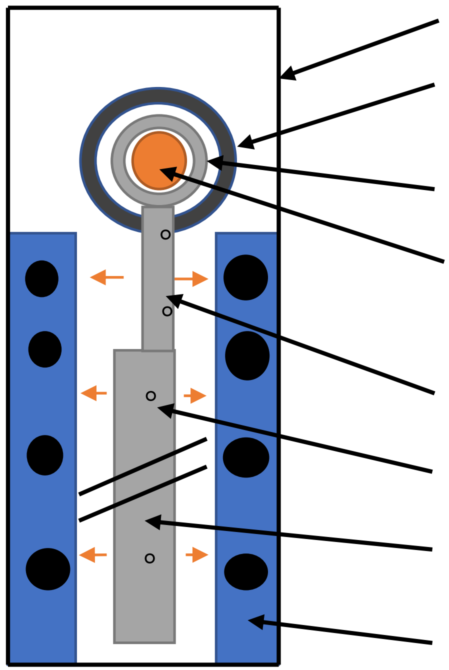
- doubles the power deposited in target ⇔ average T(in K) is increased by factor ~1.2
- PEDD is increased by factor ~1.5

Target wheel design (1)

- Continue material tests to test and confirm robustness of baseline and alternative target material
    - Remark: irradiation of thin foils test the performance of material for the exit window to the photon dump
- Optimize target geometry
    - Keep temperatures, stresses, etc. well below the limits while maintaining the required e+ yield
    - Study influence of eddy currents (heating, drag forces) caused by B field at target from OMD
    - Studies to be done with ANSYS, COMSOL,…
    - Lab test of target sector to confirm cooling performance

Set up for the lab test to confirm the radiation cooling performance using a target sector

Side View



Vacuum Tank

Multi Layer Super Insulation

Conductor to bring heat to target

Electrical Heater (~1kW), simulating the average beam power.

«Ti-Target»

Thermo-Couples

«Ti-Radiator»

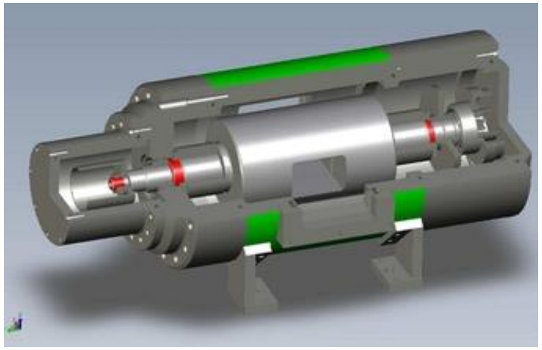
Water Cooled Cooler

Test robust connection of target material (low heat conductivity) to a "radiator" with high heat conductivity to achieve higher cooling efficiency

Target wheel design (2)

Drive and bearings

- Radiation cooling allows magnetic bearings
  - A standard component to support elements rotating in vacuum.
  - The axis is «floating» in a magnetic field, provided by permanent or electro magnets
  - Allows long time operation at high rotation speed without maintenance
  - Among other things, magnetic bearings are used as Fermi-choppers in Neutron Physics and Spallation Sources.
  - Breidenbach et al. presented at ICHEP2016 a design proposal using magnetic bearing (see backup) for the undulator target
- For the specific ILC-application, a technical specification of the required performance and boundary conditions has to be negotiated with the supplier.
  - Specification to be done based on simulation studies

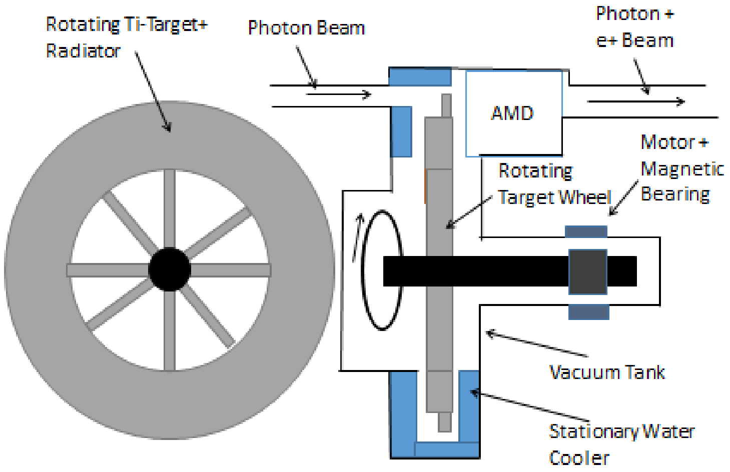


Fermi-Choppers für BRISP
Copyright: Prof. Dr. Pilgrim,
Philipps-Universität Marburg

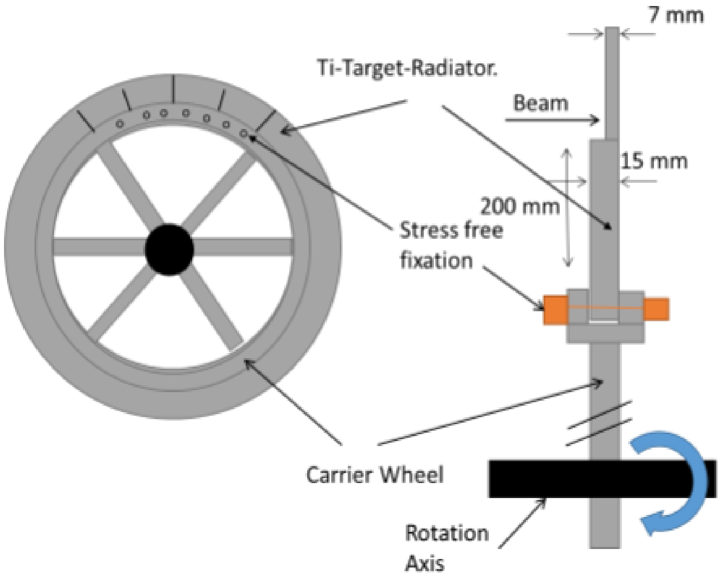
More details and considerations

see also: M. Fukuda, LCWS2017

Principle layout: Ti wheel with diameter 1m, rotating at 100m/s, 2000rpm
Main components: cooling system, magnetic bearing , OMD



Target can be connected with carrier wheel of appropriate material to optimize cooling performance



Not to scale!

Layout of wheel and details of target sectors detail mounted onto carrier wheel

- free thermal expansion
- Reduced eddy current
- synchronize rotation with beam pulses by fine tuning to avoid luminosity loss by expansion slots

Summary

- Sc helical undulator: consider realistic undulator spectrum (see talk K. Alharbi)
- Target wheel design:
  - Cooling by thermal radiation, thus avoiding a vacuum tight rotating seal (organic oil and iron powder).
    - Demonstrate the robustness of the target material against cyclic load at high temperatures
    - Laboratory test of the efficiency of the cooling by radiation on a small sector of the wheel under vacuum
  - Wheel completely, hermetically sealed in UHV-vacuum.
  - Rotating axis supported by contactless, maintenance free magnetic bearings.
- Develop a design for the capture optics (see P. Sievers' talk)
- Target wheel + OMD design:
  - Minimize temperatures and stresses in the spinning wheel including the magnetic field of the capture optics
  - optimize volume and weight
  - Magnetic bearing + drive: Specification for the a technical specification of the required performance and boundary conditions has to be negotiated with the supplier
- Prepare design of mock-up for system target+OMD, tests

Back-up

ILC250: parameters of undulator and photon beam

Undulator Prototype → **K_{max} = 0.92 and λ_u = 11.5mm is “fixed”**

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

first harmonic: $E_{1\gamma} \sim \frac{Ee}{\lambda_u(1+K^2)}$ → low K increases photon energy

  - Number of photons $N_\gamma \sim L \cdot \frac{K^2}{\lambda u}$ → low K gives less photons

- 125GeV e- beam requires high K and maximum active undulator length

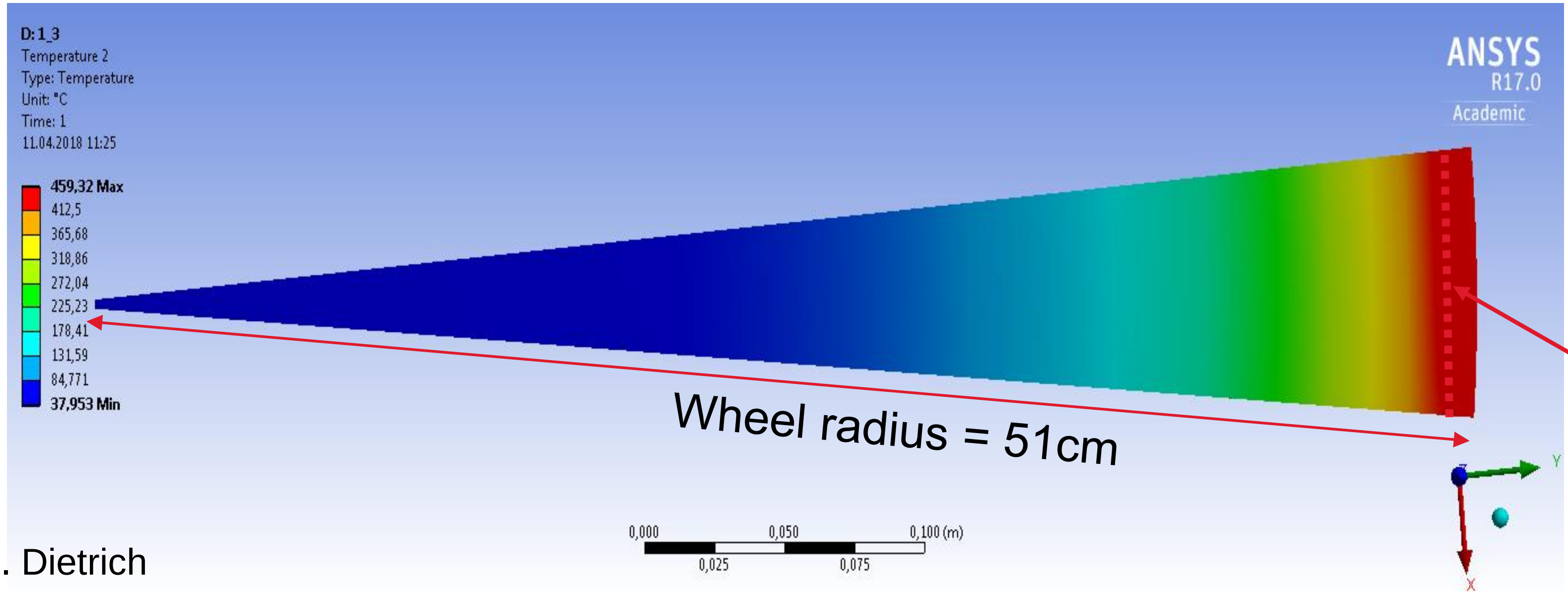
- Opening angle of photon beam ~ $\sqrt{(1+K^2)} / \gamma$ → higher synchrotron radiation level at undulator wall

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 (ε_{Ti} and ε_{Cu})

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

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



Photon beam pulse

F. Dietrich

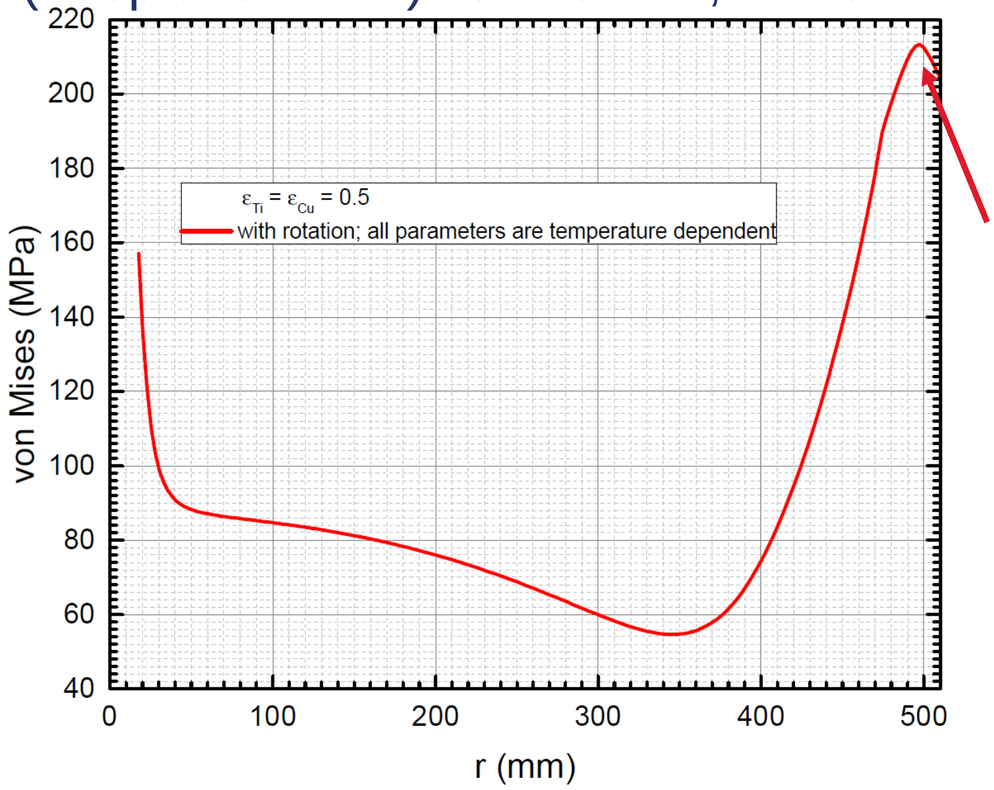
Average stress in target, ILC250, 1312b/pulse

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

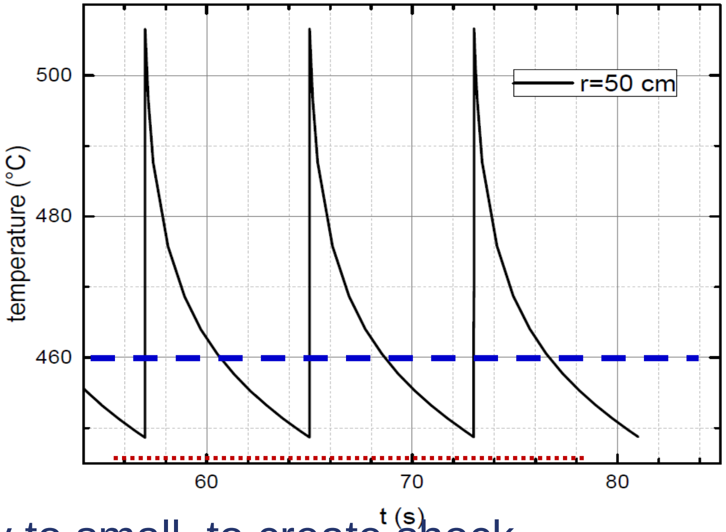


Photon beam impact at r=50cm

F. Dietrich

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, ε_{eff}= 0.33 for ε_{Ti} =ε_{Cu}=0.5)



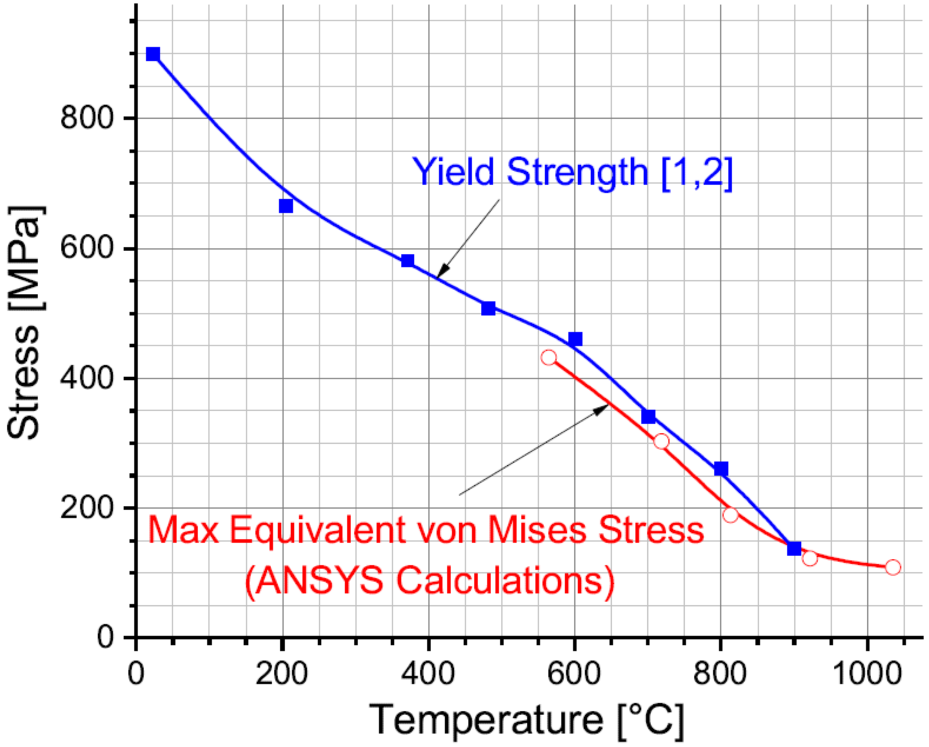
- **Resulting peak stress at beam path**
  - Time of energy deposition is to slow, intensity to small to create shock waves, thermal expansion along z is possible, restricted along r
  - Estimate stress by pulse: $\sigma_{peak} = E\, \alpha\, \Delta T / (1-\nu)$

    $\sigma_{peak} \approx 75$ 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 stress of 300 MPa for ILC250 (nom.Lumi)

Lumi upgrade → Peak stress values could exceed limits



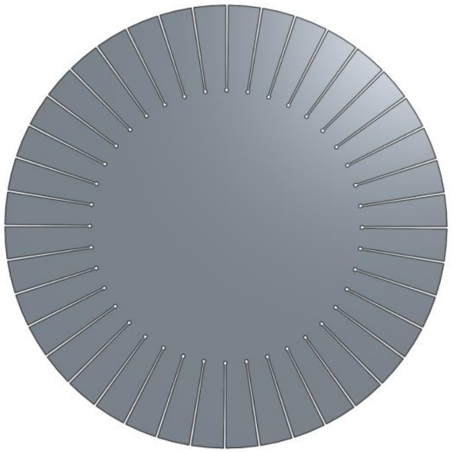
Stress reduction is possible with expansion slots

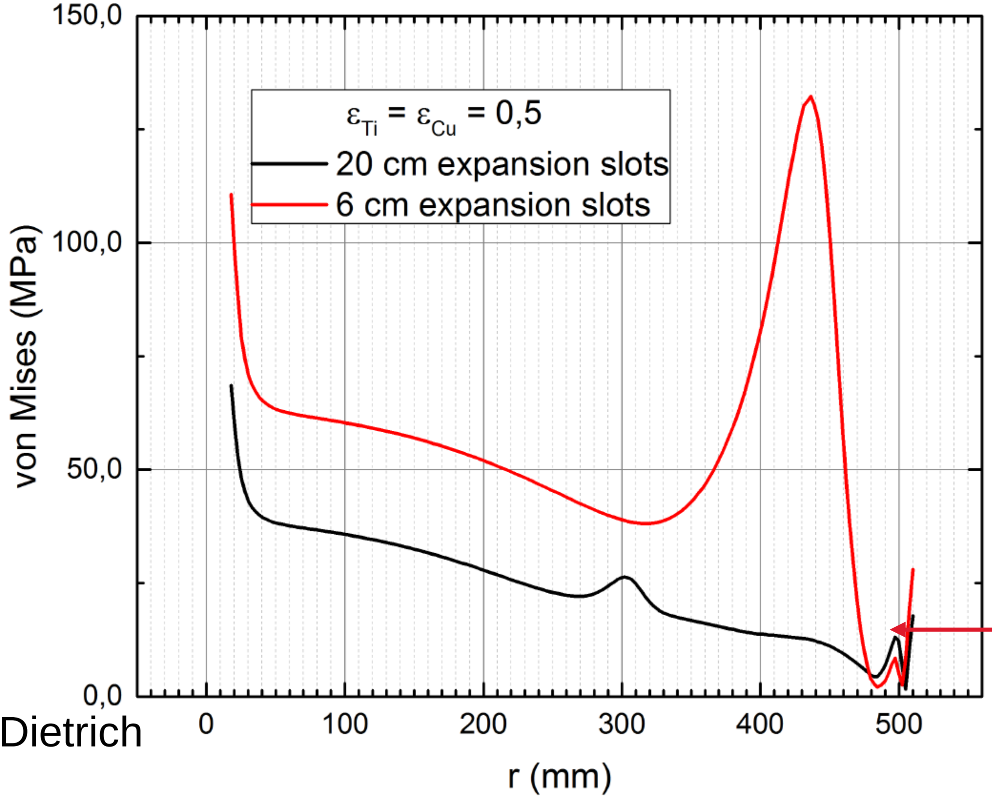
Average stress in target, ILC250, 1312 b/pulse

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!

Drive and bearing

Design Proposal by M. Breidenbach et al, ICHEP 2016: