Status of the undulator-based positron source

October 31st, 2019

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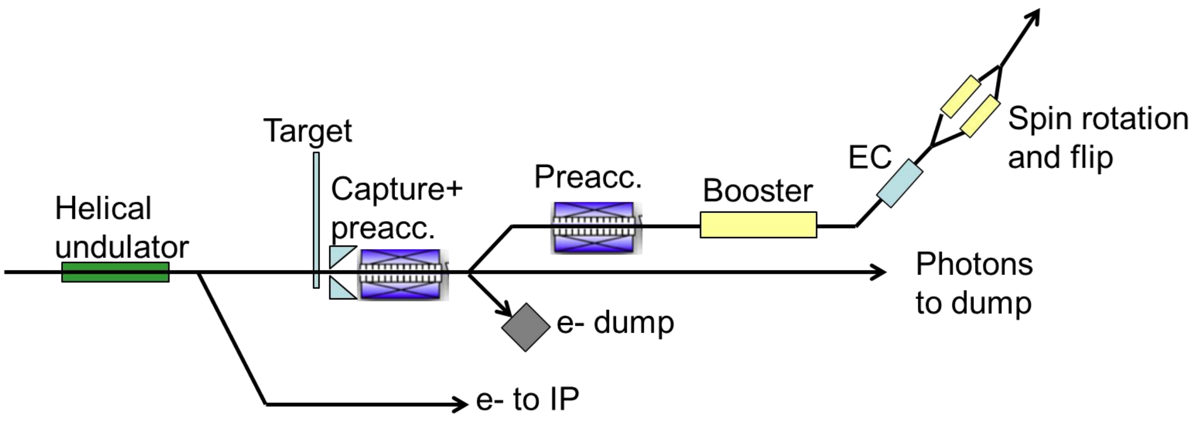
Outline



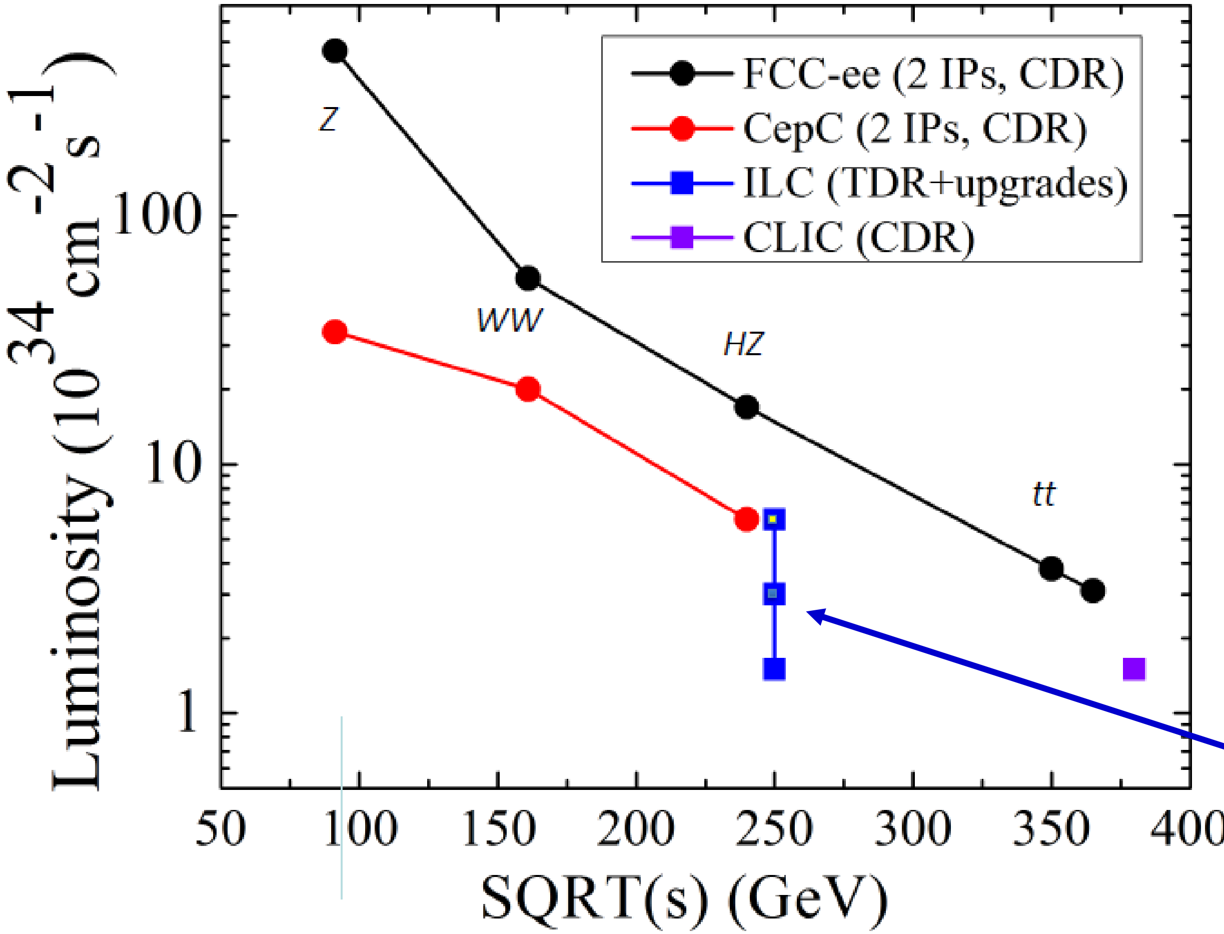
- Target design and cooling with respect to ILC250 and GigaZ
  - **Undulator issues**
  - **Target**
- OMD
- Dump of photon beam
- Summary

What is new since 2018?

- Resources
  - – DESY e+ source group decreased
- To Do List is known since 2017
    - Prototyping (radiation cooling, spinning wheel, magn. bearing)
    - OMD
    - Photon beam dump

- FCC-ee and CEPC are serious competitors → ILC250 + GigaZ are important

Comparison of luminosities

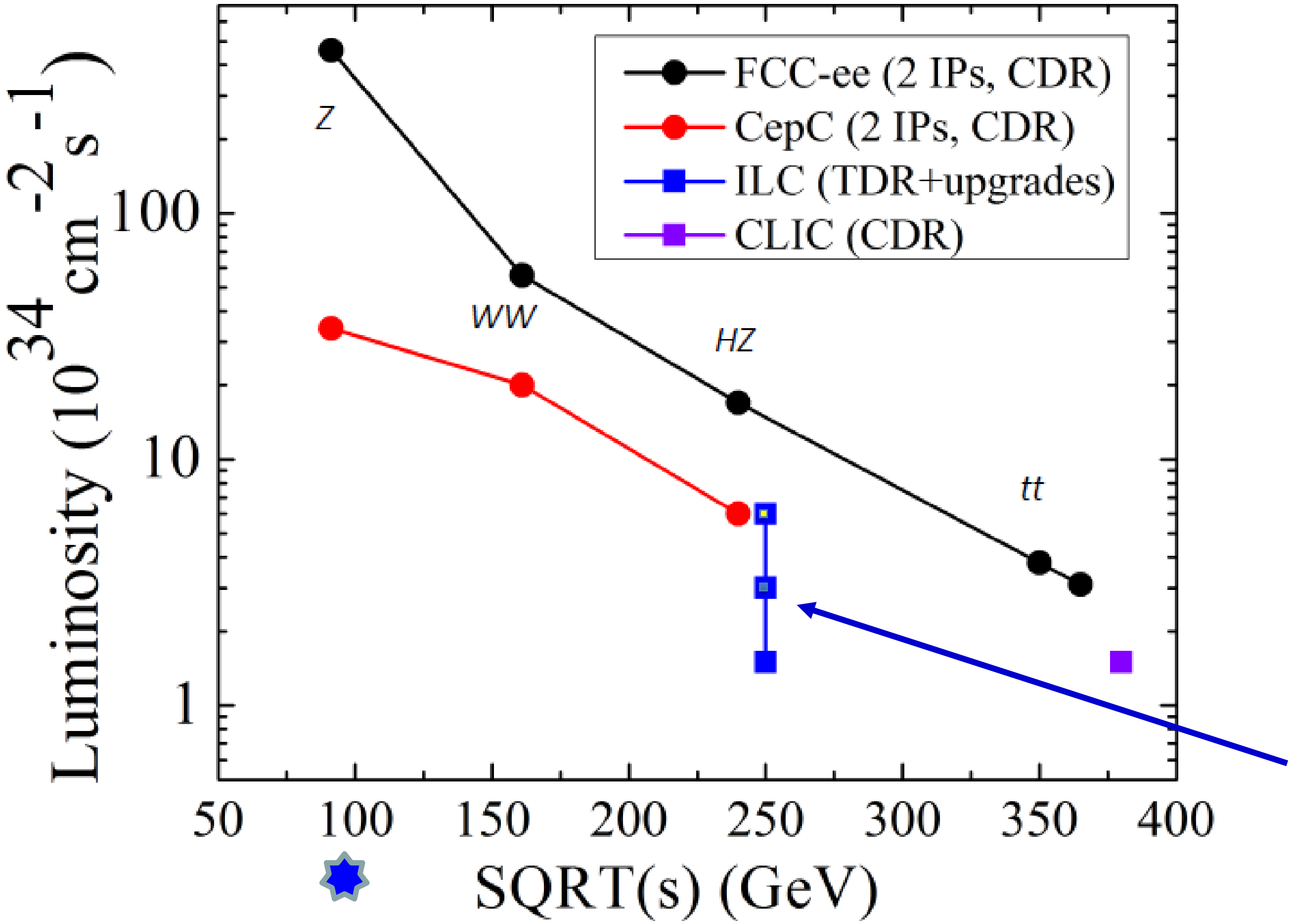


FCC-ee
arXiv:1906.02693

ILC250
arXiv:1903.01629

- 1312bunches/pulse
- 2625bunches/pulse
- 2625b/p + 10Hz

Comparison of luminosities



GigaZ

FCC-ee
arXiv:1906.02693

ILC250
arXiv:1903.01629

- 1312bunches/pulse
- 2625bunches/pulse
- 2625b/p + 10Hz

- FCC-ee: up to 5×10^{12} Z bosons expected (TeraZ)
- ILC-GigaZ: up to 10^{9} Z bosons per year

GigaZ: see talk by Yokoya-san, this workshop, and arxiv:1908.08212

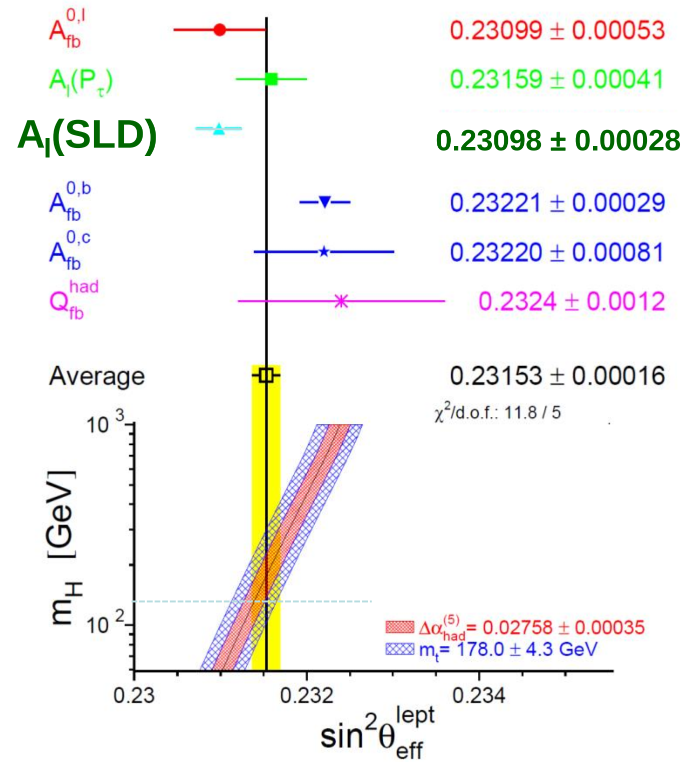
GigaZ vs FCC-ee??

Considerations on the complementarity of ILC250/GigaZ and FCC-ee can be found in arXiv:1905.00220

More details about GigaZ – see R. Poeschl's talk at LCWS19

Lesson from LEP/SLD: Measurement of $\sin^2\theta_{eff}$

Phys.Rep. 427(2006)257
[hep-ex/0509008]



LEP (circular collider)

- Unpolarized e+, e- beams, 17×10^6 Z events

SLD (linear collider)

- Polarized electron beam, 5×10^5 Z events

$$A_{LR} = \frac{2(1-4\sin^2\theta_W^{\mathrm{eff}})}{1+(1-4\sin^2\theta_W^{\mathrm{eff}})^2}$$

GigaZ

- Polarized e+ and e- beam
- Up to 10^9 Z events per year
- Expect $\Delta\sin^2\theta^{lept}{}_{eff} \sim 10^{-5}$

With FCC-ee (up to 5×10^{12} Z events) $\Delta\sin^2\theta^{lept}{}_{eff} \sim 10^{-6}$ is expected

SLC measured $\sin^2\theta_{eff}$ better than LEP!
Beam polarization substantially improves precision!

Left-Right Asymmetry A_{LR}

$$A_{LR} = \frac{A_{LR}^{meas}}{\langle P_{eff} \rangle} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}} \cdot \frac{1}{\langle P_{eff} \rangle} = \frac{N_{LR} - N_{RL}}{N_{LR} + N_{RL}} \cdot \frac{1}{\langle P_{eff} \rangle}$$

- Essential for precise A_{LR} measurement with 10^8-10^9 Z events:
  - Uncertainty of polarization measurement $\Delta P/P \leq 0.1\%$ is required
  - This can be reached with polarized positron beam; $\Delta P_{eff} < \Delta P_e$
    - Although e+ polarization increases the 80-90% e- polarization only to a slightly higher effective polarization P_{eff}, error propagation decreases substantially the uncertainty of the resulting effective polarization
  - using all 4 initial helicity combinations → determine P and A_{LR} simultaneously

$$A_{LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

$$P_{e\pm} = \sqrt{\frac{(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})(-\sigma_{++}\pm\sigma_{-+}\mp\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})\ (+\sigma_{++}\mp\sigma_{-+}\pm\sigma_{+-}-\sigma_{--})}}$$

→ Positron polarization is extremely helpful, especially at GigaZ

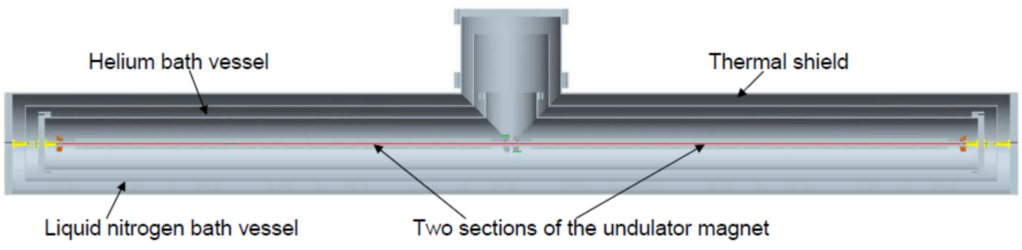
Benefit of polarized e+ and e- beam

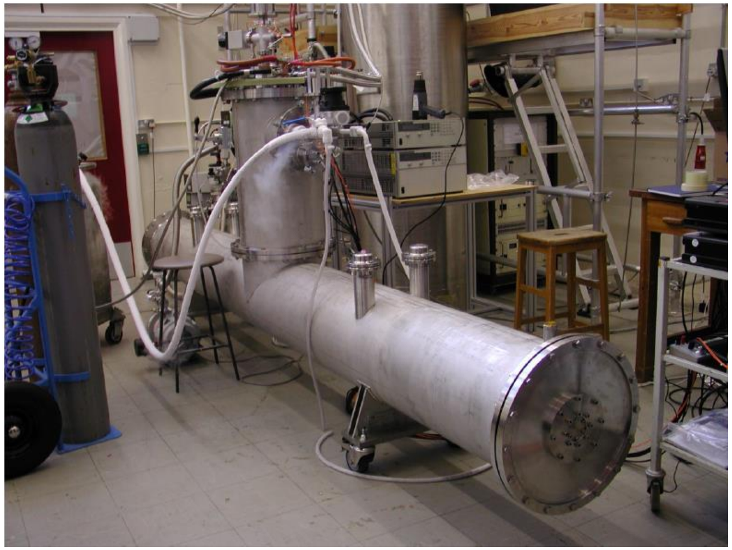
- higher effective luminosity with the 'right' helicity combination of initial states: $L_{eff}/L = 1-P_{e-}P_{e+}$
  → with P(e-,e+) = ($\pm$0.9;$\mp$0.3) L_{eff} is higher by factor ~1.3
- Improved discrimination and control of background processes
  - each of the 4 combinations of initial e+ and e− helicity states can be explicitly realized in collisions
- If both beams are polarized, systematic effects (time-dependent effects, correlations or a bias in the polarimeter measurement) can be much better controlled, and their impact on the uncertainty of observables can be substantially reduced
- In case of deviations from the Standard Model predictions, polarization of both beams enhances the sensitivity to new phenomena
- An (additional) independent determination of beam polarization and left-right asymmetries is possible only if both beams are polarized.
- also the zero polarization of an unpolarized positron beam must be confirmed to avoid any bias in the physics analyses

Superconducting helical undulator

D.Scott et al.,
Phys. Rev. Lett. 107, 174803

- Prototype developed at RAL
  - 2 unduator modules of 1.75m in 4m cryomodule





- Parameters
  - Undulator period, λ_U =11.5mm
  - Undulator strength K ≤ 0.92 (B_{max} ≤ 0.86T)
  - Beam aperture (diam.) 5.85mm

  - Max 231m active undulator length available (132 undulator modules ⇔ 66 cryomodules]
  - Quadrupoles every 3 modules → total length of undulator system is 320m

ILC250 and GigaZ

- Undulator K and length 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

ILC250:

- 125GeV e- beam requires high K and maximum active undulator length of 231m
  - Upper half of energy spectrum is emitted in cone ~1/γ masks are necessary to limit the energy deposition in the undulator walls to 1W/m (see Khaled's talk)

GigaZ: see arXiv:1908.08212

- 3.7+3.7 Hz scheme: use 125GeV e- beam for positron production, alternating with 45.6GeV beam for physics
- A 45.6GeV e- beam has low power, photon energy is low → no problem for target. But energy deposition in undulator wall has to be checked.

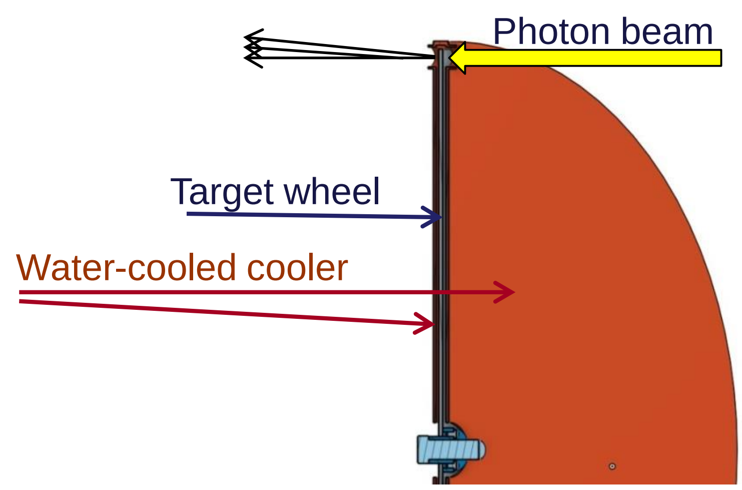
e+ source parameters

		ILC250		GigaZ
Electron beam energy	GeV	126.5		
Active undulator length L_{und}	m	231		
		With FC	With QWT	
Undulator K		0.85	0.92	
Photon energy (1st harmonic)	MeV	7.7	7.2	
Average photon beam power	kW	62.6	72.2	53.5
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	1.62
(2625 bunches/pulse)	kW	3.88	4.40	3.23
Peak energy deposition density in target (1312 b/pulse)	J/g	61.2	59.8	59.8
2625 b/pulse)	J/g	92.6	90.4	90.4
Positron polarization	%	~30		

Target for the undulator based e+ source

- Ti alloy wheel, Ø 1m, spinning in vacuum with 2000rpm (100m/s tang speed)

- ILC250, GigaZ: E(e-) = 125GeV
  - Photon energy is O(7.5 MeV);
  - target thickness of 7mm to optimize power deposition and e+ yield



- Target cooling
  - T^4 radiation from spinning wheel to stationary water cooled cooler
    - Peak temp in wheel ~550˚C for ILC250, 1312bunches/pulse
      ~500˚C for GigaZ, 1312bunches/pulse

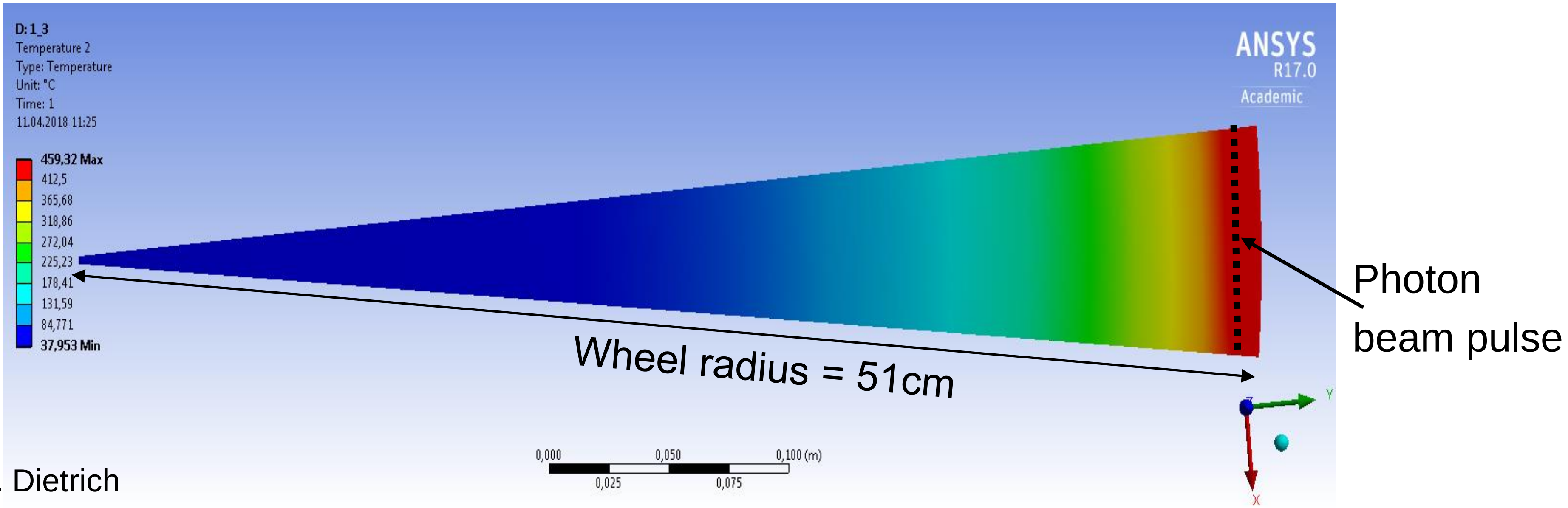
    assuming the wheel is a full Ti alloy disk (~simple design solution).

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

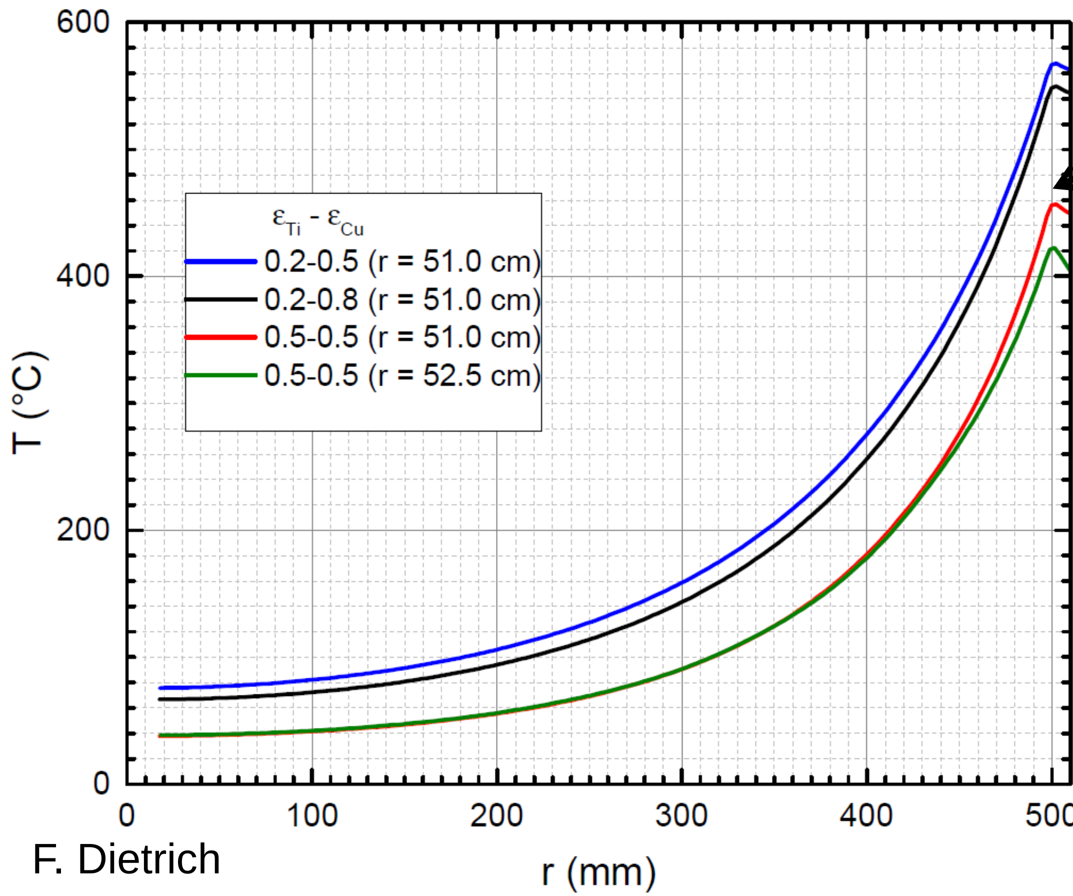
(ε_{eff}= 0.33; ε_{Ti} = ε_{Cu}=0.5)



F. Dietrich

Temperature distribution on target disk

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



F. Dietrich

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

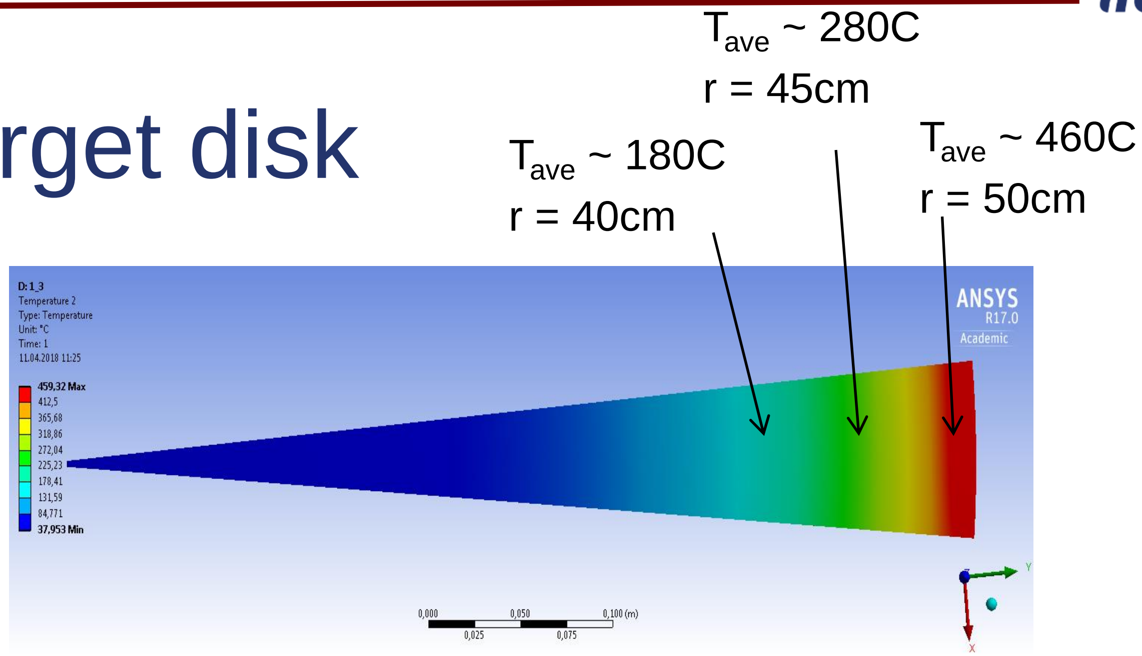
Deposited power = 2kW

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

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

→ max temperatures can be slightly decreased for larger wheel radius

Stress in the target disk

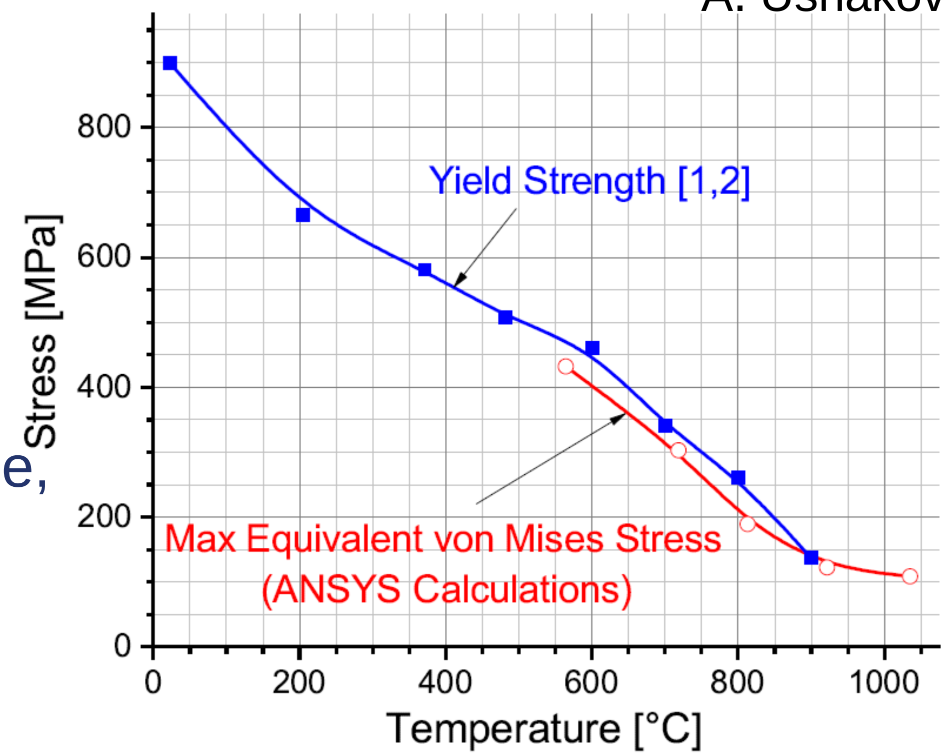


Large temperature gradient and cyclic load creates stress within disk, in particular in outer region (circumferential)

- Estimation of stress in target (ANSYS and ‘by hand’) showed max von Mises stress of 300-350MPa for ILC250 in case of a Ti alloy target disk. Rotation is included.
- Question: Does the target material resist the stress?

- Target and exit window material resistivity against high temperature and cyclic load was tested using an intense pulsed e- beam (14MeV, 3.5MeV) at the Microtron in Mainz (MAMI)
  - No substantial damage obtained although material was loaded below and above the phase transition limit
- Based on these tests Andriy Ushakov derived the stress limits depending on the temperature – see his talk at Posipol18
- For ILC250, 1312 bunches/pulse, a 7mm thick Ti alloy disk can be cooled by thermal radiation.

A. Ushakov



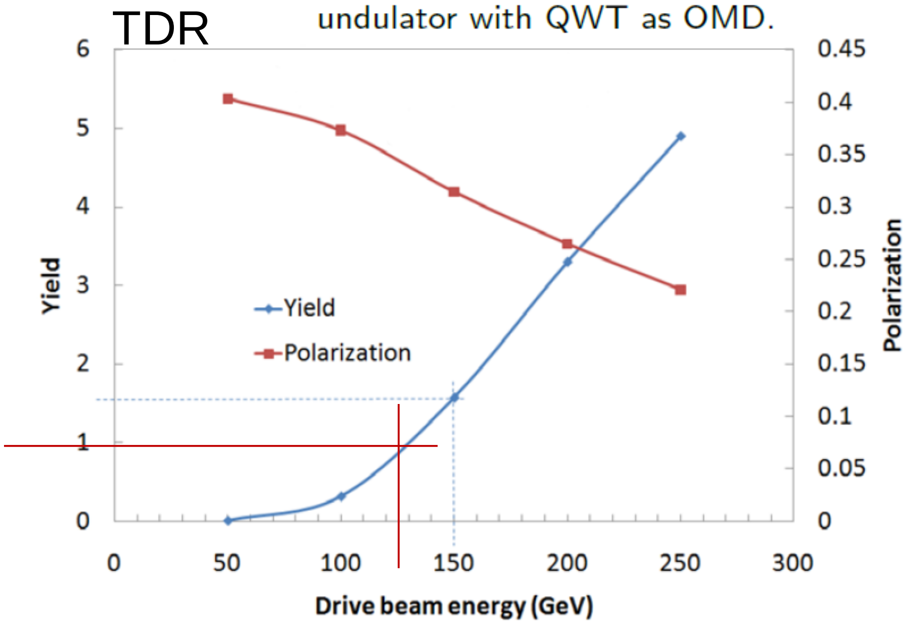
Target design & luminosity upgrade

- 2625 bunches/pulse → High average temperature ~650˚C in the rim region for full Ti disk
- At least expansion slots are required to reduce the stress in the outer rim
- Reduce max temperatures with the help of a special radiator
  - Radiator consists of material with high thermal conductivity for faster dispersal of heat
  - This option has been often discussed in the past – with and without fins, connection of Ti rim with radiator etc. A design with radiator will work. Peter Sievers will present an update. However, final engineering design including tests is needed.

Positron yield

- Electron energy 125GeV (126.5GeV to compensate loss in undulator)
- Photon energy is O(7.5 MeV)

Simulation results of positron source yield and polarization for 231 m RDR undulator with QWT as OMD.

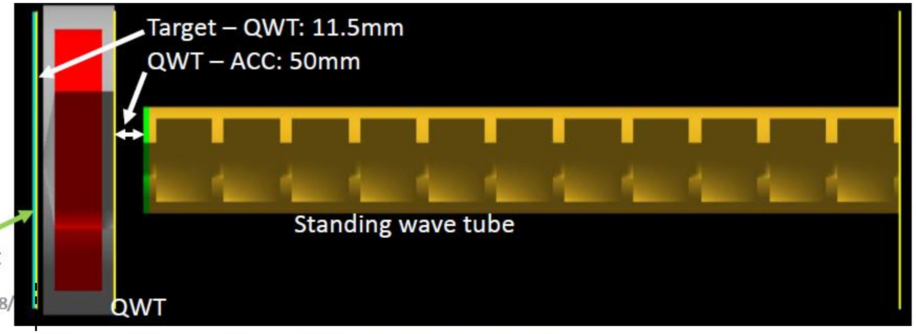


- yield is ~1e+/e-
  for E(e-) = 125GeV

Need to optimize/improve the e+ capture

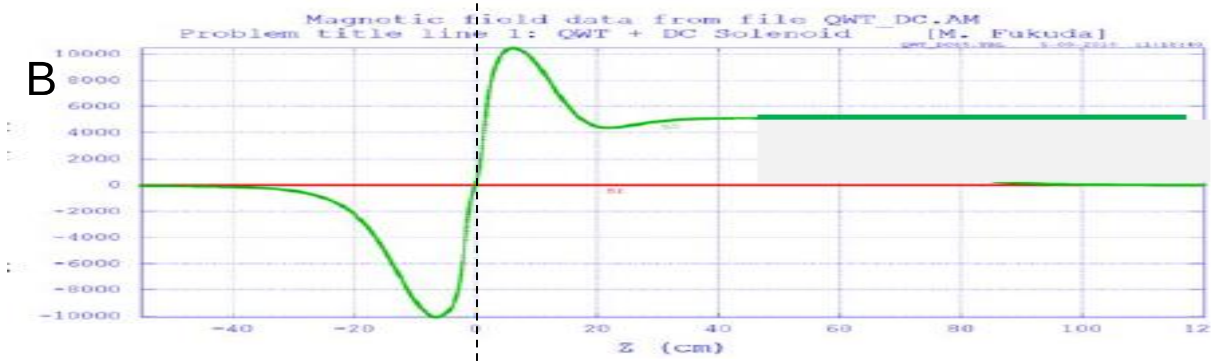
OMD: QWT

M. Fukuda, LCWS18



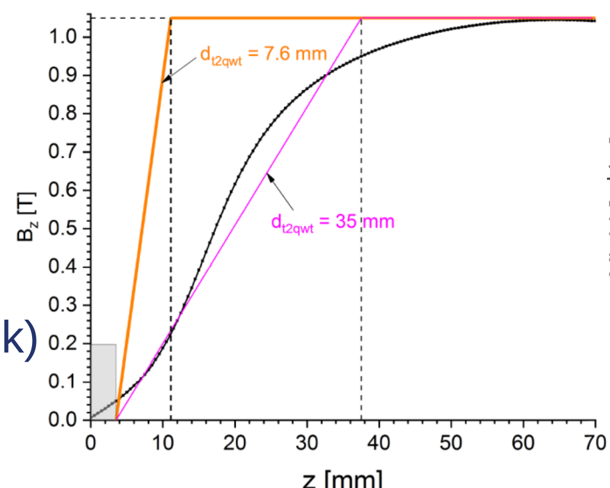
Y < 1e+/e

B

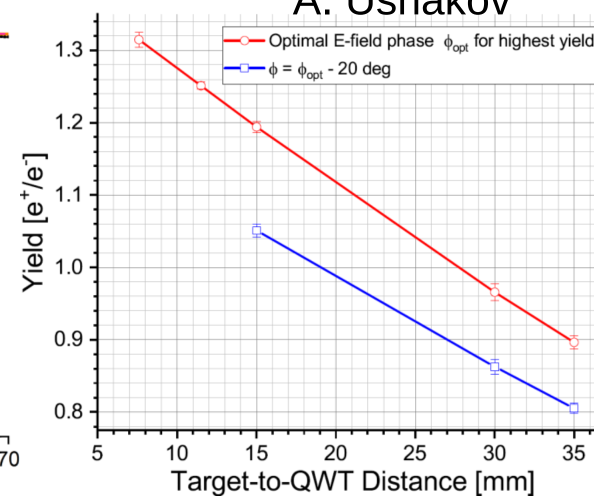


B field is decisive for positron yield

- Steeper field rise close to target needed for yield > 1 e+/e-
- Immersed target could help but eddy current increase heat load for non-pulsed operation
  (see also P. Sievers talk)
- Optimization is under study → talk Fukuda

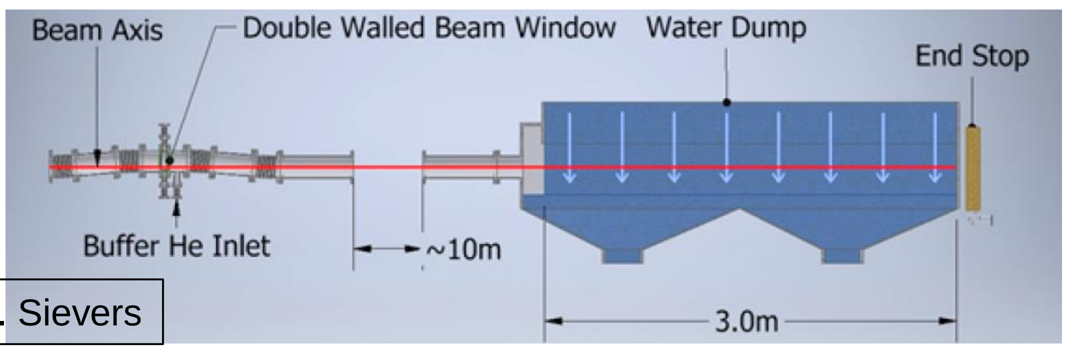


A. Ushakov



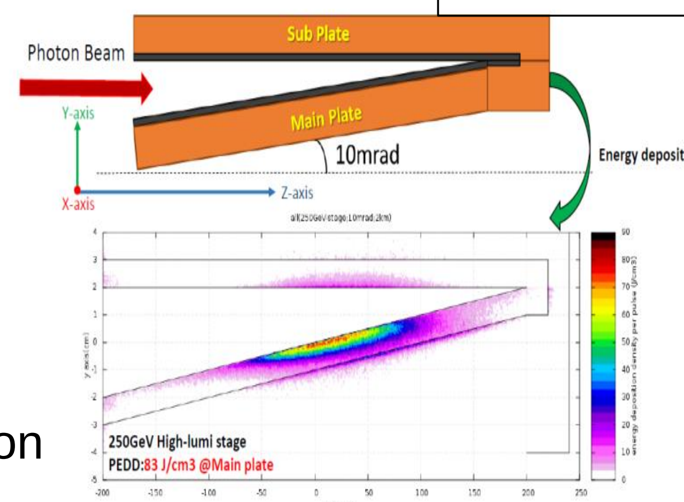
Photon dump

- Narrow 60-120kW photon beam deposits only few percent in target
- Problem: high energy density of photon beam even at distance of O(km) from target
- Options under study
  - Water dump
    - Tumbling Ti window, He cooled ⬄ stress and heat load is acceptable (see load tests on foils 2017/18 with e-beam at MAMI)
    - Free falling water curtain to absorb the photon beam and to scatter particles at safe distance to Ti window



P. Sievers

Y. Morikawa



  - Graphite dump
    - Shallow angle (~10mrad) to beam
    - No need for exit window
    - But: high peak load and graphite degradation

Summary

- e+ beam polarization is an important advantage of the undulator-based source. At GigaZ e+ polarization provides a substantial benefit for the measurement of the weak mixing angle (A_{LR} measurement)
- No showstopper seen for undulator-based source
  - However, the baseline undulator is at ‘edge’, for ILC250
  - GigaZ with (current) ILC250 has no problem with target
  - further studies for undulator parameters (?)
- Roadmap is clear; detailed engineering specifications for target wheel and experimental tests still to be done
  - Test cooling efficiencies by thermal radiation for a target piece
  - Develop full-size mock-up for the target to test the target rotation in vacuum
  - Photon dump design
- Resources
  - DESY e+ source group decreased:
    - Andriy and Felix left, SR retired; no successors
    - Khaled (PhD student) studies undulator (see his talk)

- Backup and old slides (mainly from posipol18),

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	γ/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 (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

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)
    - ΔT depends on average T in target since specific cheat depends on T
- Average temperature
  - simple scaling: max T_{ave} [K] rises by ~$2^{1/4}$ in comparison to nominal lumi
    i.e. 460 C → about 600 C for our ILC target parameters (ε_{eff} = 0.3)
  - Larger temperature rise per pulse and low thermal conductivity complicate this simple scaling;
  - ANSYS sim (Felix Dietrich): . max T_{ave} ≈ 650 C ε_{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)

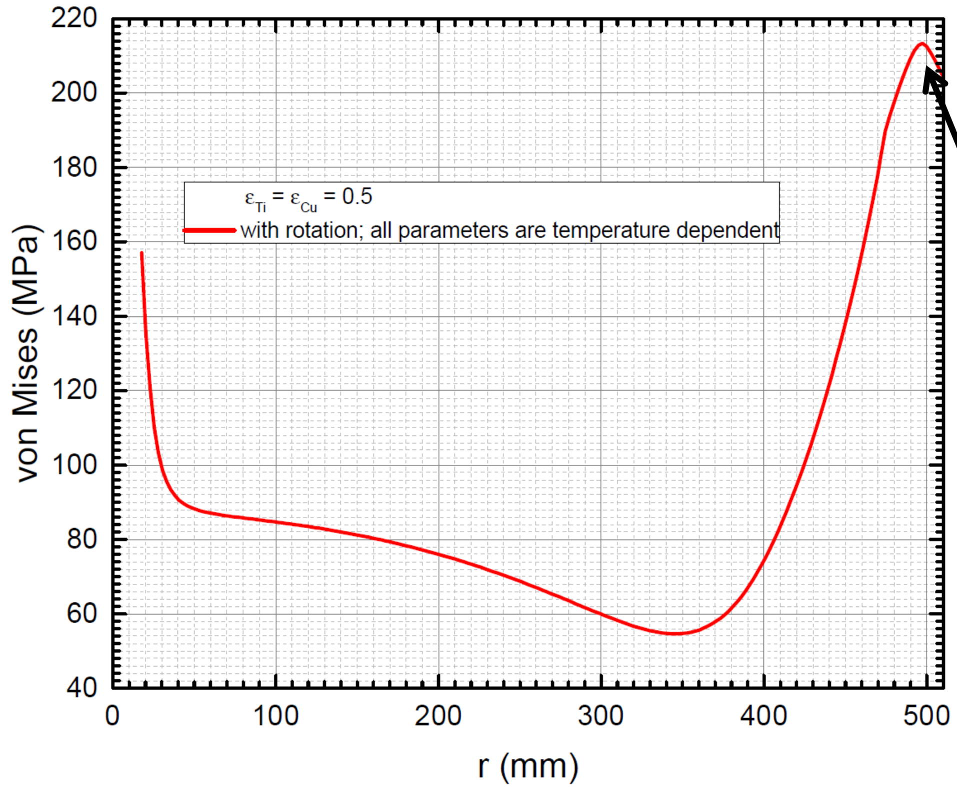
Average stress in target, ILC250, 1312b/pulse

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

σ_{vM} < 220MPa



Photon beam impact at r=50cm

F. Dietrich

Dynamic stress at radius r

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

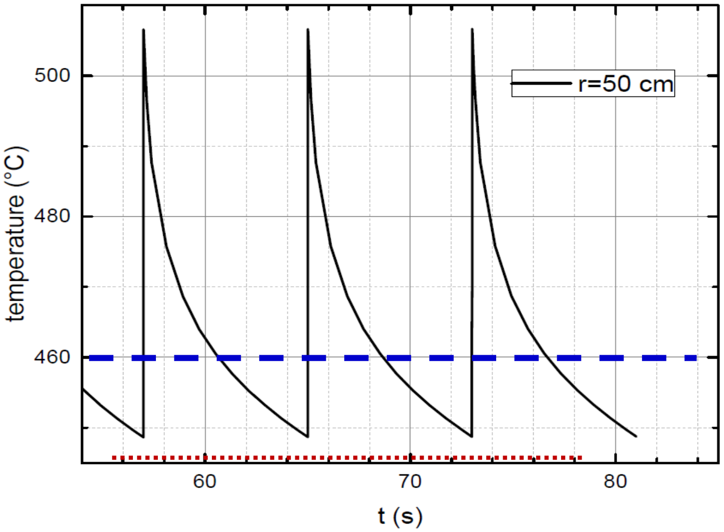
$$\sigma_{\mathrm{r}} = \frac{3+\nu}{8}\rho\omega^2\left(1+\frac{r_i^2}{r_o^2}+\frac{r_i^2}{r^2}-\frac{1+3\nu}{3+\nu}\frac{r^2}{r_o^2}\right)$$

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



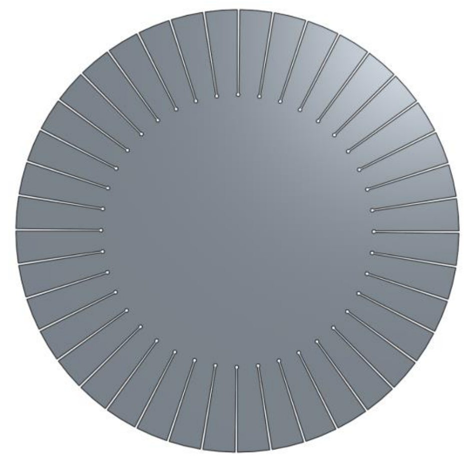
- **Resulting peak stress at beam path**
  - Time of energy deposition is too slow, intensity too small to create shock waves, thermal expansion along z is possible, restricted along r
  - Estimate stress by pulse: $\sigma_{peak} = E\,\alpha\,\Delta T\,/\,(1-\nu)$
    $\sigma_{peak} \approx 75$ MPa (ILC250, 1312b/pulse)
  - In total:
    $\sigma_{peak} <$ 220MPa (ave) + 75MPa (pulse) ≈ 300MPa (full target disk)
  - The stress is compressive

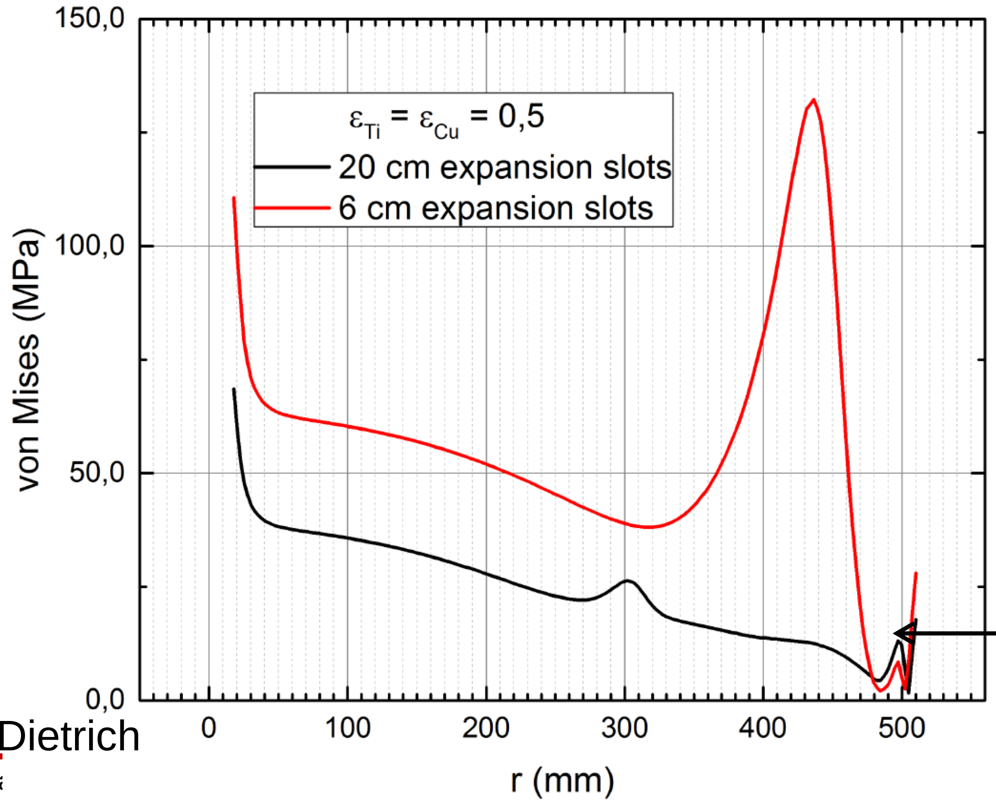
Average stress in target, ILC250, 1312 b/pulse

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

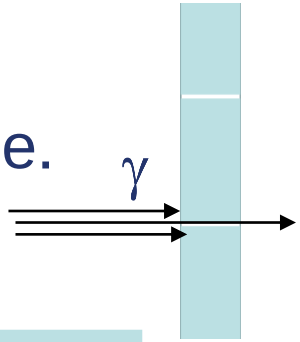
Expansion slots require synchronization with beam e- pulses ⇔ timing constraints!

F. Dietrich

Expansion slots & 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

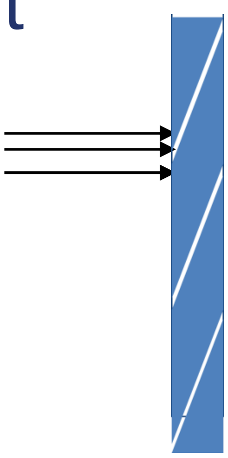
- smaller beam spot size at higher energies → less e+

		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 $T_{melt} \approx 750$K)
- 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