LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

Status and scope of the undulator-based positron source

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Sabine Riemann, Felix Dietrich, DESY,

Gudrid Moortgat-Pick, Andriy Ushakov (Hamburg U)

Peter Sievers (CERN)

Many thanks to the ILC positron group

Basic e+ source parameters

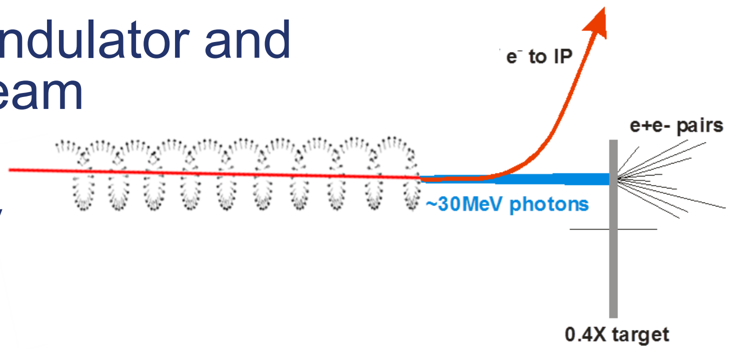
Electron beam energy	125 GeV
Number of particles per bunch	2×10^{10}
Number of bunches per pulse	1312
Repetition rate	5 Hz
Positrons per second at IP	1.3×10^{14}

(for comparison: SLC $2.4\text{x}10^{12}$/s ⇔ factor ~50)

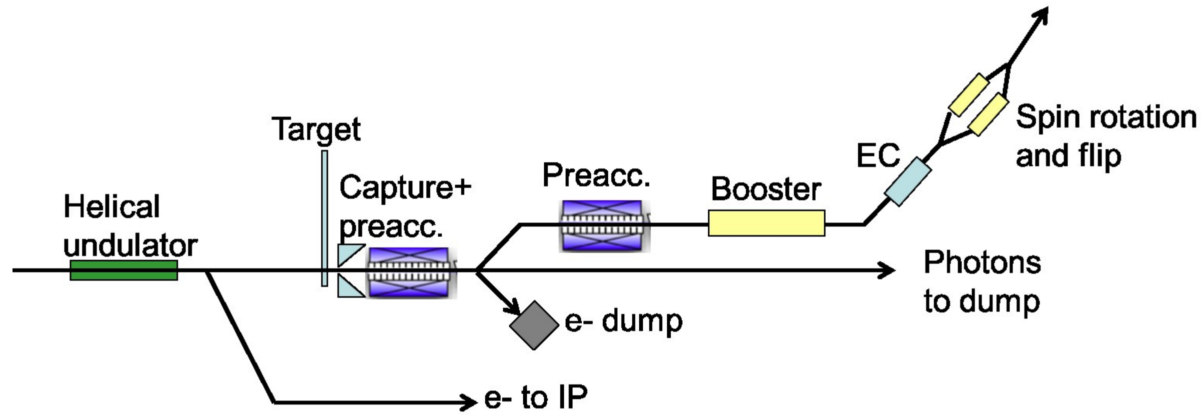
Required positron yield: Y = 1.5e+/e- at damping ring

Principle undulator based e+ source:

- High energy electrons pass a helical undulator and produce circularly polarized photon beam
- Photons strike thin target
- Generated e+ and e- are longitudinally polarized



Outline



Focus: ILC250

- Superconducting helical undulator
- Target design
  - Cooling by thermal radiation instead of water cooling
  - Discussion for engineering design
- Capture system
  - Optical matching device (OMD)
- Dump of photon beam
- Upgrade options
- Summary and plans

Results for ILC250 are documented in the Positron Source Working Group Report

ILC baseline design for the e+ source

- The undulator scheme became baseline since
  - Lower power is absorbed in the target
  - Substantially less neutrons are generated,
  - less activation of the target system
  - Positron capture more efficient due to higher phase space density
  - lower power dumped in the RF Capture section due to beam losses
  - Lower sensitivity to DR acceptance changes
  - **polarized positrons,** ~30% from beginning with option of upgrade
- Considered as "critical issues"
  - Design of spinning target wheel
  - Pulsed flux concentrator (long pulse length with high peak field)
  - Photon beam dump

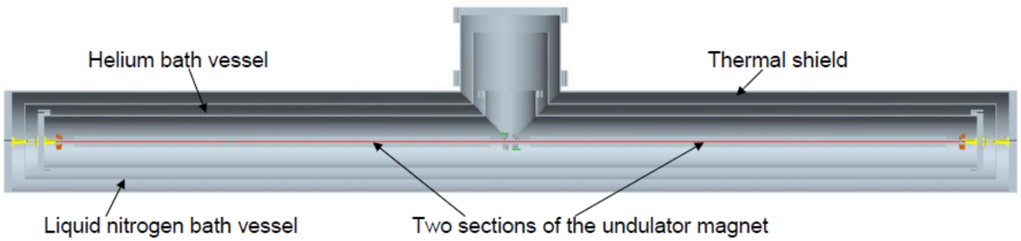
1. Is the undulator scheme feasible?
2. Can the feasibility be firmly verified in the time of design finalization?

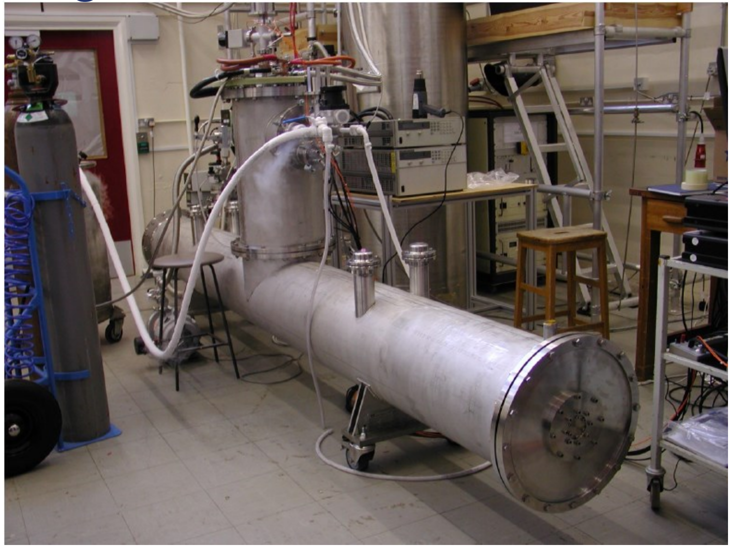
Superconducting helical undulator

- Parameters
  - Undulator period, λ_U =11.5mm
  - Undulator strength K ≤ 0.92 (B ≤ 0.86T)

    $K \sim B \cdot \lambda_U$
- 4m prototype (cryomodule) built and tested
- contains 2 undulator modules of 1.75m length

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





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

Helical undulator – parameters

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
    - photon energy depends on electron energy, λ_u and K:

      first harmonic: $E_{1\gamma} \sim \frac{E_e}{\lambda_u(1+K^2)}$

      → low K increases photon energy
  - Number of photons $N_\gamma \sim L \cdot \frac{K^2}{\lambda_u}$

    → low K gives less photons
  - Using the 125GeV e- beam for e+ production requires high K and maximum active undulator length
- Opening angle of photon beam ~$1/\gamma$
  - Spot size on target determined by electron energy
  - Small beam spot size even at large distance from undulator

ILC250

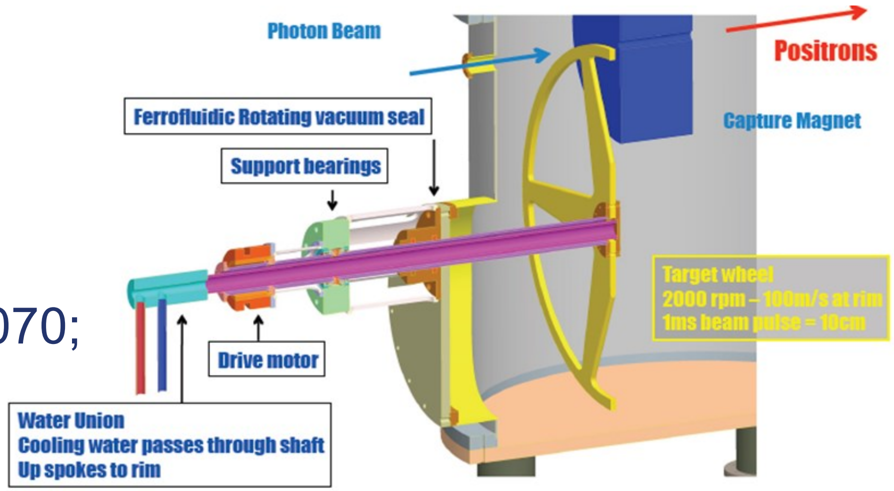
Parameters of undulator and photon beam

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

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 (TDR)
- Water cooled target rim with spokes (TDR)

- Prototyping at LLNL
  - Test ferrofluid vacuum seals
  - Test bearing
  - See Gronberg et al., arXive1203.0070; Gronberg et al., POSIPOL2013

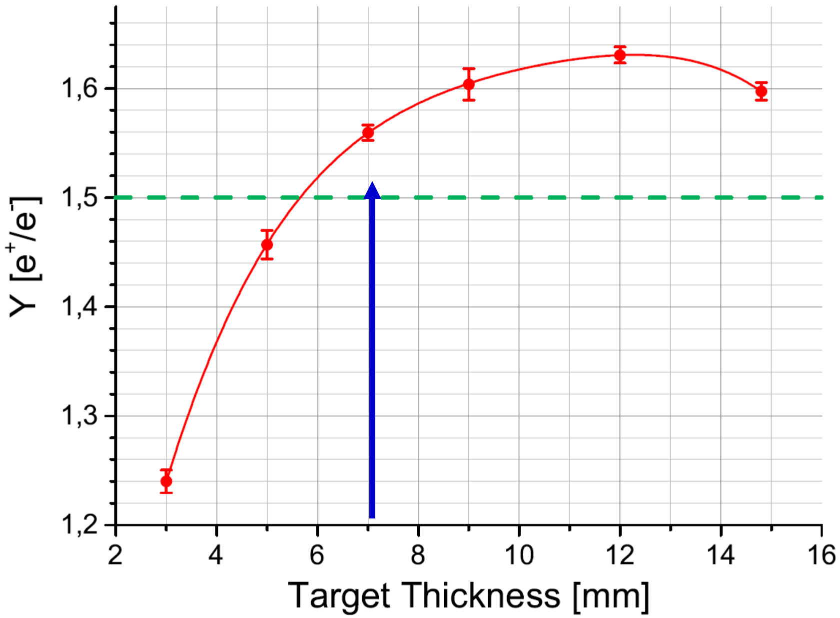


- Important lesson from prototyping
  - water-cooling of the wheel will be extremely difficult → Find an alternative, e.g. radiative cooling

Positron target for ILC250

Target thickness

- Photon energy is lower for ILC250 (~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

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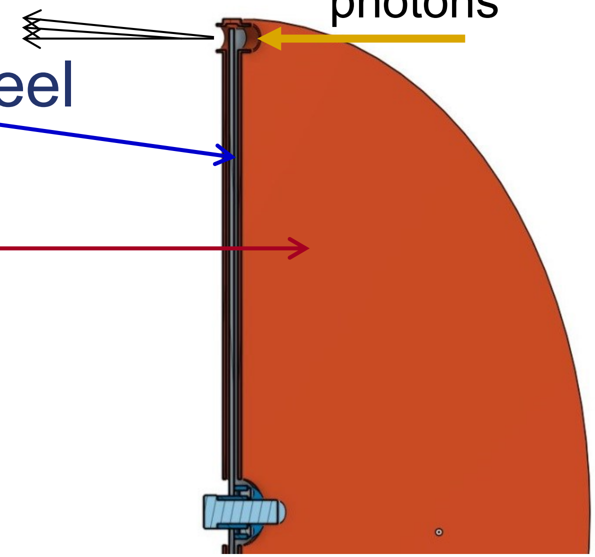
Average photon beam power	kW	62.6
Distance target – middle undulator	M	401
Photon beam spot size on target (σ)	mm	1.2
Target (Ti6Al4V)thickness	mm	7
Average power deposition in target	kW	1.94
Peak Energy Deposition Density (PEDD) in spinning target per pulse	J/g	61.0
Polarization of captured positrons	**%**	**29.5**

Cooling by thermal radiation



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

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

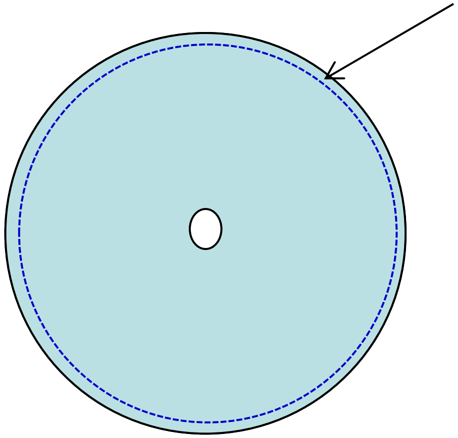
ε = effective emissivity

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

- But: high-temperature Ti alloys have low thermal conductivity (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 a 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

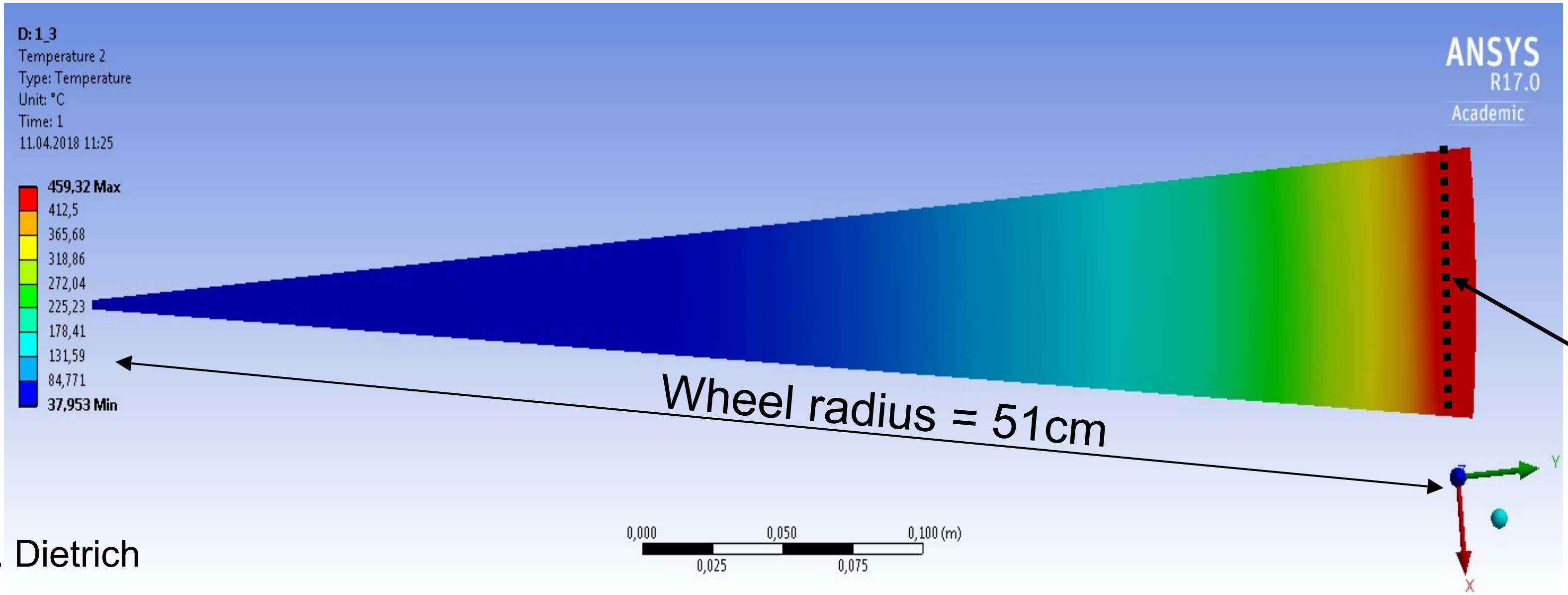


Temperature distribution in target wheel

- ANSYS simulations for radiative cooling of the target wheel
  – Efficiency of cooling depends on emissivity of surfaces of wheel and cooler (ε_{Ti} and ε_{Cu})

Average temperature distribution in a target piece corresponding to 1 pulse length

(ε_{eff}= 0.33; ε_{Ti} = ε_{Cu}=0.5)

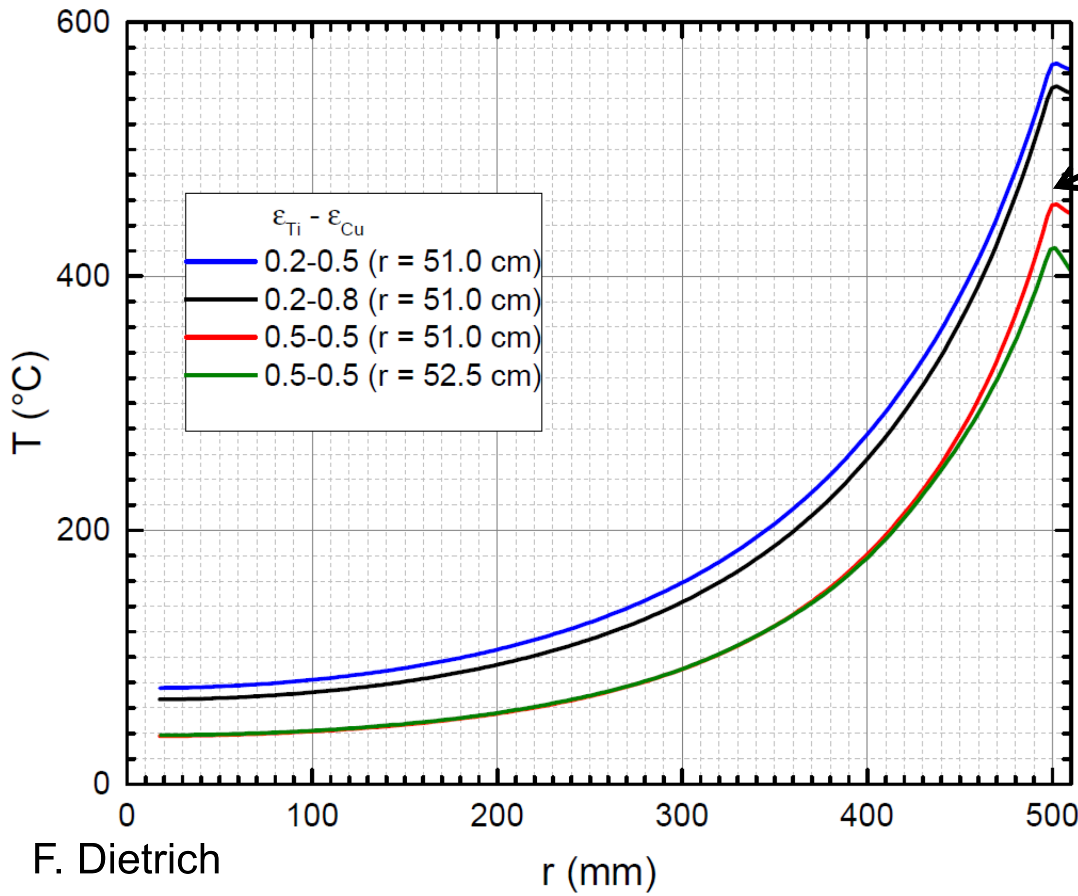


Photon beam pulse

F. Dietrich

Average temperature on target

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



ε_{eff}= 0.33 for ε_{Ti} = ε_{Cu}=0.5

Deposited power = 2kW

T_{ave} ≤ 460˚C

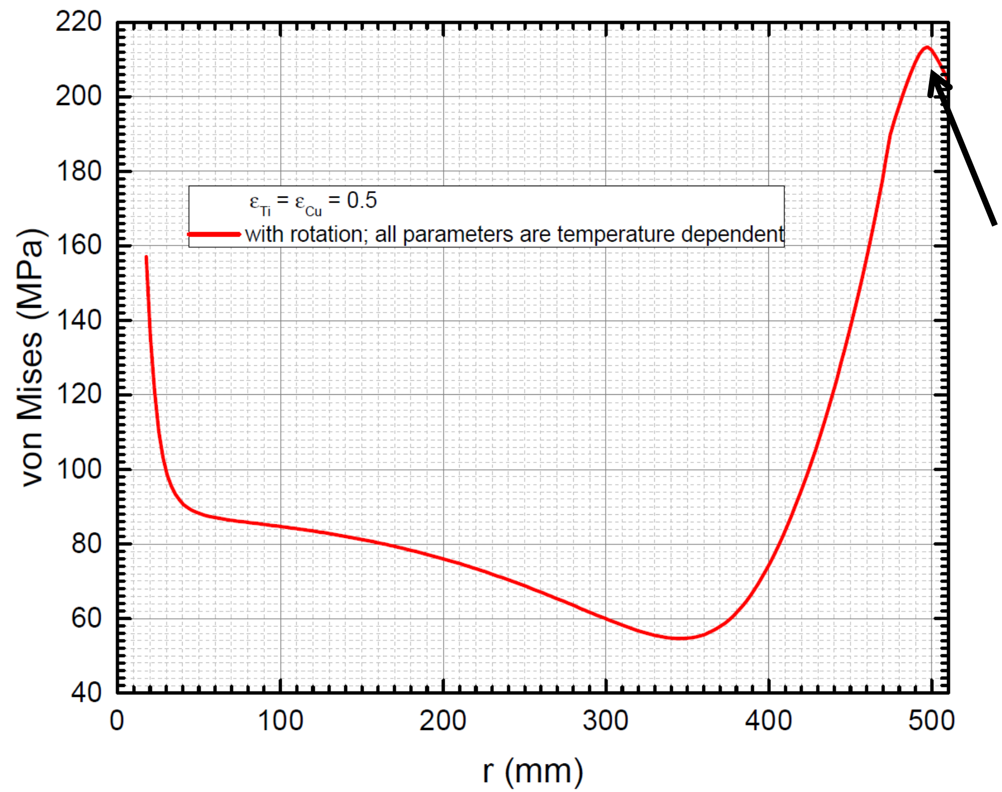
F. Dietrich

Average stress in target (1)

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

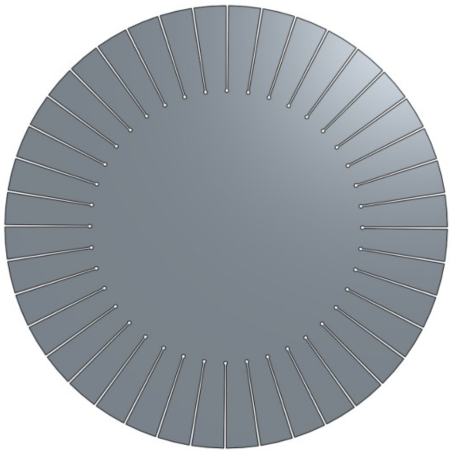
F. Dietrich

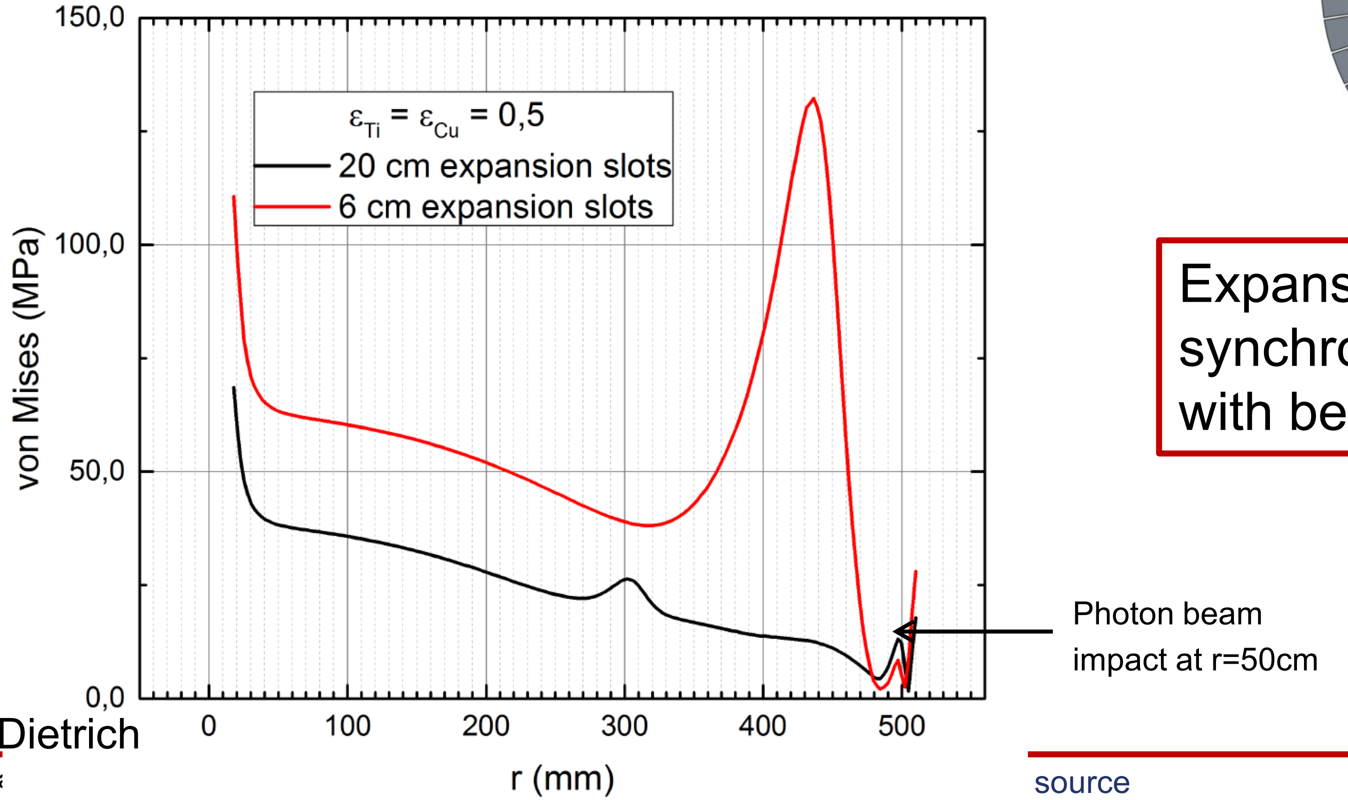
Average stress in target (2)

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



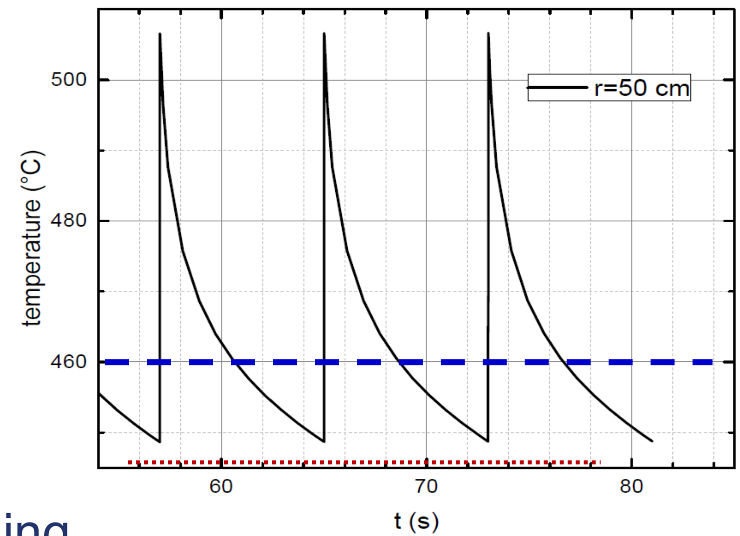


F. Dietrich

Expansion slots require synchronization with beam pulses

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)



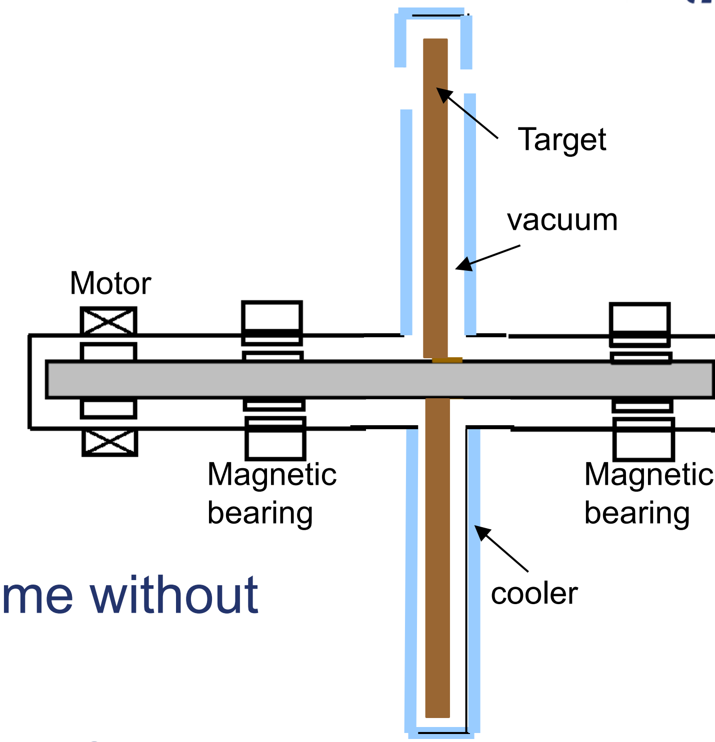
- Resulting peak stress at beam path:
  - detailed ANSYS simulations are still running
  - Time of energy deposition is to slow, intensity to small to create shock waves
  - Estimate: σ_{peak} ~ E α ΔT
    σ_{peak} <150 MPa
  - In total:
    σ_{peak} < 220MPa+150MPa = 370MPa without expansion slots
  - The stress is compressive

Cyclic load – what does the target material stand?

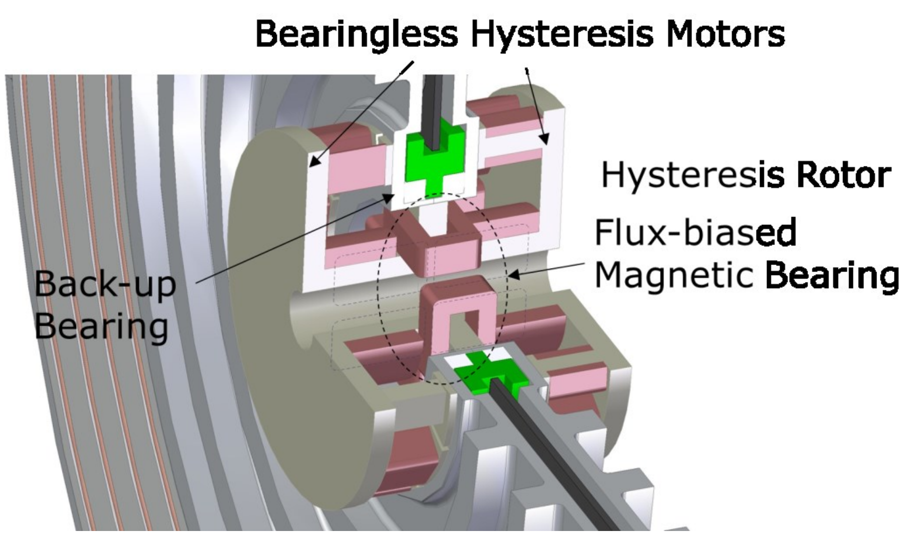
- Material limits depend on
  - temperature
  - type of load (compressive or tensile)
  - Duration of load and cyclic load, …
- References for Ti6Al4V give no clear answer; we concluded to be safe if cyclic stress amplitudes are below 300 MPa for temperatures up to ~500C.
- We performed tests with the e- beam at the Microtron in Mainz: We simulated cyclic load similar as expected at ILC e+ target.
  - Ti6A4V samples were radiated with pulses that create stress amplitudes similar as expected at ILC e+ target
  - Number of load cycles corresponded to 1-2 years ILC operation,
  - The material Ti6A4V was heated up to ~900C
  - Material survived well (see IPAC2017, TUPAB002)
    - Structure in beam area was changed to larger grains
    - Max dimensional change was ≤3% in the centre of the beam spot

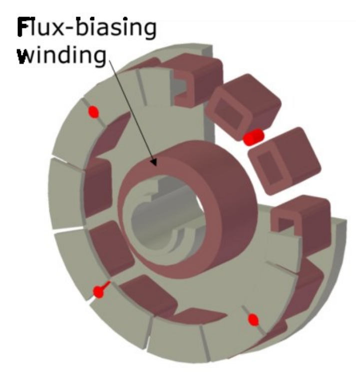
Drive and bearing

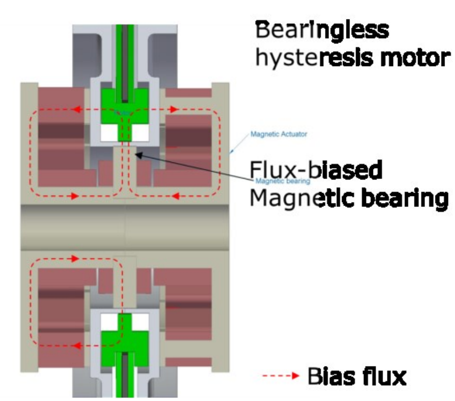
- Must be designed by engineers
  - Specification to be done based on simulation studies
- Radiation cooling allows magnetic bearings
  - Vacuum-tight
  - widely used, are operated over long time without maintenance at high rotation speed



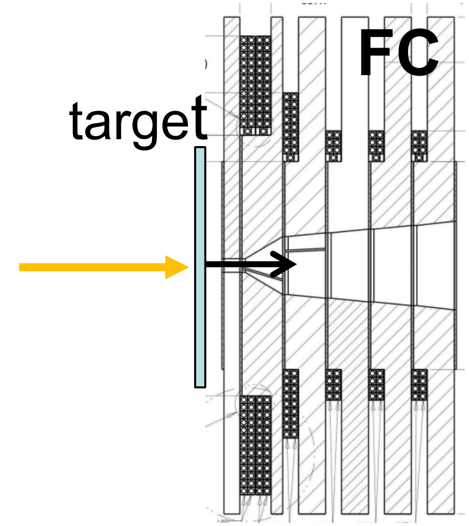
Design Proposal by M. Breidenbach et al, ICHEP 2016:







Optical matching device (1)



Requirements

- Stable B field during 1ms pulse, no gradient in time
- Field on target <0.5T (eddy currents!)

Flux concentrator (FC) :

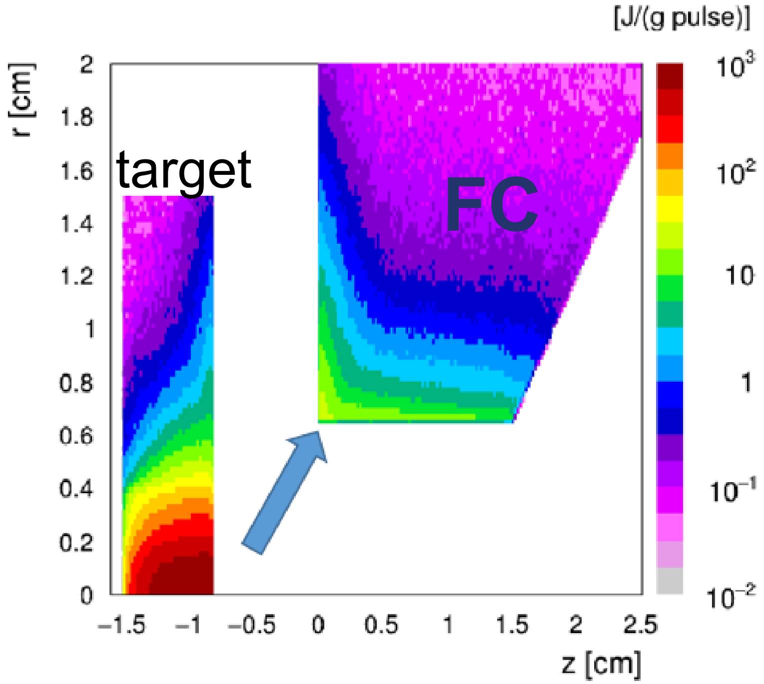
- peak B field 3.2 T at 2cm from target;
- LLNL developed and engineered a prototype

Concerns:

- prototype had problems with time-dependent B field
- At ILC250 too high load at FC although aperture increased to achieve Y=1.5 e+/e-

→ even with photon collimator too high load

(no target rotation for this plot)



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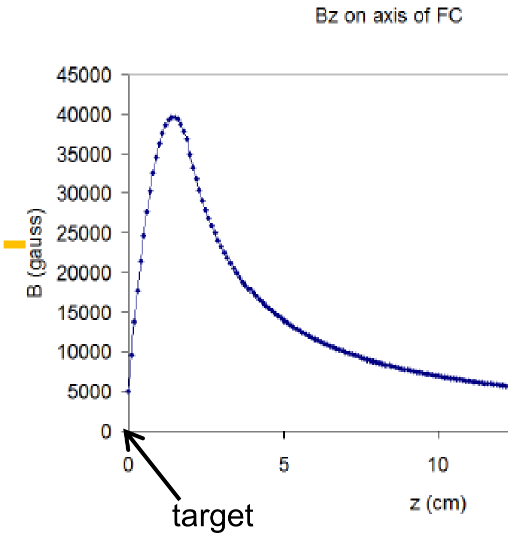

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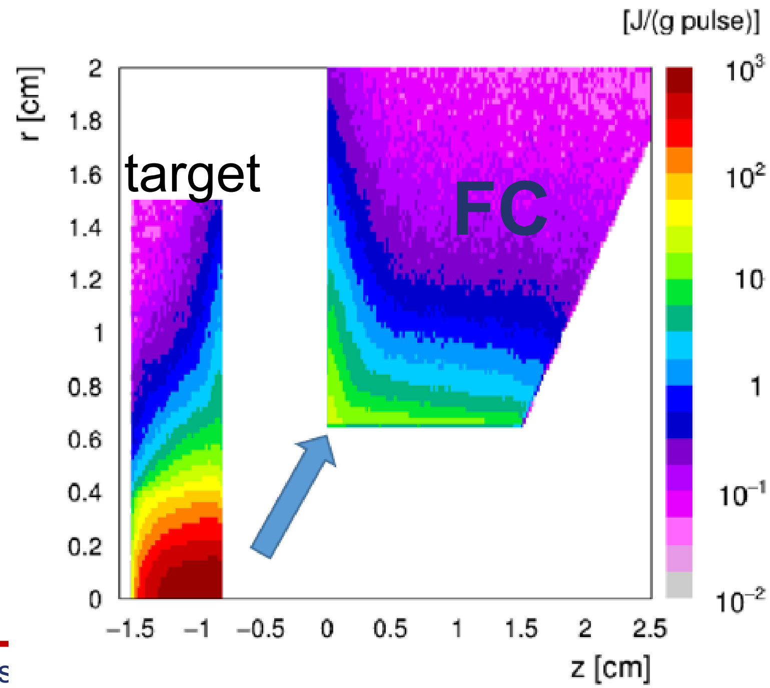
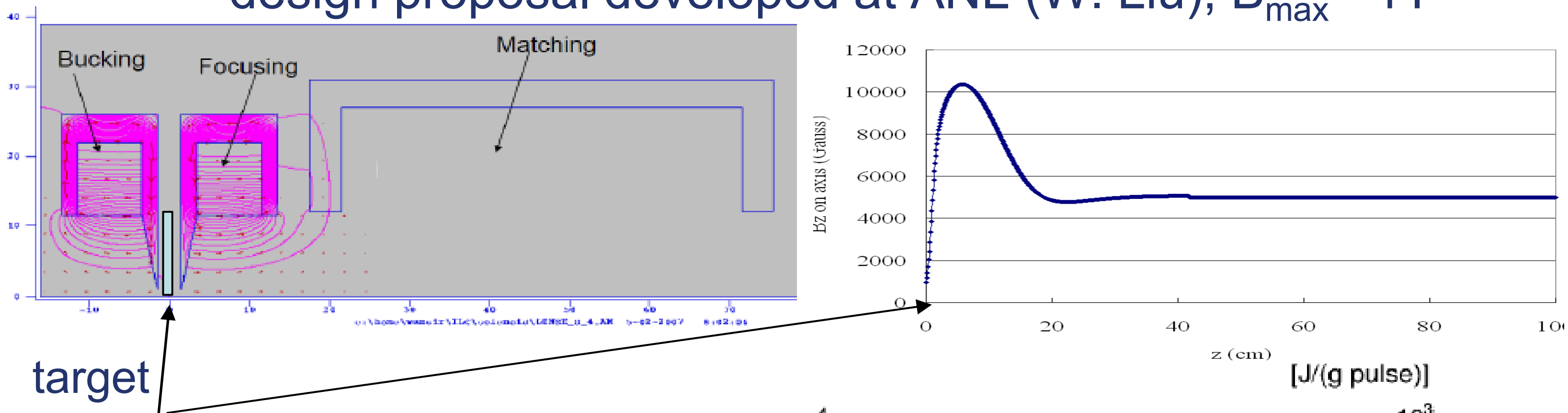


Optical matching device (2)

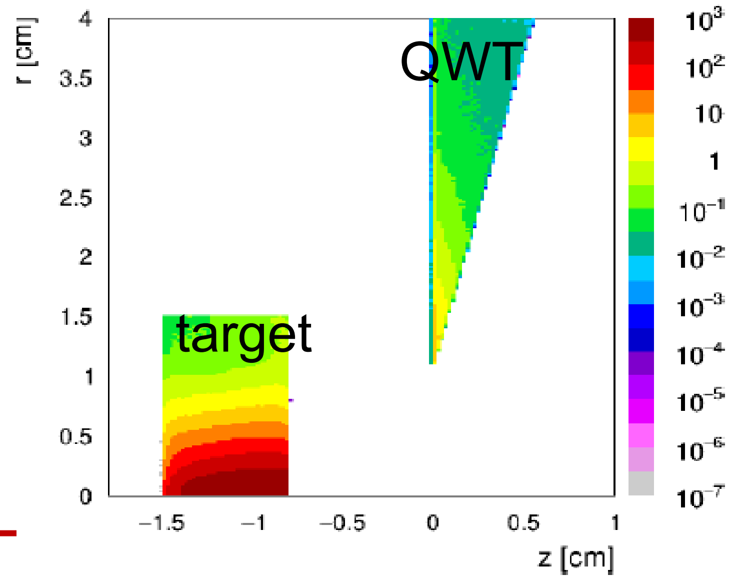
- Alternative: Quarter Wave Transformer
  - design proposal developed at ANL (W. Liu), B_{max} ~1T



energy deposition in QWT

→ Ok

(no target rotation for this plot))



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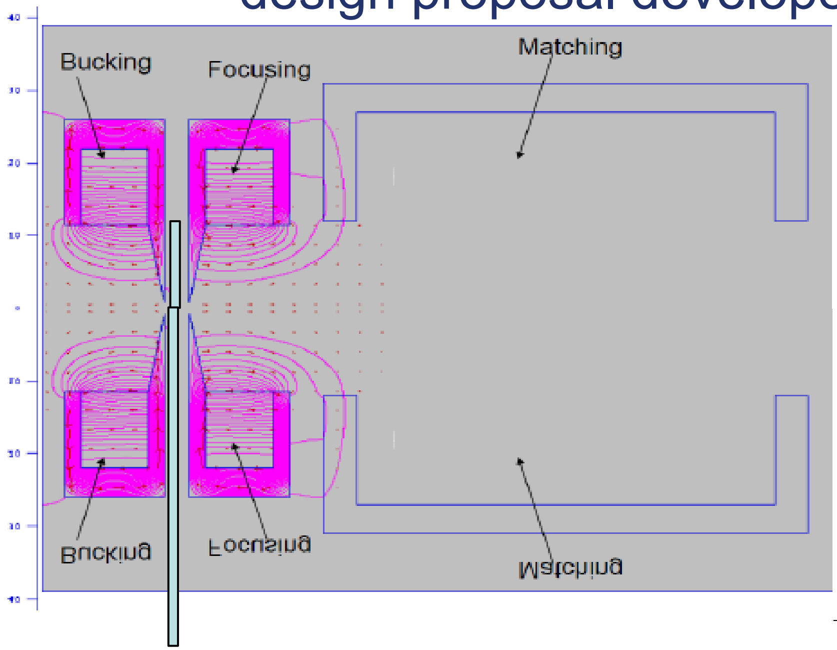
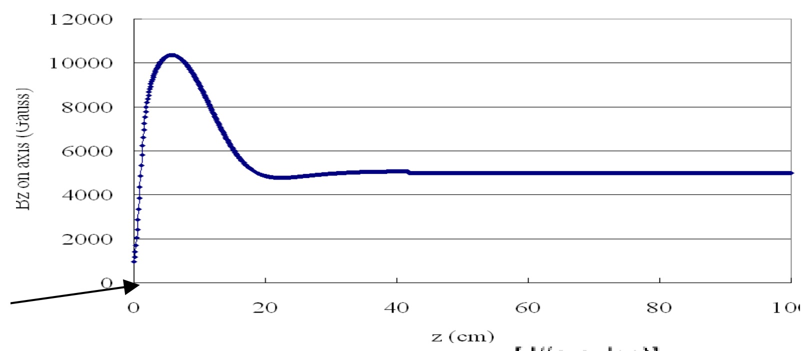
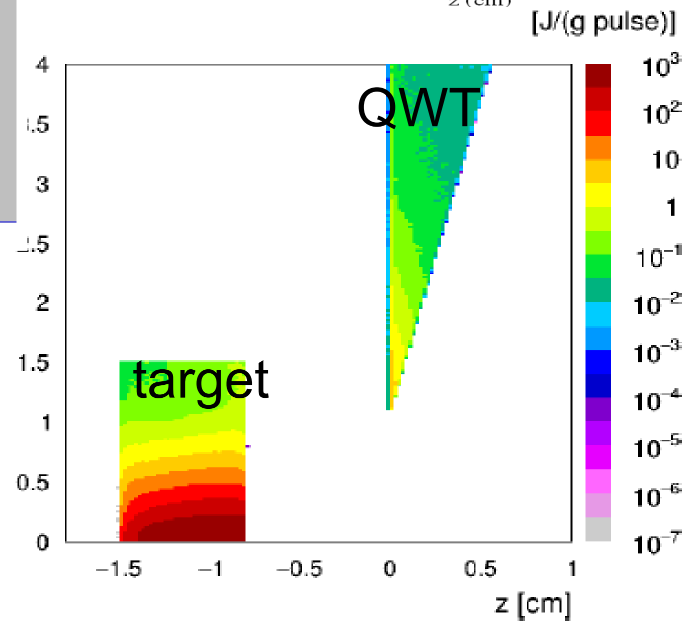






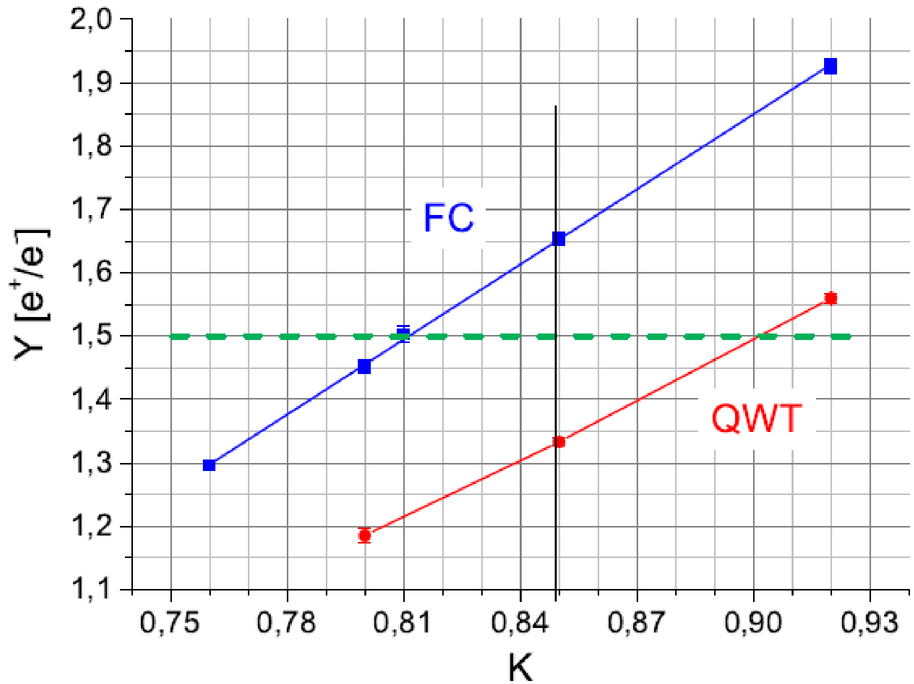
energy deposition in QWT
→ Ok

(no target rotation for this plot))

QWT instead of flux concentrator

Can the yield Y = 1.5 e+/e- be reached?

L_{und} = 231m,
max B_{QWT} = 1.04T



Required yield achieved for K = 0.92 → max undulator B (0.86T) is reached, i.e. this is the upper limit of the ideal, perfect source (more details see A. Ushakov, talk at ALCW 2018)

Electron beam energy	GeV	126.5
Active undulator length L_{und}	m	231
Undulator K		0.85 → 0.92
Photon energy (1st harmonic)	MeV	7.7 → 7.2
Average photon beam power	kW	62.6 → 72.2
Distance target – middle undulator	m	401
Photon beam spot size on target (σ)	mm	1.2 → 1.45
Average power deposited in target	kW	1.94 → 2.20
Peak energy deposition density in target per pulse	J/g	61.2 → 59.8

Details see A. Ushakov, talk at ALCW 2018

Photon dump

- Narrow 60-120kW photon beam deposits only few percent in target → permanent absorption of high power beam
- Water dump proposed in TDR will not work
  - window will break due to large energy deposition, high pressure from water
  - Narrow photon beam will evaporate water (shocks) → dump is opaque for the end of a pulse, i.e. does not work well for the whole beam

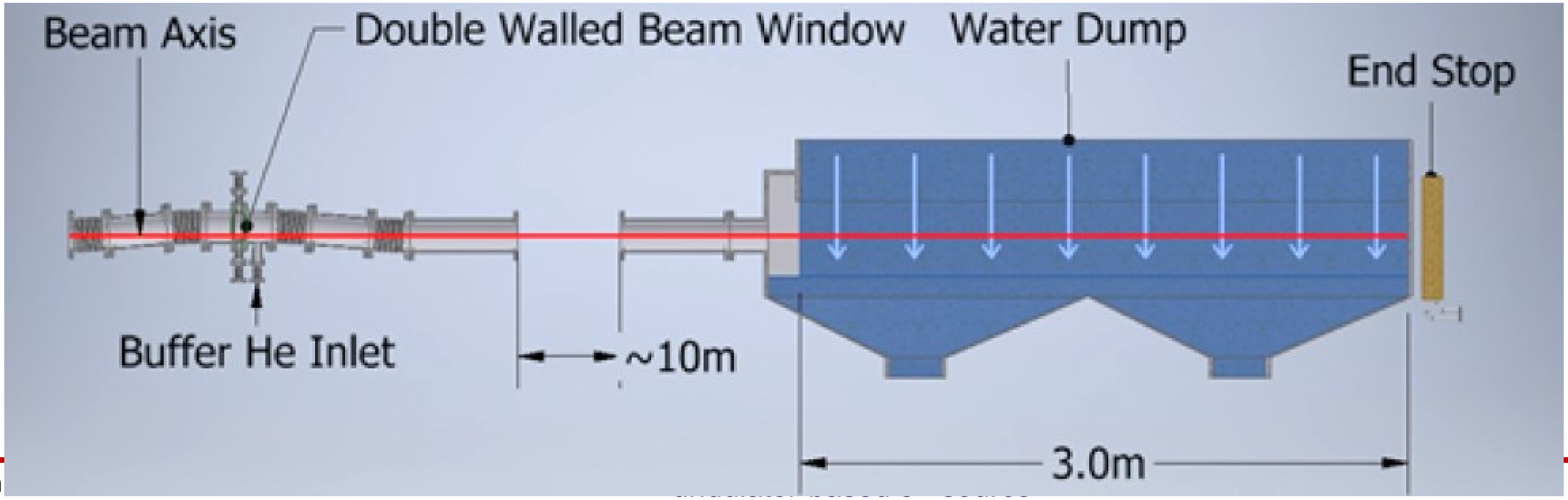
- Alternatives are under consideration (Yu Morikawa, Peter Sievers, Andriy Ushakov)

New dump position: ~2km downstream the e+ target

A water dump for the photon beam

- Proposed by Peter Sievers, ECFA-LC 2016
  - Tumbling double-walled Ti window (0.4mm) , He cooled
    - Tumbling radius ~1.5cm

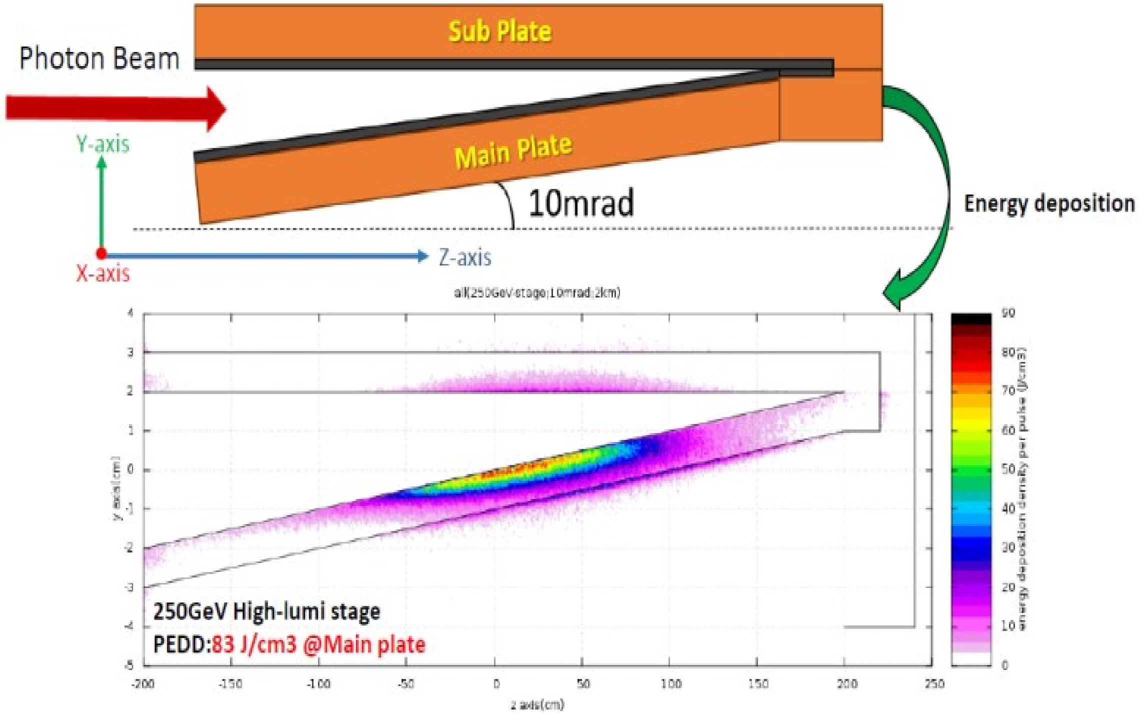
    → acceptable stress and heat load
  - Free falling water curtain to absorb the photon beam and to scatter particles →
    - evaporation bubbles immediately disappear
    - Safe distance between exit window and water part
  - Design needed



Graphite dump

- Considered by Yu Morikawa at LCWS2017
- inclined ‘front’ to distribute the γ beam load
- No need to introduce an exit window, no fluid absorber, no leak risk.
- But: Graphite degradation
  - thermal conductivity,
  - swelling,
  - contact of graphite holder

work will be continued



Upgrade to high luminosity (2625 bunches/pulse)

- Doubled energy deposition in target increases average T [K] by ~$2^{1/4}$
  - 460 C → about 600 C for our parameters (ε_{eff} = 0.3)
- Peak temperature rises by factor ~1.5 ⇔ $\Delta T \approx 100K$
- Possible options to handle the higher temperatures
  - Design with increased radiation area near the beam path (fins) is required. First studies exist
  - connect the Ti alloy target rim with a material of high heat conductivity to achieve higher cooling efficiency

Upgrade to higher energies

- For nominal luminosity the energy deposition and max temperatures are no problem:
  - 500GeV → E_{dep} in target ~2kW
  - Optimize target thickness for the CM energy
- Luminosity upgrade at higher energies:
  - Design with increased radiation area near the beam path (fins) is required. First studies exist
  - connect the Ti alloy target rim with a material of high heat conductivity to achieve higher cooling efficiency

General remark:

- Think about materials/Ti alloys which are designed for high load at working temperatures up to 700-800C
- M. Breidenbach (SLAC) LCWS 2015, ICHEP 2016: use Ti-SF 61

Polarization upgrade

- All studies so far: polarization upgrade to 50% - 60% is possible with a photon collimator (e.g., IPAC 2012, TUPPR042; arXive 1412.2498)
  - 1312 bunches/pulse
  - Distance target to undulator 500m
  - Y = 1.5e+/e-

E_{e-}	GeV	150	175	250
P(e+)	%	55	58.5	50
K		0.92		
Active L_{und}	m	231	196	70
$P_{ave}(\gamma)$	kW	98	114	83
P_{dep}(coll)	kW	48	69	43.5
Iris radius of collimator	mm	2	1.4	1

  - Peak energy deposition density on target increases – but is ok
  - Photon beam power increases
- polarization optimization must include the overall source design
  - Include the realistic B field of undulator

“Critical issues” ??

- Spinning target wheel
  - radiation cooling will work; target could be designed as disc
  - engineering design needed, prototype must be built
- Optical matching device
  - Pulsed flux concentrator has a problem
  - Quarter Wave Transformer allows almost same e+ yield.
    - Hardware design still required
- Photon beam dump
  - proposals exist, detailed design needed
- Upgrades L, E, P possible

- Is the undulator scheme feasible? **Yes**
- Can the feasibility be firmly verified in the time of design finalization? **Yes – but we need resources**

R&D plan

- Finalize the parameter list for the undulator based source
- Finalize the engineering specifications for a target wheel
- Test in the lab the cooling efficencies by thermal radiation for a target piece
- 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

Thank you!

Positron target for ILC250

Average and peak energy deposition in target (1312 bunches/pulse):

→ Cooling option

→ Acceptable material load

Electron beam energy	GeV	126,5	125
Active undulator length	m	231	
Undulator K		0.85	
Photon energy (1st harmonic)	MeV	7.7	7.5
Average photon beam power	kW	62.6	60.2
Distance target – middle undulator	M	**401**	**570**
Target (Ti6Al4V)thickness	mm	**7**	14.8
Average power deposition in target	kW	**1.94**	5.4
Photon beam spot size on target (σ)	mm	**1.2**	1.72
Peak Energy Deposition Density (PEDD) in spinning target per pulse	J/g	**61.0**	43.7
Polarization of captured positrons	%	**29.5**	30.7

Improvements? Re-optimize undulator parameters

- higher E_1, E_{ave} of γ beam to increase pair production efficiency
  - $E_1 \sim \frac{1}{\lambda(1+K^2)}$ ⇔ lower K, lower λ_{und}
  - However: $N_\gamma \sim \lambda K^2$
  - Opening angle $\theta \sim \sqrt{1 + K^2}$
- First attempts:
  - **K = 0.8, λ = 10.5mm ⇔ Y = 1.5 e+/e-, L_{und} = 202m**
  - **K = 0.8, λ = 10.0mm ⇔ Y = 1.5 e+/e-, L_{und} = 180m**
  - Estimated energy deposition with these parameters:
    - ED in target reduced by ~15…20%
    - PEDD in FC may be lower by ~ 15-20% → most likely still to high

→ Should be studied – including undulator performance for E_{e-} = 125 GeV (large undulator length)
  - Collimators to remove SR in the undulator
  - Magnetic field errors, …

Last but not least: realistic undulator

D.Scott et al., PRL 107(2011)1784803

Ideal ⇔ real undulator:

- Ideal undulator is a good approximation
- For the final design B field errors should be taken into account.
- First studies show that yield remains almost unchanged (Okugi, M, Jenkins)

But:

→ Influence on e+ polarization must be checked

→ power deposition in undulator walls must be known, and prevented by masks, in particular for ILC250

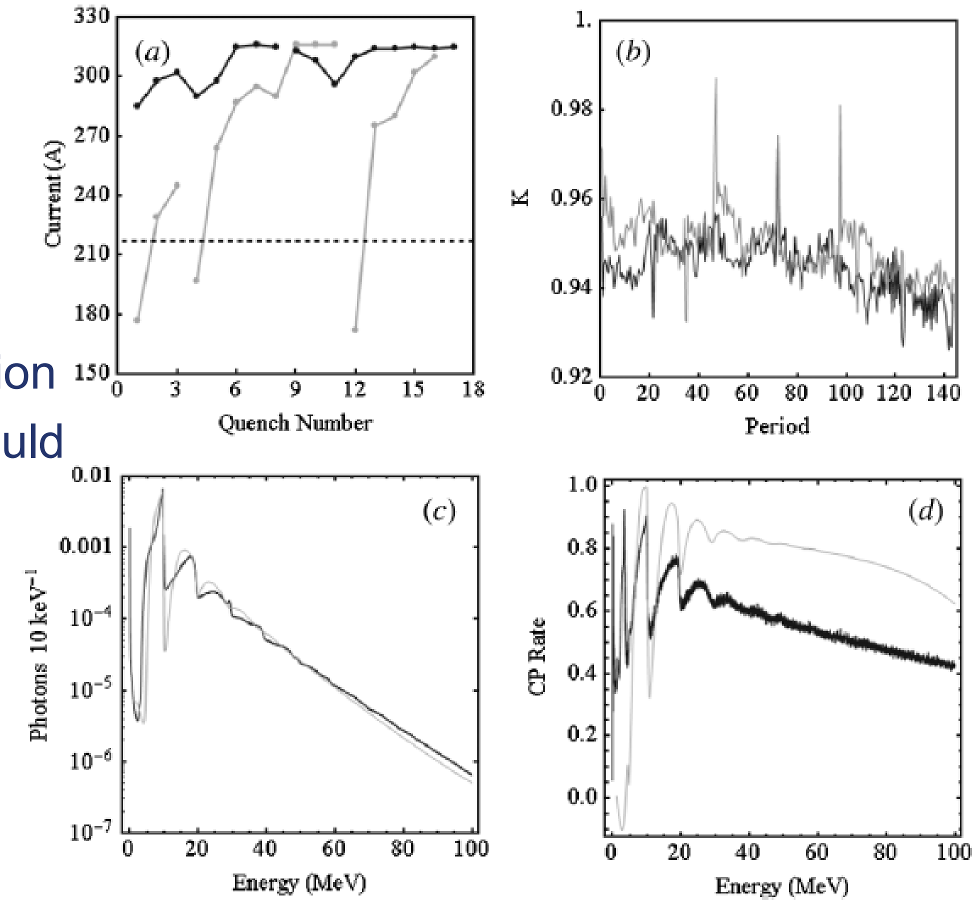


FIG. 3. Training curves (a) and K per period (b) for M1 (black lines) and M2 (gray lines). Number of photons per electron per 10 keV bandwidth (c) and CP rates (d) for measured fields (black lines) and ideal fields (gray lines).

electron beam energy	GeV	126.5	125	150	175	250
undulator active length	m	231		147		
undulator K		0.85		0.8	0.66	0.45
photon yield per m undulator	$\gamma/(e^- m)$	1.70		1.52	1.07	0.52
photon yield	γ/e^-	392.7		223.9	157.3	76.1
photon energy (1st harmonic)	MeV	7.7	7.5	11.3	17.6	42.9
average photon energy	MeV	7.5	7.3	10.4	13.7	26.8
average photon beam power	kW	62.6	60.2	48.8	45.2	42.9
photon bunch energy	J	9.6	9.2	7.4	6.9	6.5
electron energy loss in undulator	GeV	3.0	2.9	2.3	2.2.	2.0
Ti6Al4V target thickness	mm	7	14.8	14.8		
energy deposition per photon in target	MeV	0.23	0.7	0.8	1.0	1.4
relative energy deposition	%	3.1	9.0	8.0	7.3	5.3
average power deposited in target	kW	1.94	5.4	3.9	3.3	2.3
energy deposition per bunch	J	0.3	0.83	0.60	0.50	0.35
space from middle of undulator to target	m	401	570	500		
photon beam spot size on target (σ)	mm	1.2	1.72	1.21	0.89	0.50
PEDD in target per bunch	J/g	0.65	0.40	0.49	0.66	1.19
PEDD in target per pulse (100 m/s)	J/g	61.0	43.7	41.0	42.4	45.8
polarization of captured positrons at DR	%	29.5	30.7	29.4	30.8	24.9

1312 bunches/pulse, 5Hz

A. Ushakov

PEDD=peak energy depositon density

Used for current ILC250 sim's