LINEAR COLLIDER COLLABORATION

Designing the world's next great particle accelerator

Status of the undulator-based positron source

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Basic e+ source parameters

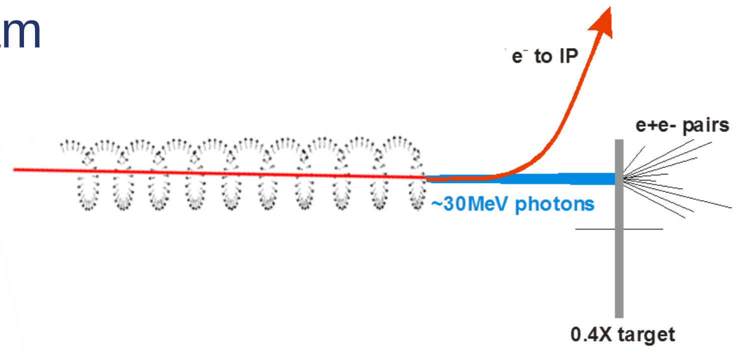
Electron beam energy	125 GeV
Number of particles per bunch	2×10^{10}
Number of bunches per pulse	1312
Repetition rate	5 Hz
Positrons per second at IP	1.3×10^{14}

(for comparison: SLC $2.4x10^{12}$/s ⇔ factor ~50)

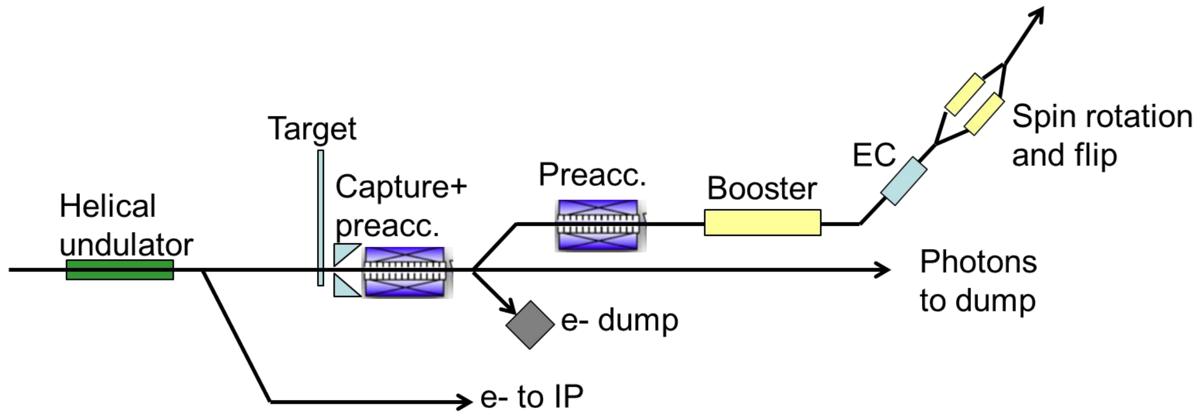
Required positron yield: Y = 1.5e+/e- at damping ring

Principle undulator based e+ source:

– High energy electrons pass a helical undulator and produce circularly polarized photon beam
– Photons strike thin target
– Conversion efficiency ~few %
– Generated e+ and e- are longitudinally polarized



Outline



Focus:

- What has been reached?

  Baseline e+ source:
  - Superconducting helical undulator
  - Spinning target wheel
  - Capture system
  - Dump of photon beam
  - Upgrade options

- What next?
  - Our (DESY/Uni Hamburg) perspectives

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

Undulator-based e+ source

Pros

- polarized positrons, ≥30% from beginning
- ~25% higher luminosity for Higgs strahlung process with 30% positron polarization
- More precise polarization measurement for electrons and positrons
- e+ polarization is extremely useful to interpret and disentangle new physics phenomena

→ ILC250 (and beyond) is an excellent precision machine

- Lower power is absorbed in the target and capture section
- Substantially less neutrons are generated, less activation of the target system

Cons

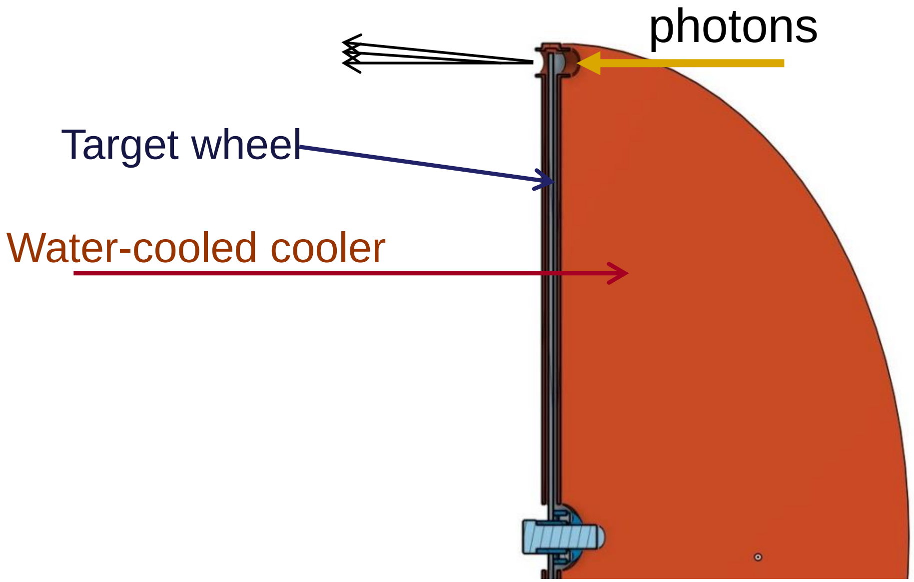
- Commissioning of the undulator source
- e+ beam depends on e- beam

The undulator e+ source through the ages

- Shock waves in target ?
  - Energy deposition in target is too slow and too low to create real shocks in Ti alloy
  - Tests with the e- beam at the microtron in Mainz (MAMI) demonstrated that Ti6A4V is a very robust material that stands load as expected at ILC
    - it stands a high number of load cycles (> 1 ILC year) up to temperatures near (and above) the phase transition temperature (~1000˚C)
    - See also talk by Andriy Ushakov (and previous talks about material experiments)
- Target cooling
  - Instead of water cooling thermal radiation into stationary cooler
- 10Hz scheme for ILC250 ?
  - Longer undulator, thinner target → e+ yield at ILC250 is ok with 5Hz
  - long undulator ⇔ masks to protect undulator walls (see also talks of Khaled Alharbi, Manuel Formela)
- FC → QWT
- Eddy currents
  - Are minimized by low B field on target (QWT ☺)
  - Are further reduced by expansion slots
- Photon beam dump
  - Pressurized water → water curtain or graphite target

The target wheel

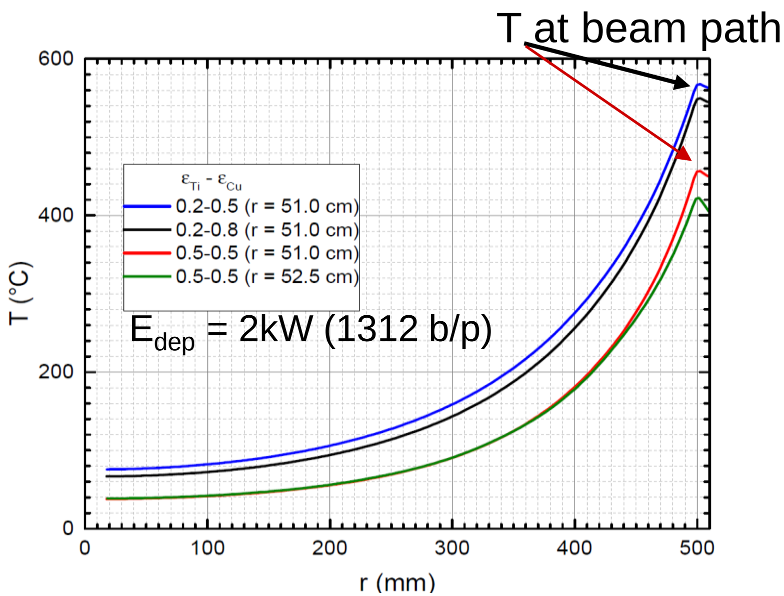
- Does the wheel stand the high load from the photon beam?
  - 1m-wheel spinning in vacuum is cooled by thermal radiation

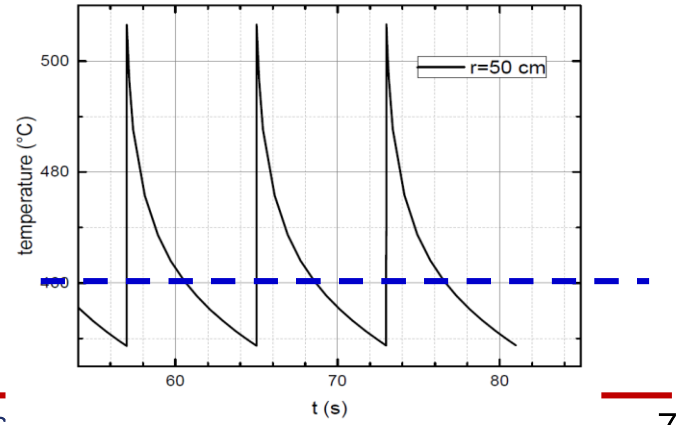


Target wheel – average and peak temperatures (ILC250)

Target thickness reduced to 0.2X0 (7mm) without loss in positron yield ⇔ 50% reduction of energy deposition in target

- ANSYS simulations for radiative cooling of the Ti6Al4V wheel
  - Efficiency of cooling depends also on emissivity of surfaces of wheel and cooler (ε_{Ti} and ε_{Cu})
- 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)





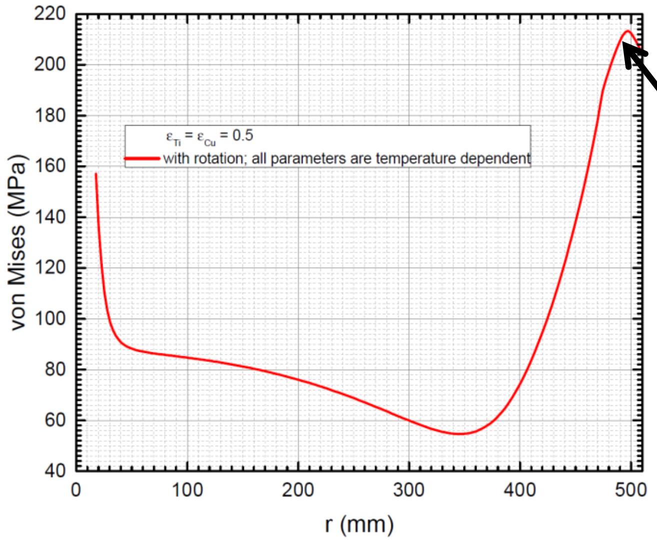
Target wheel – average and peak stress

ANSYS simulations for spinning Ti6Al4V target disc

7mm thick, r_{out}= 51cm , beam hits target at r=50cm

- Stress due to rotation (hoop and radial) is <50MPa, in the rim region <10MPa
- Material expansion yields high thermal stress in beam impact region
  - Expansion slots → stress substantially reduced, $\sigma_{vM} \leq$ 20MPa in rim region

Target: full disc w/o expansion slots



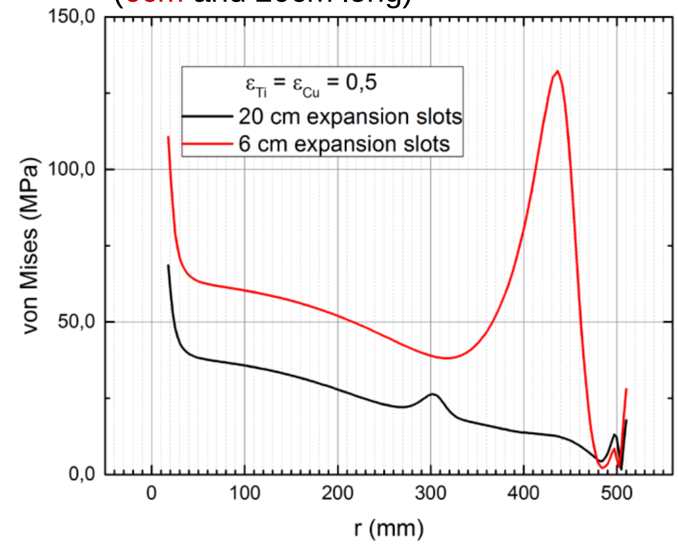
Photon beam impact

Average von Mises stress along radius r

σ_{vM} < 220MPa

Target disc with expansion slots

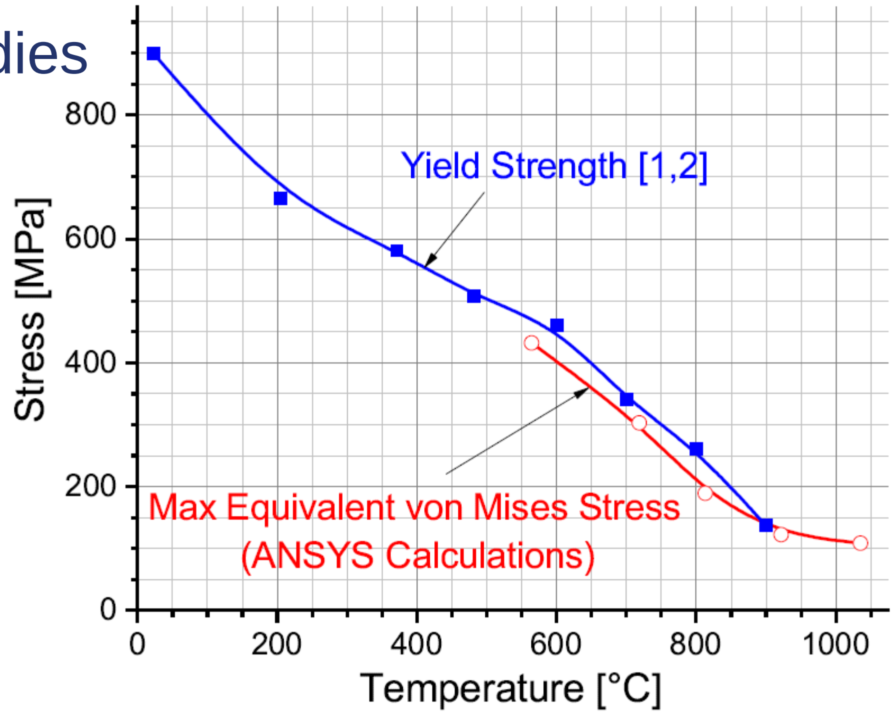
(6cm and 20cm long)



Resulting peak stress at beam path

- Estimated stress by pulse: $\sigma_{peak} = E\,\alpha\,\Delta T / (1-\nu)$ → $\sigma_{peak} \approx$ 75 MPa (ILC250, 1312b/pulse)
- In total: σ_{peak} < 220MPa (ave) + 75MPa (pulse) ≈ 300MPa (full target disk)

Following the irradiation tests at MAMI and Andriy Ushakov's studies (see his talk at POSIPOL18), we are safe with the von Mises stress of 300 MPa (ILC250, nom. lumi)



Lumi upgrade → could exceed material limits without expansion slots

→ The target wheel – as required with expansion slots – will stand the load of the photon beam

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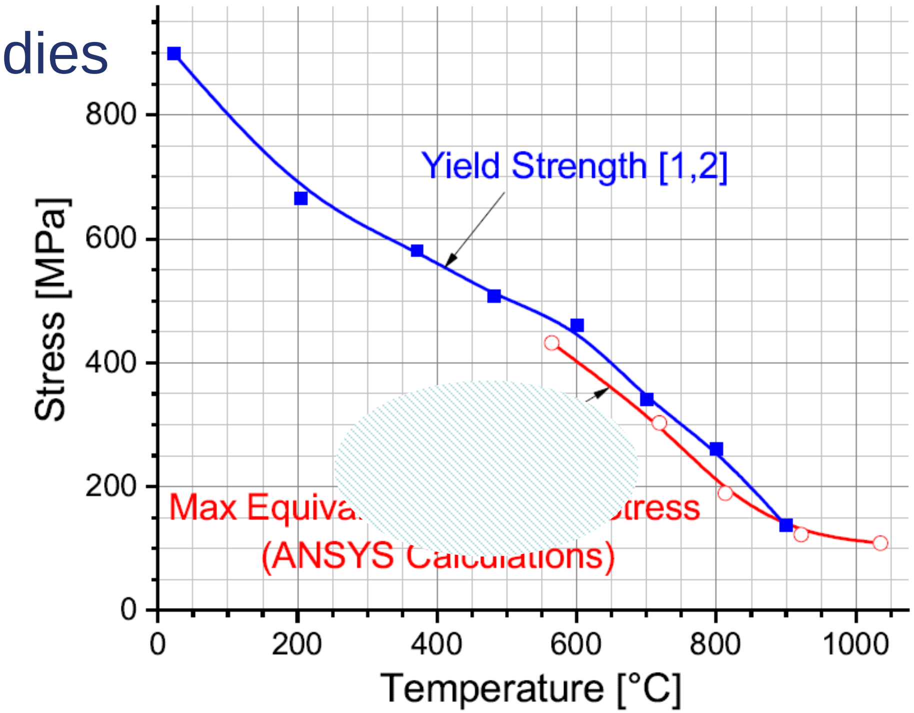


Lumi upgrade → could exceed material limits without expansion slots

→ The target wheel – as required with expansion slots – will stand the load of the photon beam

Positron target for ILC250

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

→ Cooling by thermal radiation

→ Acceptable material load

→ OMD = FC

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

Target and ILC upgrade options

- Luminosity upgrade
  - Temperature rise per pulse increases by factor ~1.5 ⇔ $\Delta T \approx$ 100K
  - Average temperature rises ~$2^{1/4}$, i.e. T_{ave} increases from 460˚C to ≈650˚C for $\varepsilon_{eff} = 0.3$
  - Peak temperatures ≤750˚C

  → Design with expansion slots, possibly fins to increase cooling surface
- Energy upgrade
  - ILC500: E_{dep} in target ~2kW (nominal luminosity)
  - Optimize target thickness for the CM energy
- Polarization upgrade
  - Photon collimator studies exist, see arXive 1412.2498
  - Further studies required including realistic undulator spectrum

Optical matching device

Requirements

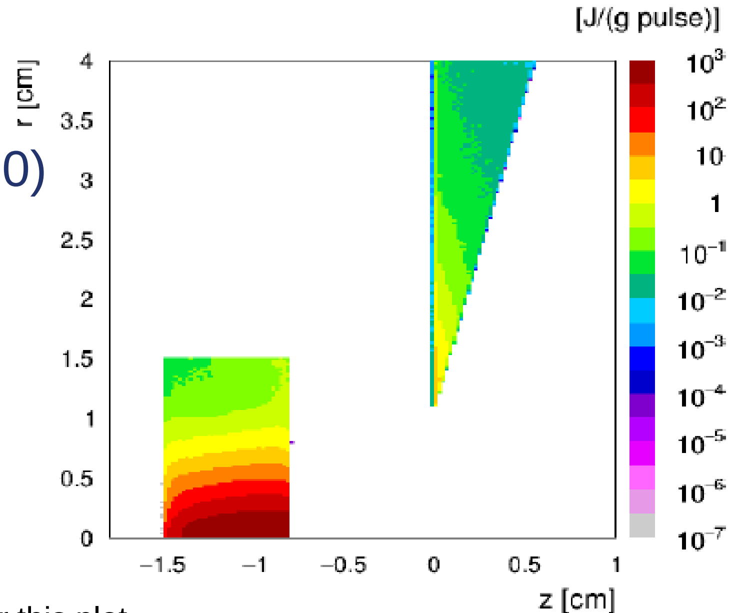
- Stable B field during 1ms pulse, no gradient in time
- Field on target <0.5T (eddy currents!)

Flux concentrator (FC) :

- peak B field 3.2 T at 2cm from target;
- Prototype developed and engineered at LLNL
- Concerns:
  - time-dependent B field
  - Too high load at FC front aperture (ILC250)

Alternative: Quarter Wave Transformer

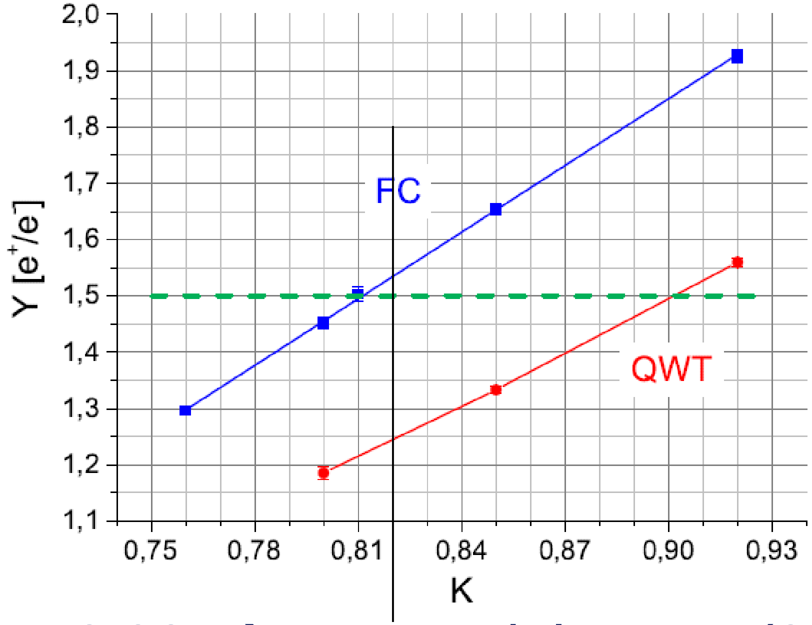
- design proposal developed(W. Liu), B_{max} ~1T
- energy deposition in QWT is ok



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)

POSIPOL18: slightly lower e+ yield obtained by M Fukuda

→ Update at LCWS18 ?

Positron target for ILC250

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

→ Cooling by thermal radiation
→ Acceptable material load
→ **OMD = QWT**

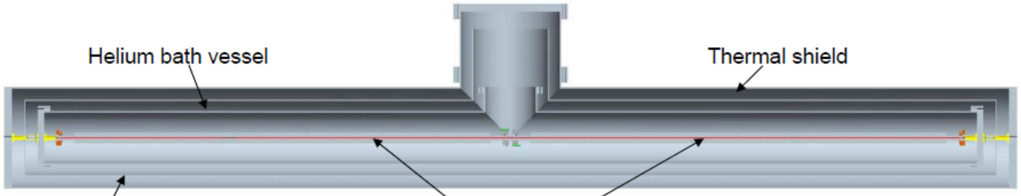
Electron beam energy	GeV	126.5
Active undulator length L_{und}	m	231
Undulator K		0.85 → 0.92
Photon energy (1st harmonic)	MeV	7.7 → 7.2
Average photon beam power	kW	62.6 → 72.2
Distance target – middle undulator	m	401
Photon beam spot size on target (σ)	mm	1.2 → 1.45
Average power deposited in target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

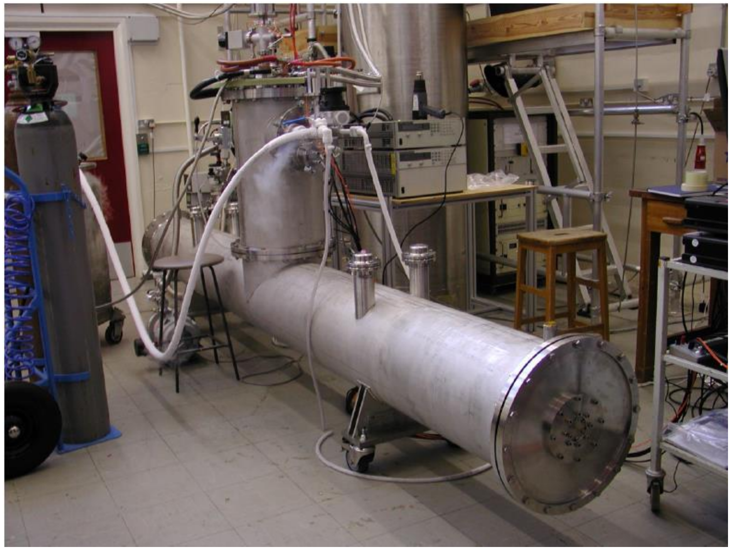
Details see A. Ushakov, talk at ALCW 2018

The helical superconducting undulator

- Prototyping in UK → 4m module

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





- Lessons learned (see also Y. Ivanyushenko at POSIPOL 2013); sc helical undulators for ILC are feasible
- However, no further development for the ILC undulator since ~2010

Helical undulator – parameters for ILC250

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

→ L_{und} = 231m active length (320m in total)
K_{max} = 0.92

Energy deposition in undulator wall

- Currently under study (Khaled Alharbi, Manuel Formela)
- The problem:
  - Load from synchrotron radiation at sc undulator walls should be smaller 1W/m
- Simple calculation: photon beam power: ~60kW
  - Half opening angle of photon beam:

$$\theta = \frac{1}{\gamma}\left[n\frac{\omega_1(1+K^2)}{\omega} - 1 - K^2\right]$$

  - Photons deposit power in the walls of sc helical undulator, in particular photons created in the first undulator modules will load the modules at the undulator 'end'
- Masks can prevent this but one has to take into account:
  - Field errors along undulator modules
  - Period uncertainty
  - Alignment errors

To be studied: realistic undulator

Test module study:

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

Ideal ⇔ real undulator:

- Ideal undulator is a good approximation
- First studies show that B field errors influence only slightly
  (Okugi, 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

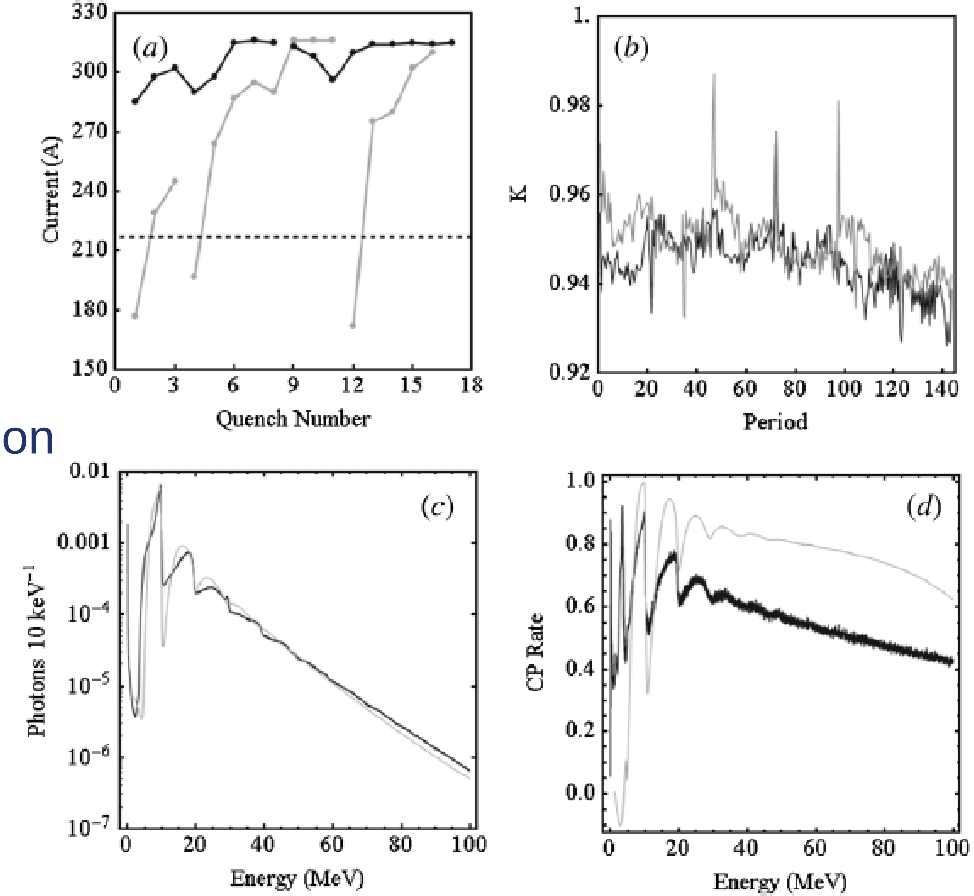


FIG. 3. Training curves (a) and K per period (b) for M1 (black lines) and M2 (gray lines). Number of photons per electron per 10 keV bandwidth (c) and CP rates (d) for measured fields (black lines) and ideal fields (gray lines).

Re-optimize undulator parameters ?

- higher E_1, E_{ave} of γ beam to increase pair production efficiency ⇔ shorter undulator period
- 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:
    - Energy deposition in target reduced by ~15…20%
    - PEDD in FC may be lower by ~ 15-20% → most likely still to high ⇔ QWT

→studies started, see also talk by Manuel Formela

"Critical issues" of the undulator e+ source??

- Spinning target wheel
  - radiation cooling will work; no showstopper identified
  - 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
  - Water curtain dump: Irradiation tests at MAMI demonstrate that exit windows made of Ti allow stand the load from photon beam
- Upgrades L, E, P possible

- The undulator scheme is feasible
- The feasibility can be firmly verified in the time of design finalization if resources are available

Future R&D

- Target – to be done:
  - Test a stationary target piece to verify and optimize the efficiency of radiative cooling
    - Construct flexible test module which simulates temperature conditions and surface emissivity similar as expected in target
    - Consider alternative Ti alloys suitable for even higher operation temperatures (Ti SF-61)
  - Specifications for engineering target wheel design including safety margins
  - Engineering design for full wheel + cooler including drive, bearings, seals,…
  - Construct and operate full test module
- Photon dump design
- Radiation aspects, shielding
- Ideas for effective commissioning

- The roadmap towards the undulator-based e+ source and the target wheel is clear
- Resources ???
  - The e+ source group at DESY/Uni Hamburg will shrink substantially in 2019; unfortunately the efforts at DESY on the undulator based source will effectively terminate
  - We will document our work, and finalize and publish all analyses for the material load experiments in Mainz
  - Hopefully, also in future significant contributions will be possible

Thank you!