R&D for e+ Source at high-energy lepton colliders

- **Status and importance of polarization**
- **Status ILC positron source**
- **Upgrade for HALHF design**
- **Conclusion**

G. Moortgat-Pick, M. Formela, N. Hamann, T. Lengler,
G. Loisch, S. Riemann, P. Sievers, C. Tenholt, G. Yakopov

What is the current status of HEP?

- One Higgs particle discovered in 2012
  - strongly consistent with Standard Model (SM) predictions
- Few excesses around.....(e.g. a light scalar at about 95 GeV)
  - but not (yet) confirmed discoveries
- Still strong motivation for Beyond SM (BSM) physics
  - Dark Matter, Gravitational Waves, Baryon-Asymmetry, etc.
- However, scale of new physics window still unclear
  - .....the research field might be in great danger

  ➡Therefore, high precision and/or high energy in specific areas needed and additional tools complementary to (HL)LHC analyses required to identify the promising windows
- But in a responsible, sustainable manner, i.e.
  - stageable, tuneable, shortest as possible lepton collider(s) with polarized beams and new imminent technologies mandatory

➡Mature e+e- collider design(s) with sane polarization!

Remember the past: physics gain of polarized beams

- **Past experience:**
  - **excellent e- polarization ~78% at SLC:**
  - **led to best single measurement of $\sin^2\theta=0.23098\pm0.00026$ on basis of $L\sim10^{30}\ cm^{-2}s^{-1}$ (~600000 Z's)**

- **Compare with results from unpolarized beams at LEP:**
  - **$\sin^2\theta=0.23221\pm0.00029$ but with $L\sim2x10^{31}cm^{-2}s^{-1}$ (~ 17 million Z's)**

➡ **Polarization essential for suppression of systematics**

➡ **can even compensate order of magnitude in luminosity for specific observables!**

➡ ***Polarized e- sources well under control, why in addition polarized e+ required.....?***

Short reminder: why are polarized $e^{\pm}$ needed?

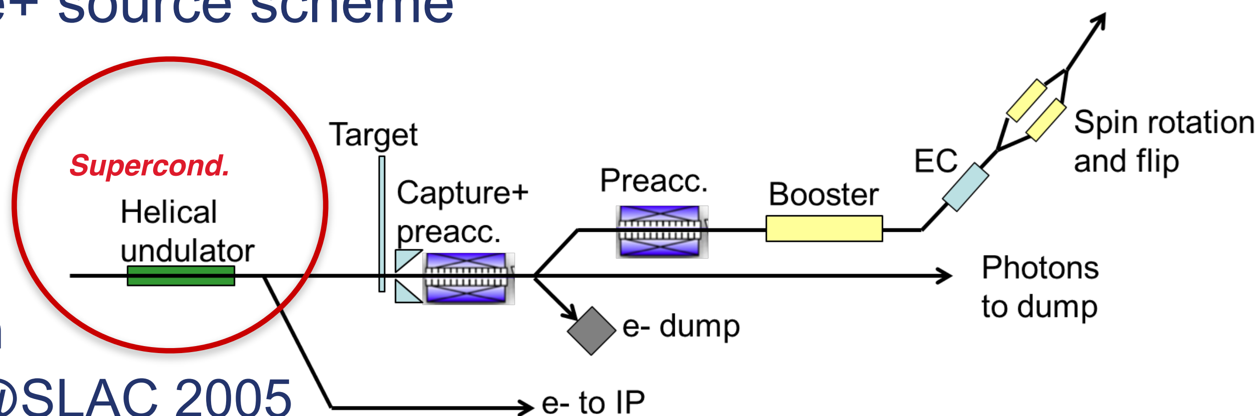
- **Important issue: measuring amount of polarization**
  - **limiting systematic uncertainty for high statistics measurements**
  - **Compton polarimeters (up- /downstream): envisaged uncertainties of ΔP/P=0.25%**
- **Advantage of adding positron polarization:**
  - **Substantial enhancement of eff. luminosity and eff. polarization**
  - **new independent observables**
  - **handling of limiting systematics and access to in-situ measurements: ΔP/P=0.1% achievable!**
  - **Windows to new physics already at low energy!** see talk Cheng Li on transv. pol. beams
- **Substantial physics impact: EWPO, Higgs-Physics, WW/Z/top-Physics, New Physics !**

Literature: polarized e+e- beams at a LC (only a few examples)

- *LCC-Physics Group: 'The role of positron polarization for the initial 250 GeV stage of ILC', arXiv: 1801.02840*
- *G. Moortgat-Pick et al. (~85 authors) : `Pol. positrons and electrons at the LC', Phys. Rept. 460 (2008), hep-ph/0507011*
- *G. Wilson: `Prec. Electroweak measurements at a Future e+e- LC', ICHEP2016, R. Karl, J. List, LCWS2016, 1703.00214*
- *many more (only few examples): 1206.6639, 1306.6352 (ILC TDR), 1504.01726, 1702.05377, 1908.11299,2001.03011, …*
- *G. Moortgat-Pick, H. Steiner, `Physics opportunities with pol. e- and e+ beams at TESLA, Eur.Phys.J direct 3 (2001)*
- *T. Hirose, T. Omori, T. Okugi, J. Urakawa, Pol. e+ source for the LC, JLC, Nucl. Instr. Meth. A455 (2000) 15-24,…*

Most mature LC design: ILC

- The polarized e+ source scheme



Principle tested with
E-166 experiment @SLAC 2005

G. Alexander et al., NIMA 610 (2009), G. Alexander et al., Phys.Rev.Lett.100 (2008)

- ILC e+ beam parameters (nominal luminosity)

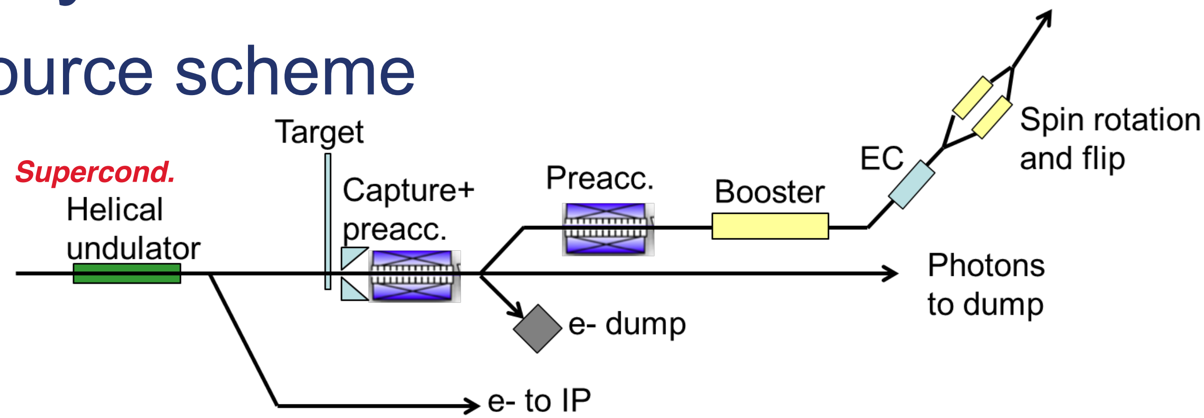
Number of positrons per bunch at IP	2×10^{10}
Number of bunches per pulse	1312
Repetition rate	5 Hz
Positrons per second at IP	1.3×10^{14}

That's about a factor 100 more compared to SLC!

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

ILC baseline layout of the e+ source

The polarized e+ source scheme

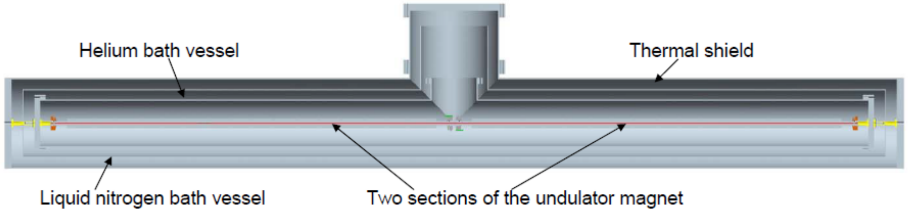


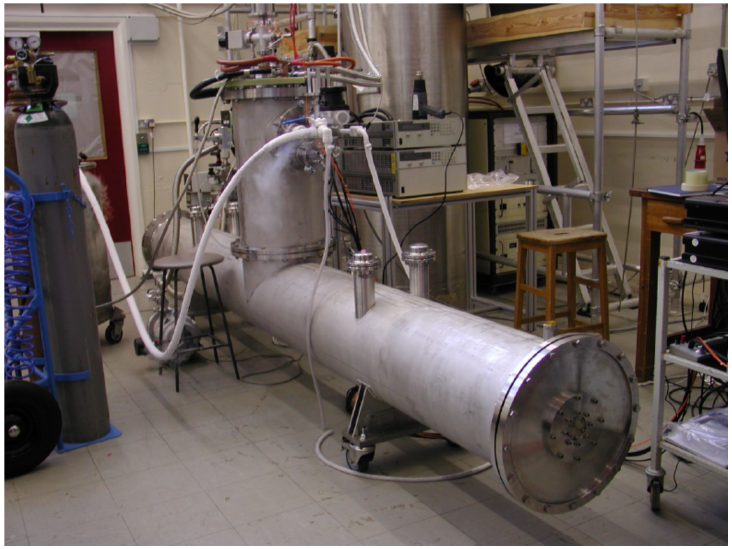
Work packages	I(nternational)T(echnology)N(etwork) Items
WP-5: Undulator	Simulation (field,errors, alignment) √
WP-6: Rotating target	Design finalization, partial laboratory test, mock-up design
	Magnetic bearings: performance, specification, test
	Full wheel validation, mock-up
WP-7: Magnetic focusing system	Design selection (pulsed solenoid, plasma lens), with yield calculation
	OMD with fully assembled wheel, prototype

Undulator technology - Status

- Parameters
  – Undulator period, λ_U =11.5mm
  – Undulator strength $K \leq 0.92$ ($B \leq 0.86T$); $K \sim B \cdot \lambda_U$
  – Undulator 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 (2013):
  – Max 231m active undulator length available (132 undulator modules in 66 cryomodules]
  – Quadrupoles every 3 cryomodules
    → total length of undulator system is 320m

Progress since TDR

K. Alharbi, PhD 2024
S. Riemann, GMP

- **Detailed ILC undulator simulations performed:**
  - realistic fields, masks and power deposition, misalignments
- **Undulator operation: experience with long undulators**
  - XFEL: 91 undulators with 5m length each
  - energy loss due to particle loss negligible small (unmeasurable)
  - beam alignment up to 10-20 microns for 200 m (undulator length), remeasured every 6 months
  - during beam operation: beam trajectory controlled better than 3 micron with both slow and fast feedback systems

W. Decking/XFEL
LCWS21

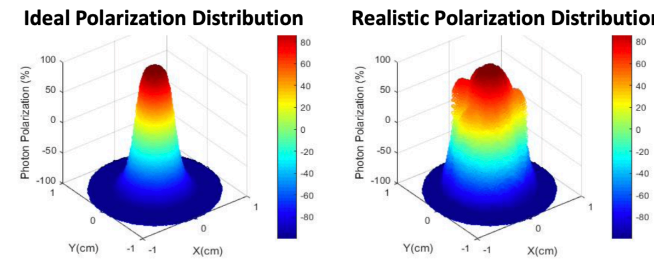
- **Stable operation and alignment experience**
  - Beam requirements at XFEL more challenging than at ILC due to FEL requests of photons
  - Tolerances of IIC undulator more relaxed than for XFEL!
- **Result: no operation&alignment issues for ILC undulator**

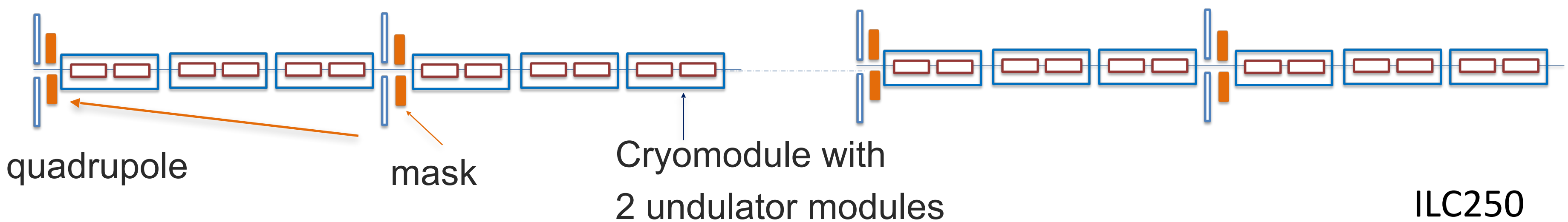
WP5 Undulator: Simulation (field errors, alignment)

- Misalignments:
  - beam spot increases slightly, yield decreases slightly
- Realistic undulator with B field (K) and period (λ) errors
  - provides beam size, polarization, target load
  - impact depends on K-value!
- Synchrotron radiation deposit in undulator walls
  - Masks protect wall to levels below 1W/m
  - ILC250: power deposition in 'last' mask near undulator exit: ~300W

see A. Ushakov, AWLC18

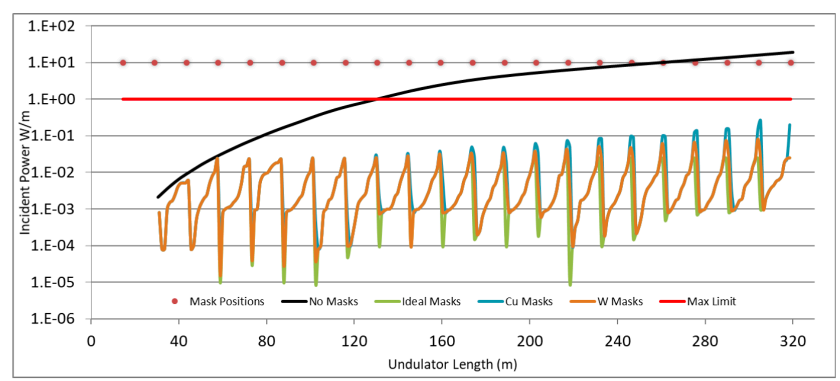
Alharbi, Thesis finished!





- ***Result: Masks substantial but sufficient in all cases!***

- Studied for ILC250, ILC350, ILC500 and GigaZ !



Analyses of ILC targets

- **History: target material tests at Mainz Microtron (MAMI) using e-**
  - Strategy: electron-beam on ILC target materials, generating cyclic load with same/ even higher PEDD at target than expected at ILC
  - Numerous successful tests performed on Ti-Alloy, W
  - target analyses with both scanning and synchrotron diffraction methods *A. Ushakov et al.*
- **Ongoing: (final) tests, analyses and publication**
  - still one (final?) more test run at MAMI in 9/24
  - dilatometer tests: disentangling target damage originating from thermal vs radiation load T. Lengler et al.
  - α- and β- phase of Ti-alloy depend on T, have different mechanical properties
  - Tested: fast and cyclic stress in the range of $T=300^0$-800^0C
  - variation of T_{max} as well as different heating/cooling rates of 25^0C/s-100^0C/s

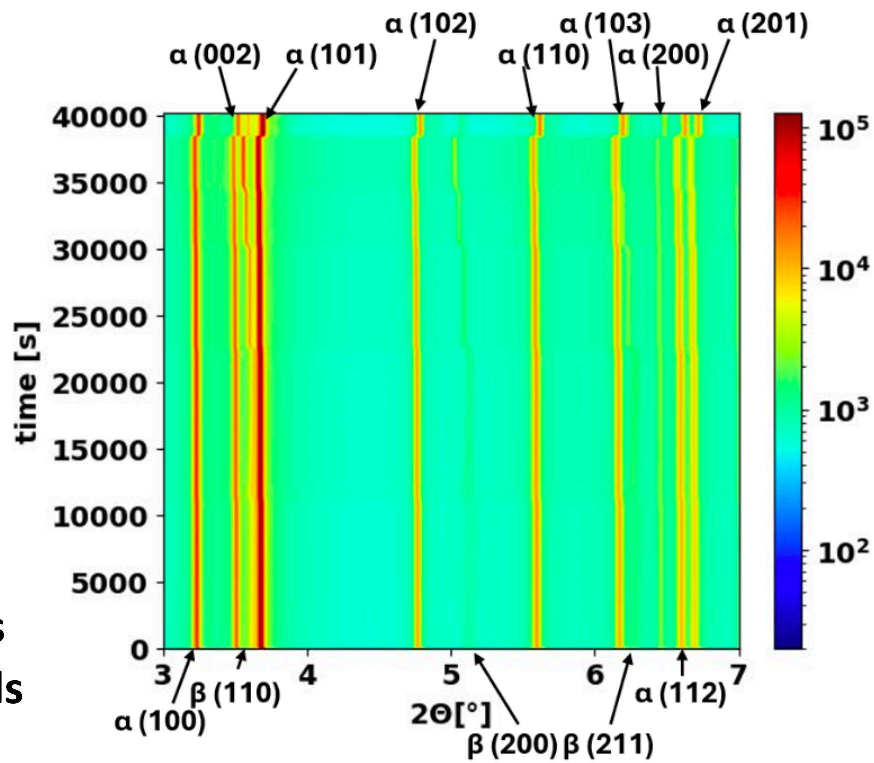
- ***Result: ILC undulator target will stand the load !***

Analyses of ILC targets

- **History: target material tests at Mainz Microtron (MAMI) using e-**
  - **Strategy: electron-beam on ILC target materials, generating cyclic load with**

Example:
- step-wise heating
- peaks measured of both phases

- Results written up, will be submitted to Journal soon
- In addition: IPAC 24 Paper on radiation damages on e+ source materials



T. Lengler

- *Result: ILC undulator target will stand the load !*

WP-6: Rotating Target for Undulator Scheme

- Target specification
  - Titanium alloy, 7mm thick (ILC250: 0.2 X_0), 14mm (ILC500), diameter 1m
  - Rotating at 2000 rpm (100 m/s) in vacuum
  - Photon power ~60 kW, deposited power ~2 kW
  - Radiation cooling
  - Magnetic bearings, widely used for Fermi choppers, vacuum pumps and fast rotating masses

- R&D ongoing
  - Detailed simulations in close contact with OMD design on-going (Grigory's Talk
  - OMD Design finalization, laboratory test of mock-up design
  - Contact with SKF (Canada) started: technical specifications done, engineering design, test

WP6: R&D activities rotating wheel

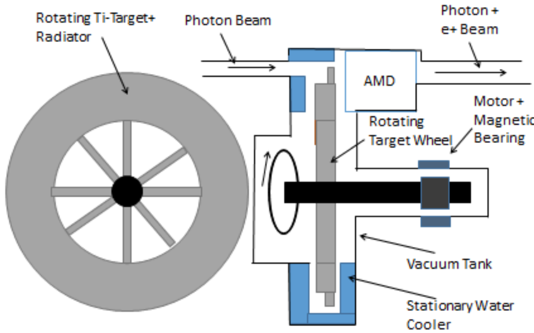
Drive and bearings

- Radiation cooling allows magnetic bearings
  - The axis is «floating» in a magnetic field, provided by permanent or electro magnets
  - Discussion with SKF (Canada) started

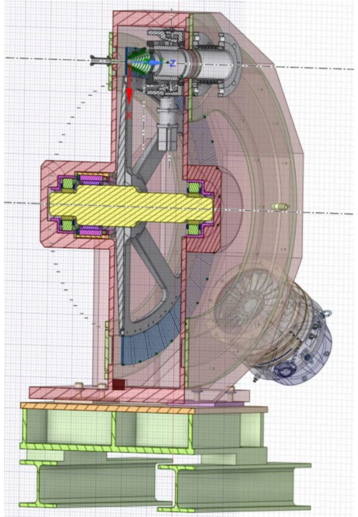
- Within ITN initiative: manufacturing drawings at Uni&DESY
- Ongoing discussion with company SKF

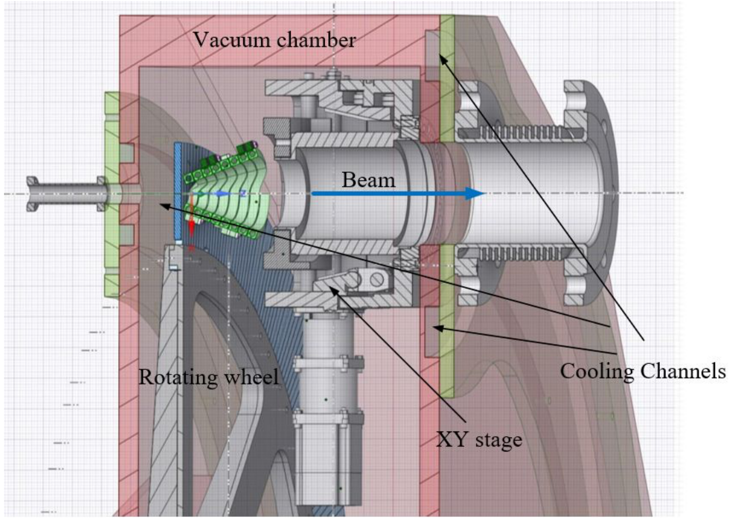
P.Sievers

Principal Layout: Ti-Wheel with a Diameter of 1.0 m, rotating at 100 m/s, 2000 rpm.

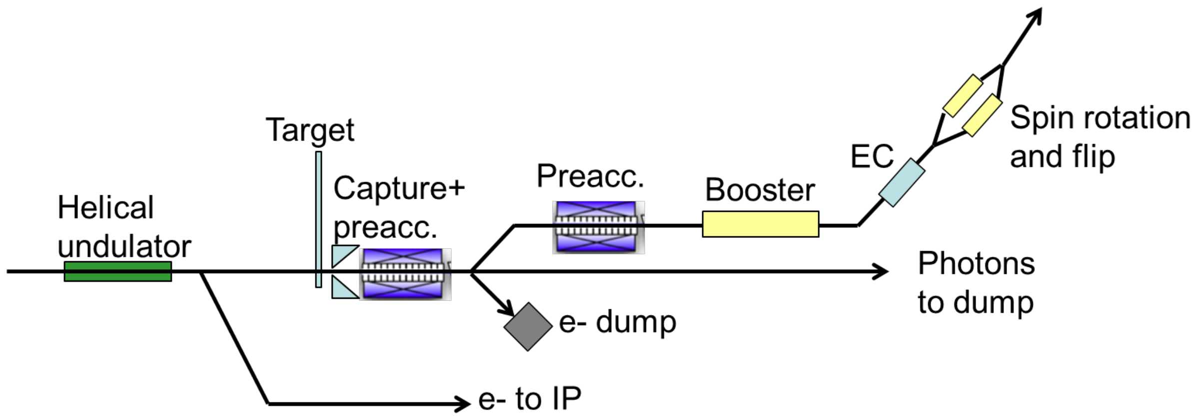


G. Yakopov 2024





WPP-7: Focusing System for Undulator Scheme



- The critical item for the undulator scheme is the magnetic focusing system right after the target
- Possible candidates are: (a) Pulsed solenoid, (b) Plasma lens
- The strongest candidate is (a) pulsed solenoid.
- R&D items ongoing:
  - ➢ Detailed simulations for (a) (already on-going)
  - ➢ Principal design & engineering for a prototype pulsed solenoid
  - ➢ Field measurements with 1kA (pulsed and DC) and with 50kA both in a single pulse mode and finally with pulse duration of 5ms at 5 Hz
  - ➢ Prototype plasma lens (funded study on-going)

OMD Design: Pulsed Solenoid

‘Baseline’ proposal by P. Sievers: Pulsed Solenoid

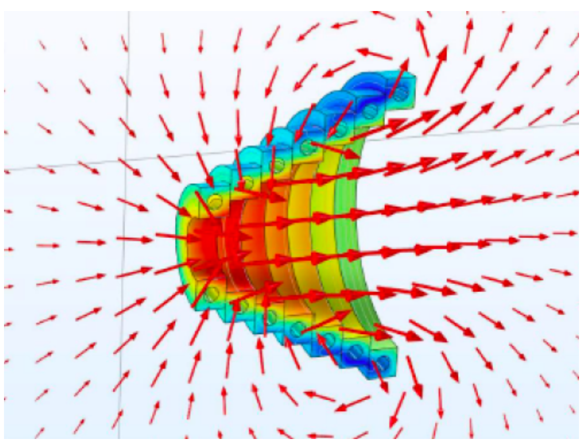
- Yield of e+ (OMD&capture Linac): 1.64-1.81 Fukuda-san, 2021
- ITN initiative: manufacturing drawings for prototype done@ DESY

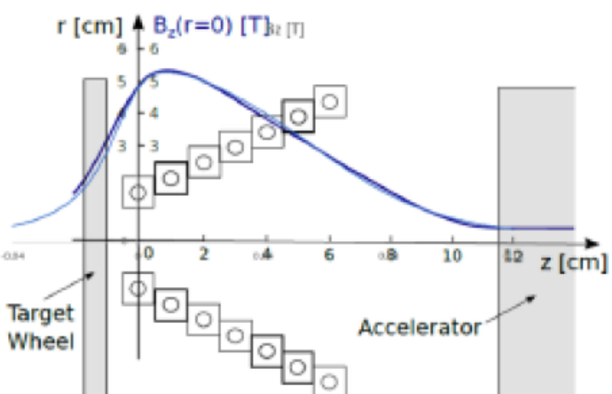
➡ **Absolutely great initiative, thanks a lot!!!**

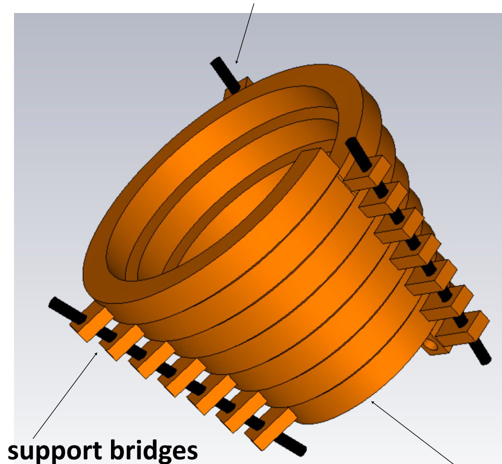
G. Yakopov 2024

- advanced design, several manufacturing approaches
- Planned: prototype will be sent and tested at CERN

Mentink, Tenholt, Loisch, 2021







OMD Design: Pulsed Solenoid

'Baseline': Pulsed Solenoid

- Yield of e+ (OMD&capture Linac): 1.64-1.81 Fukuda-san, 2021
- Within ITN initiative: manufacturing drawings at DESY G. Yakopov 2023
- Planned: prototype will be sent and tested at CERN

C. Tenholt 2021

	Beamloss Power				Positron Yield	
	@dogleg	**@booster**	**@EC**	**@DR**	**@capture (|Z|<7mm)**	**@DR**
QWT	0.677 kW	0.014 kW	4.01 kW - 5.56 kW	13.15 kW - 14.3 kW	1.07	**~1.1**
Pulsed ´solenoid w/ o shield	0.927 kW	0.055 kW	5.86 kW - 7.93 kW	17.39 kW - 16.01 kW	1.81	**1.91**
Pulsed solenoid with shield	0.871 kW	0.064 kW	5.58 kW - 7.90 kW	17.73 kW - 16.24 kW	1.64	**1.74**

OMD Design: Plasma Lens

IPAC 24, Formela, Hamann, Loisch, et al

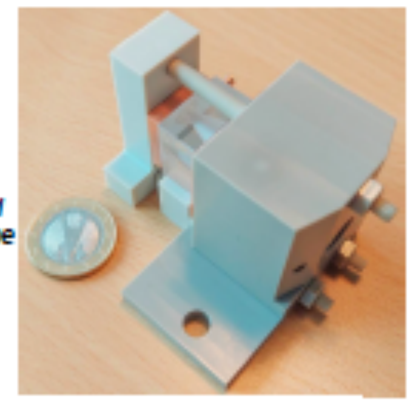
'Future': Plasma Lenses

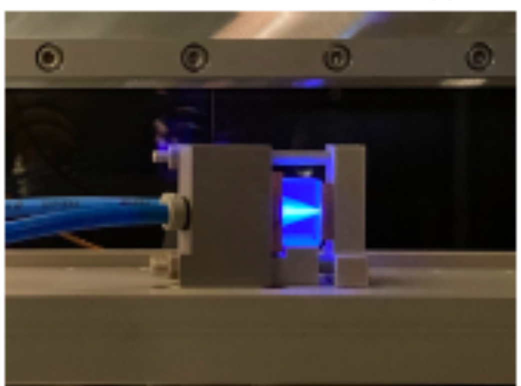
- increases e+ yield but increases load at target only slightly
- advantages in matching aspect
- downscaled prototype designed and produced

Prototype design

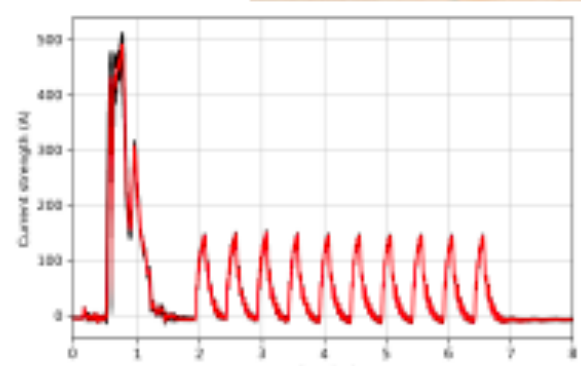
- Principle: lens is pressed in between mounts with threaded rods and sealed with O-rings
- Mounts made out of PEEK
- Electrodes made out of copper
- Plasma lens made out of sapphire block

Finished Prototype





Produced plasma



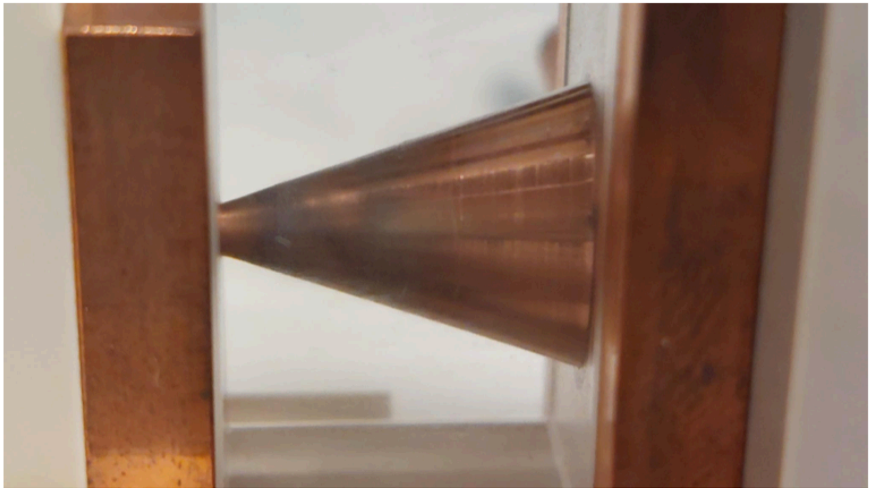
Ingoing current measured

OMD Design: Plasma Lens

IPAC 24, Formela, Hamann, Loisch, et al

'Future': Plasma Lenses

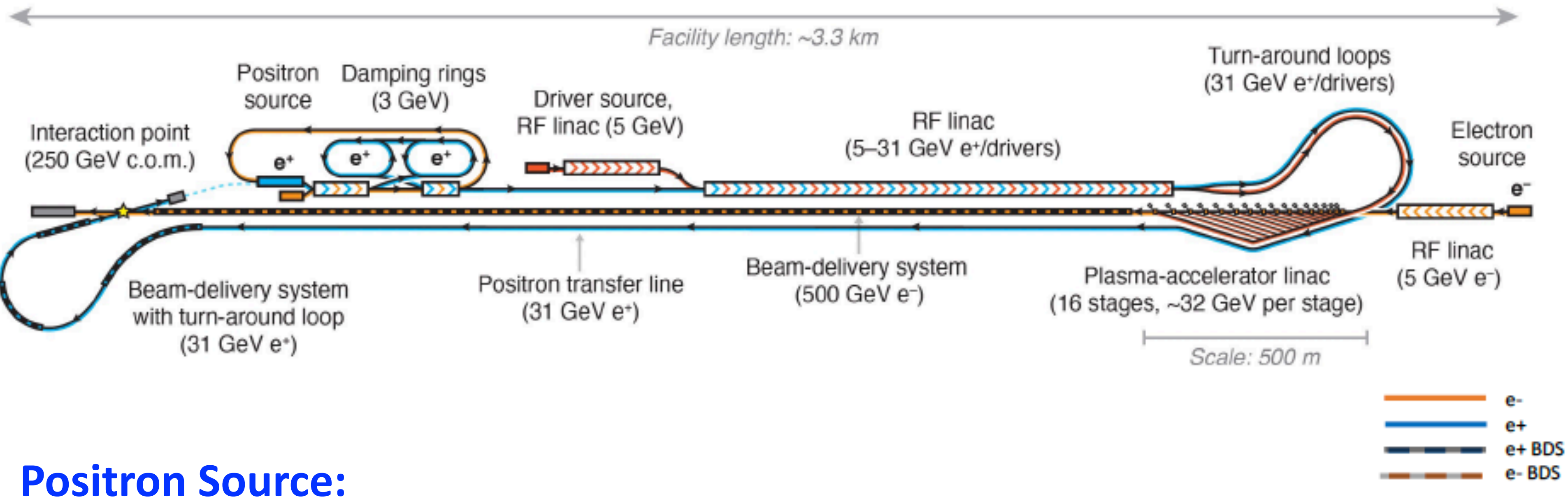
- increases e+ yield but increases load at target only slightly
- advantages in matching aspect
- downscaled prototype (~factor 5) designed and produced
- first measurements done
- surprising copper coating from electrodes …other material?



➡ please stay tuned, lots of exciting work on prototypes ongoing !

H(ybrid)A(symmetric)L(inear)H(iggs)F(actory) Design

B. Foster, R. D'Arcy, C.A. Lindstrom



Positron Source:

- **Conventional e+ source with up to 31 GeV e- drive beam**
  - **needs RF**

- **Undulator-based source: mature for ILC parameters**
  - **'sustainable' double-use of electron drive beam**
  - **higher physics potential**

Just started, ongoing R&D

Overview positron requirements

	rep rate/Hz	#bunch/pulse	#e+/bunch	#e+/pulse	#e+/s
SLC	120	1	$5x10^{10}$	$5x10^{10}$	$6x10^{12}$
ILC/Tesla	5	1312	$2x10^{10}$	$2.6x10^{13}$	$1.3x10^{14}$
CEPC	100	1	$2x10^{10}$	$2x10^{10}$	$2x10^{12}$
CLIC	50	312	$4 x10^{9}$	$1.2x10^{12}$	$6x10^{13}$
HALHF	10000	1	$2\text{-}3x10^{10}$	$2\text{-}3x10^{10}$	$2\text{-}3x10^{14}$

Status and Strategy

Goals: implement undulator with L=176m, K=2.5, λ=43 mm and collimator aperture R_c= 0.9 mm

- **Similar as for ILC set-up….. undulator at 'end-of-the-linac'**
  - ➡ **e- emittance growth was a few % and energy loss 3-4 GeV**
  - ➡ **starting point for e+: target = rotating wheel**
    OMD = pulsed solenoid / Plasma

- **What's about using HALHF as upgrade of ILC250? ….**
  - ➡ **now: immediately start with ILC250 run (~20 km tunnel length)**
  - ➡ **later: use e- tunnel (10 km) for PWA acceleration (~100 m) and reach with ILC e+ beam & PWA e- beam $\sqrt{s}$~500GeV**

- **But…..so far no true simulations on target loads etc…. stay tuned…**

Conclusion and plans

- **ILC undulator-based source mature and feasible:**
  - **Undulator simulations done**
  - **Thanks to ITN initiative: prototype work on pulsed solenoid and next steps on rotating wheel ongoing**
    - **collaboration University Hamburg&DESY&CERN&KEK**
  - **Future OMD design: plasma lens prototypes under tests**

  ➡ **substantial progress since last year and protoypes 'just ahead'**

  ➡ **please remember: Simultaneous $e^{\pm}$ polarization allows highest physics potential, best control of systematics, higher statistics in less running time!**

- **HALHF plans (only short tunnel for e- beam acceleration):**
  - **new technology (PWA) in combination with SRF would allow upgrade to higher energies in short tunnels**
  - **try to adapt undulator-based e+ source for HALHF e- beams, combine R&D issues**

➡ ***ILC can be built NOW and maybe future upgrade as HALHF…?***

WP5: GigaZ operation

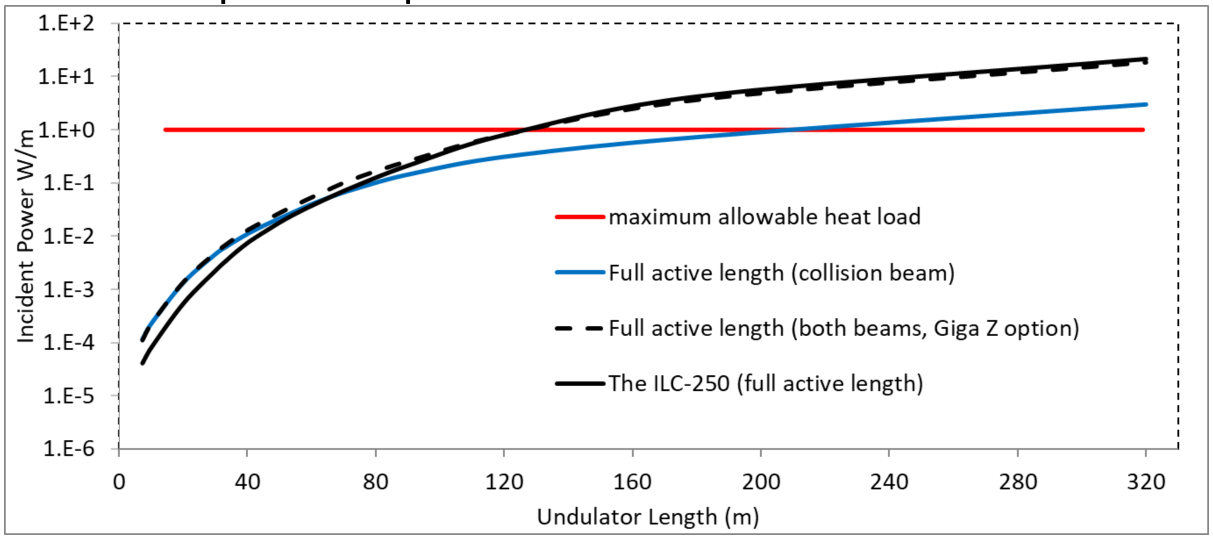
- Parameters for GigaZ operation

  Yokoya-san, 1908.08212

Parameters	e^+ production	collision	Unit
Final beam energy	125	45.6	GeV
Average accelerating gradient	31.5	8.76	MV/m
Peak power per cavity	189	77.2	kW
Beam pulse length	0.727	0.727	ms
RF pulse length	1.65	1.06	ms
Repetition rate	3.7	3.7	Hz

- Incident power at undulator walls: Compare GigaZ and ILC250

power deposition in wall without masks



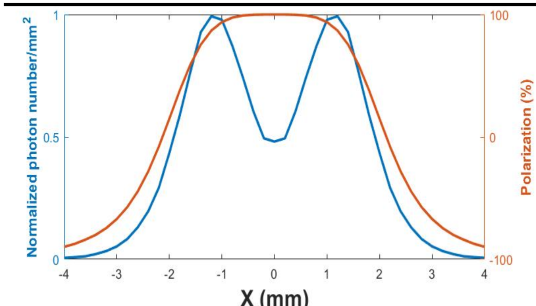
➡ Incident power at GigaZ below /comparable with ILC250

➡ Mask protection will also be sufficient for GigaZ running

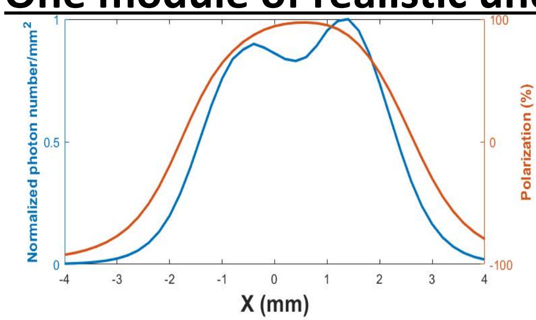
ILC-250 Ideal and Realistic Photon Beam Distribution at Target

Full undulator length (132 modules)

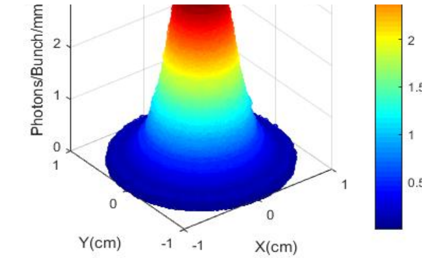
One module of ideal undulator, Y=0



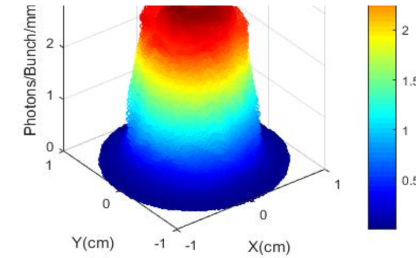
One module of realistic undulator, Y=0



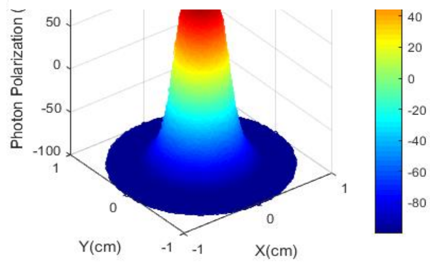
Ideal Photon Distribution



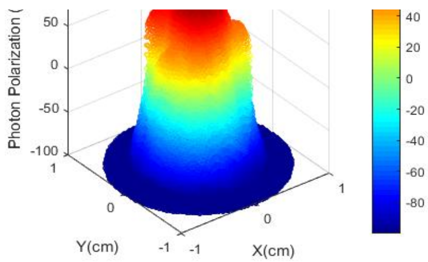
Realistic Photon Distribution



Ideal Polarization Distribution



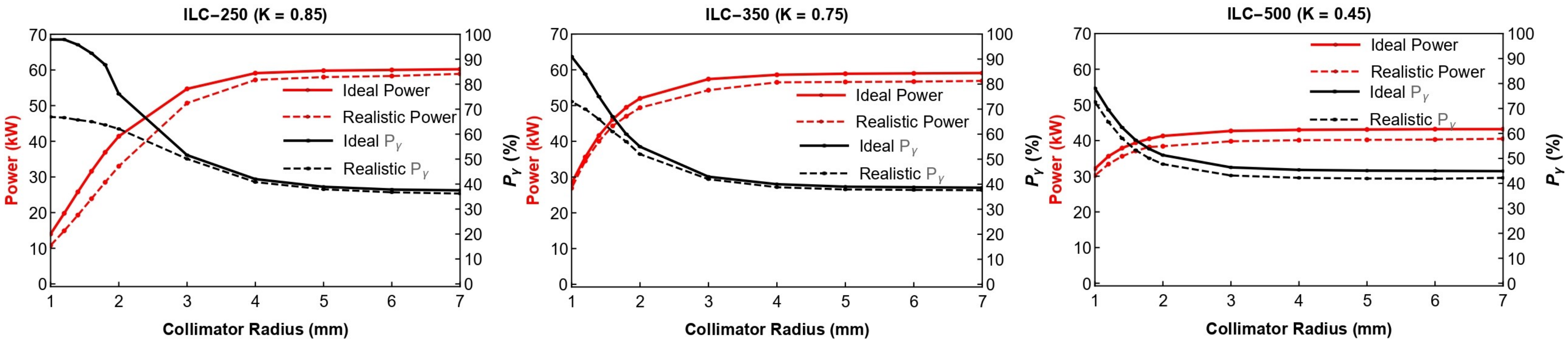
Realistic Polarization Distribution



In case of the realistic case: the photon beam is **no longer** at the centre.

Photon Parameters at Target for Different Photon Collimator Radii

The effect of different photon collimator radii on photon beam parameters at the target for both ideal and realistic undulator cases for ILC-250, ILC-350 and ILC-500:



Substantially lower photon beam polarization for non-ideal undulator, especially, for higher K values.

Deposited Energy & Target Stress

Goals: high #e+@DR, high P(e+)>30%, target lifetime~1y

Ushakov ea 1301.1222

- **So far: FLUKA and ANSYS simulation done 'only'**
  - ➡ **for ILC e- beam and rotating target wheel with 100 m/s ('ILC target')**
  - ➡ **Results: Stress is ~25% tensile yield stress and 44% of fatigue stress of Ti-alloy target (but done without centrifugal forces of wheel and superposition effects)….but should be safe (for ILC e- beam)!**

Simulations have now to be redone for HALHF e- beam and for non-ideal undulator fields!

(since deviations between 'ideal' and 'realistic' unduator fields get larger for larger K,….)

Khaled Alharbi, Thesis 2024

Undulator with E(e-)=500 GeV

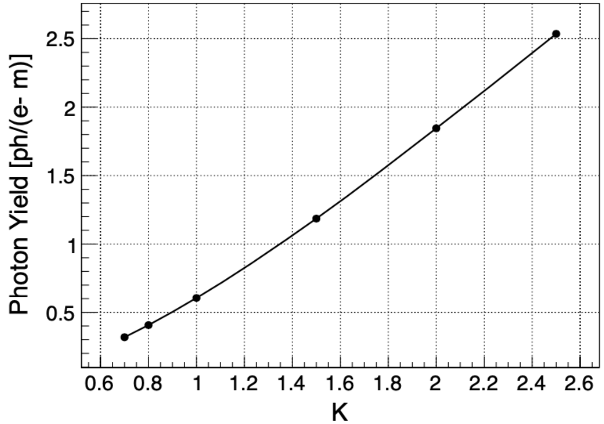
Goals: high #e+@DR, high P(e+)>30%, target lifetime~1y

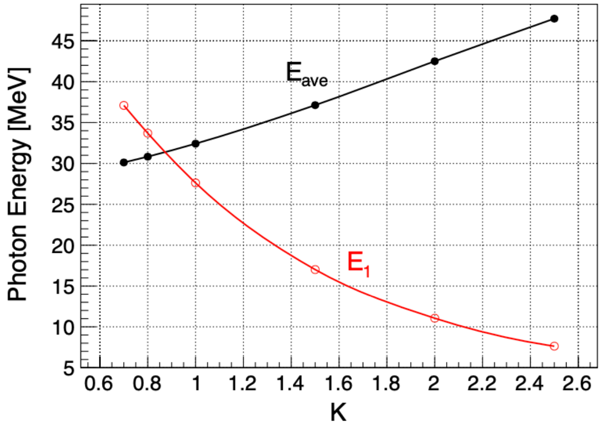
Proposal: Use new undulator parameters

Ushakov ea 1301.1222

➡ **e.g. higher K = 2.5, period λ=43 mm**

➡ **leads to more higher harmonics, higher yield,**





➡ **higher γ_{ave} energy and higher energy spread**

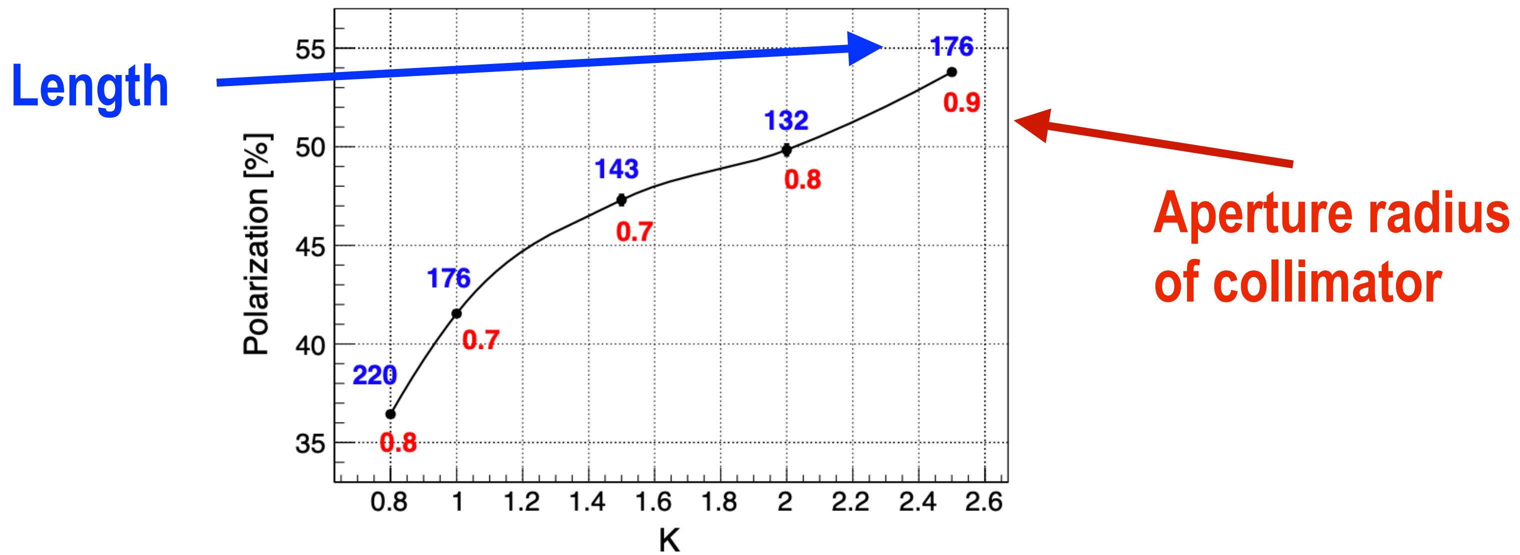
➡**larger γ spot size**

➡ **e+ capture more difficult…..but more know-how (PS, PL) now!**

Undulator with E(e-)=500 GeV

Goals: high #e+@DR, high P(e+)>30%, target lifetime~1y

- **Apply photon collimator:**



- **High P(e+) achievable: ~54%**

➡ **stick to this undulator parameters: capture& target issues**

➡ **but…..factor 1.5-2 more e+ needed than at ILC….**