The E166 Experiment: Undulator-Based Production of Polarized Positrons

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for the E166 Collaboration

- ILC: - physics with polarised e^+e^-
  - undulator source scheme for ILC
- E166 – proof-of-principle of the undulator method
  - undulator basics
  - transmission polarimetry
  - Geant4 upgrade with (de)polarisation
- results & conclusions

Physics with Polarised e^+e^-

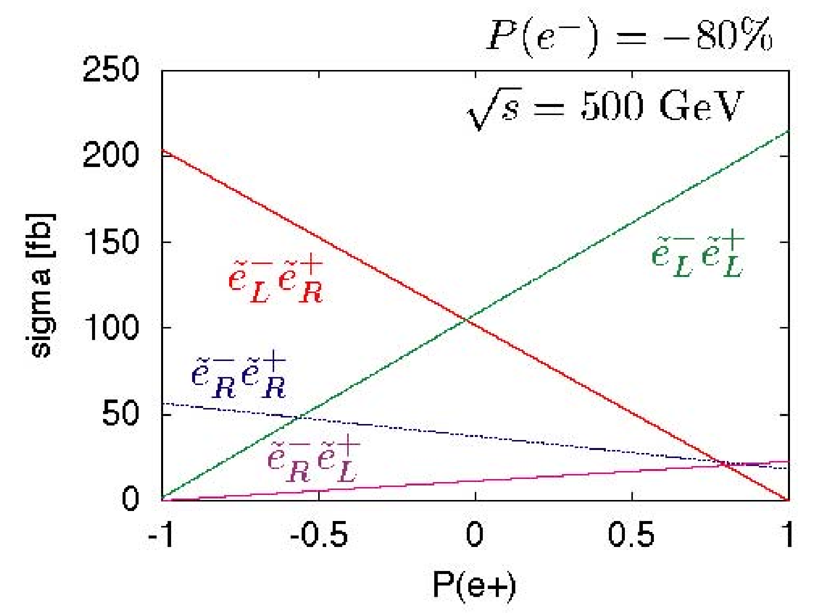
Polarized e^+-beams in addition to polarized e^--beams offer*:

- Higher effective polarization
- Reduction of background
- Selective enhancement of processes
- Access to non-SM couplings
- New physics, e.g. extra dimensions
- ….

Example: SUSY physics

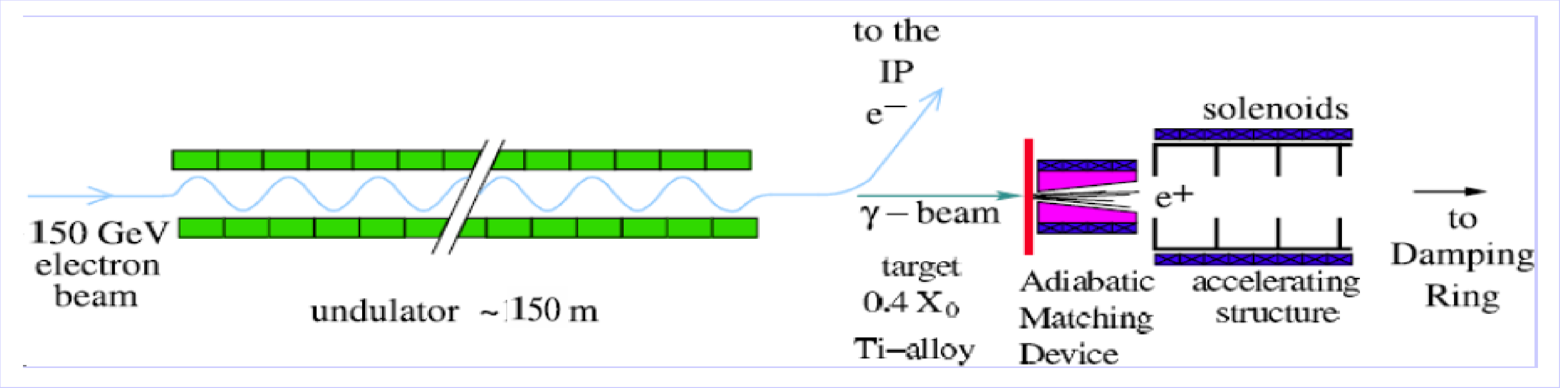
Separation of selectron pairs

$$e^+e^- \to \tilde{e}^+_{R,L}\ \tilde{e}^-_{L,R}$$



*G. A. Moortgat-Pick et al.: **"The Role of polarized positrons and electrons in revealing fundamental interactions at the linear collider".** Phys. Rept. 460:131-243, 2008. (e-Print: hep-ph/0507011SLAC-PUB-11087, CERN-PH-TH-2005-036)

Undulator Source for ILC

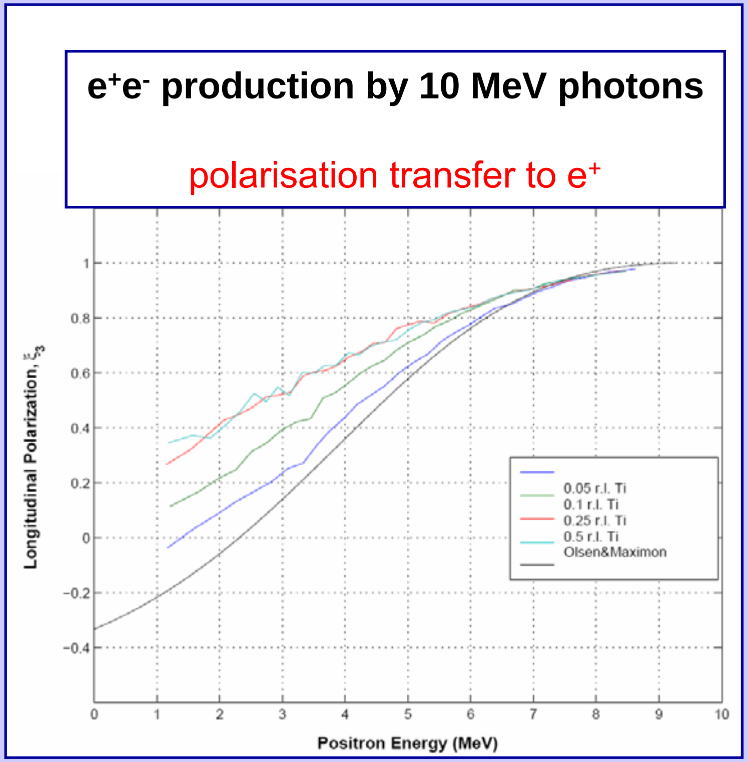


PRO:

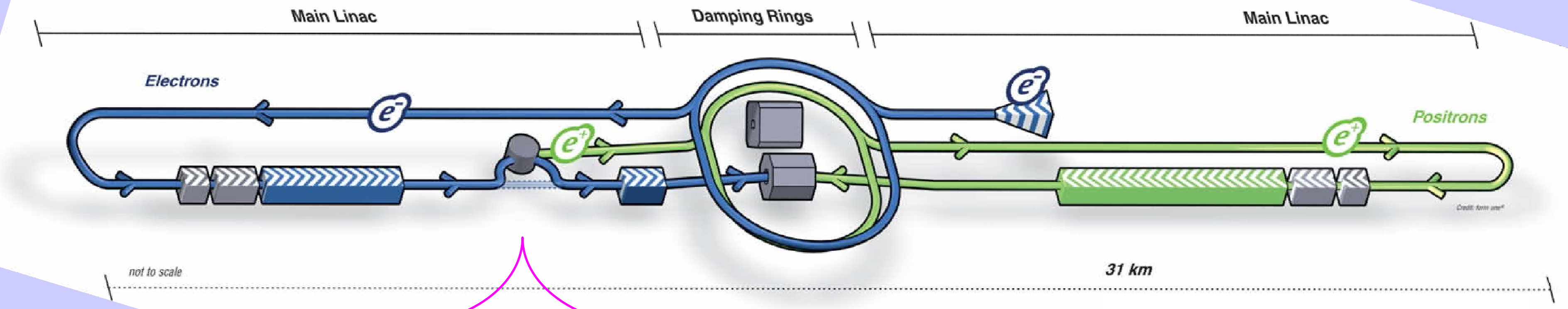
- **target 0.4 X_0 Ti-alloy $\rightarrow$ lower e^+ emittance**
- **less energy deposition in target and AMD**
- **less neutron activation**
- **polarized positrons**

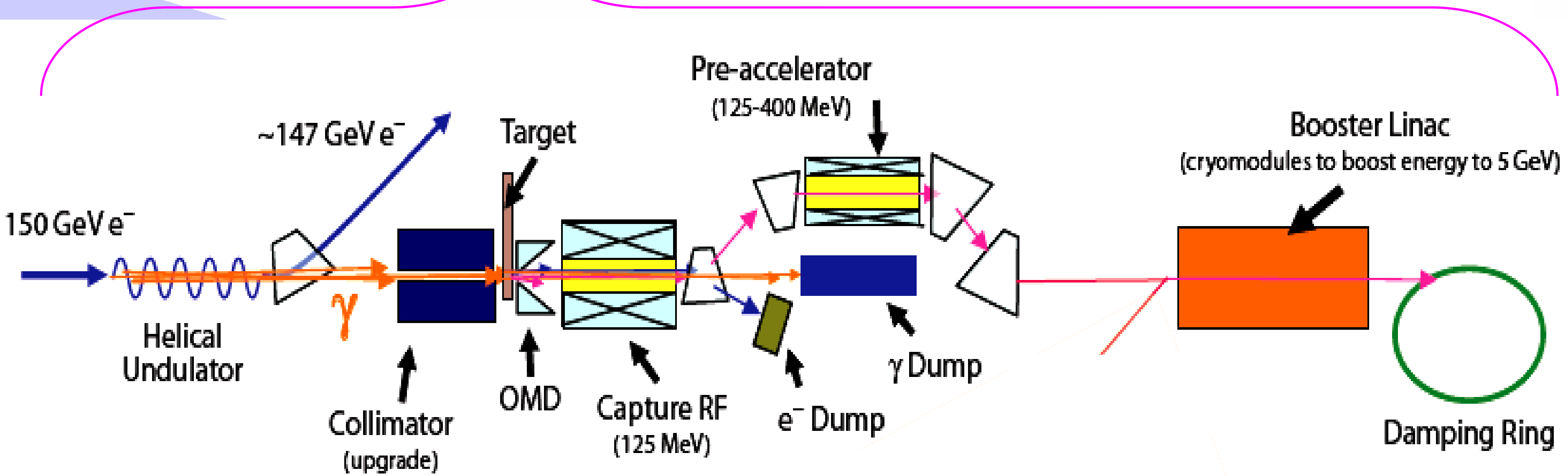
CON:

- **need high-energy electron drive beam (coupled e+/e- operation)**
- **long undulator (150-300 m)**



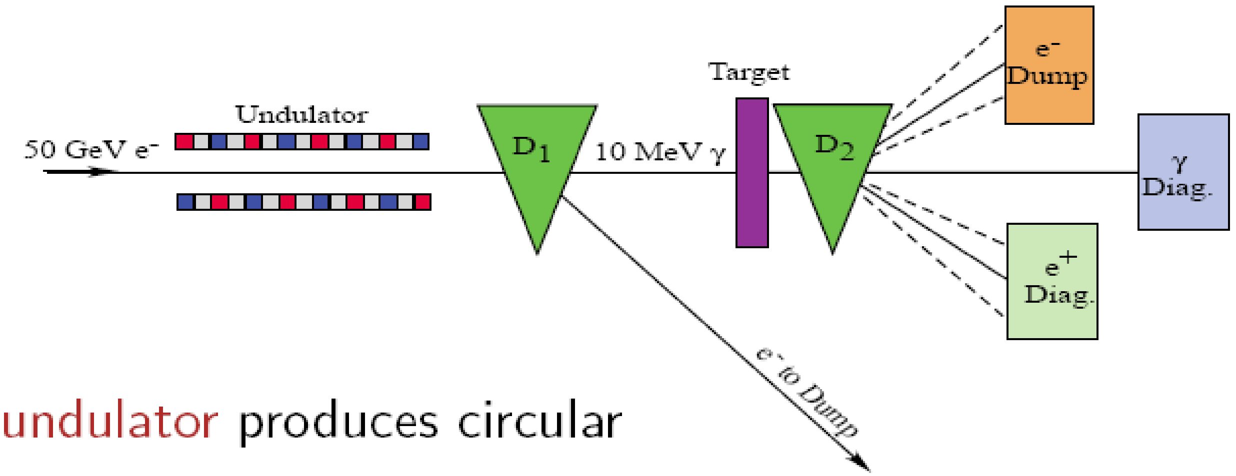
Undulator Source Scheme for ILC





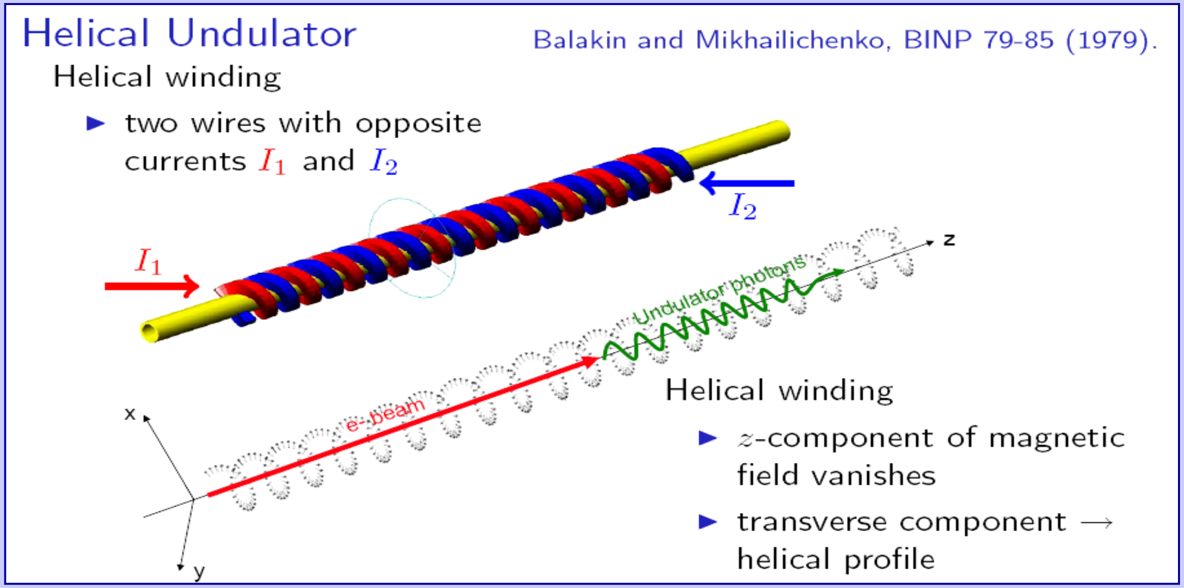
E166 – proof-of-principle demonstration of the undulator method

Schematic layout



- 1 meter helical undulator produces circular polarized photons
- utilizing 50 GeV electron final focus test beam (FFTB) at SLAC
- photons are converted to positrons in thin W-target
- measurement of photon and positron polarization by Compton transmission polarimetry

Undulator Basics

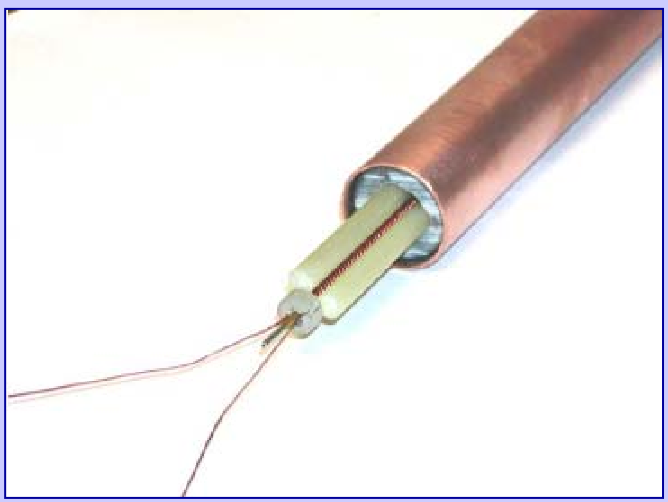


$$E_1 \approx \frac{2\gamma^2 hc}{\lambda_u} \frac{1}{1+K^2}$$

$$\approx \frac{23.7\ \text{MeV}}{\lambda_u / \text{mm}} \left(\frac{E_e}{50\ \text{GeV}} \right)^2$$

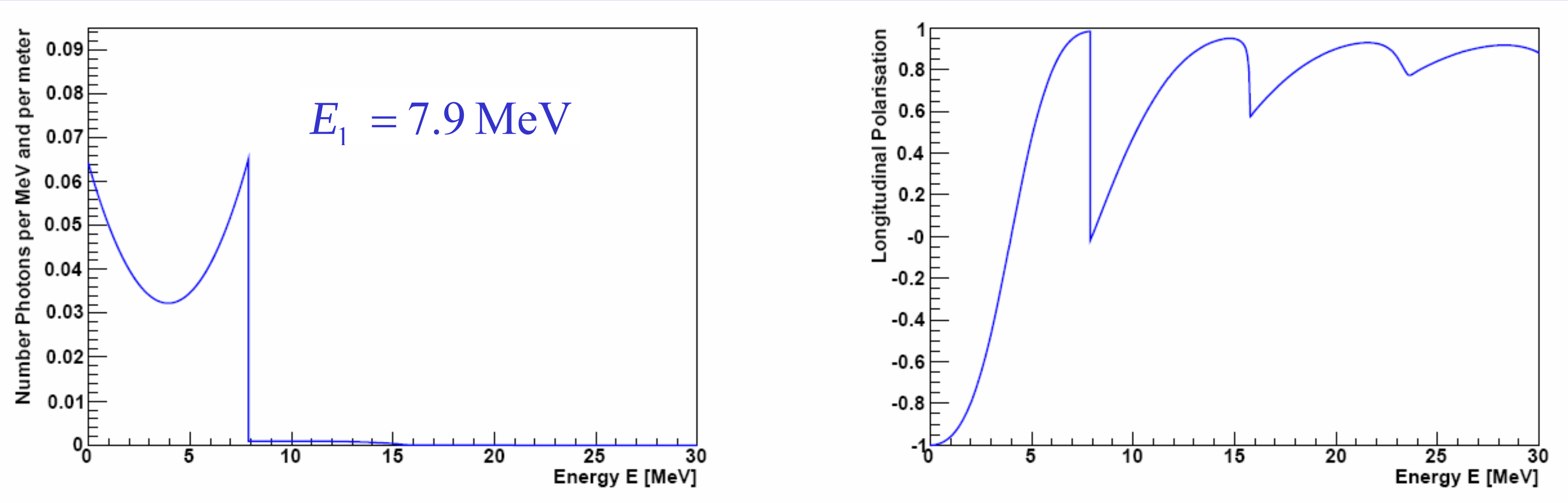
$$K = \frac{eB_0 \lambda_u}{2\pi\ mc}$$

$$\frac{dN_\gamma}{dL} \approx \frac{4}{3} \frac{\pi\alpha}{\lambda_u} K^2 \cong \frac{30.6 \cdot K^2}{\lambda_u / \text{mm}} \frac{\gamma\text{'s}}{e^-} \text{m}^{-1}$$



	E166	ILC(RDR)
electron beam energy (GeV)	46.6	150
field (T)	0.71	0.86
period (mm)	2.54	11.5
K value	0.17	0.92
photon energy E_1 (MeV)	7.9	10.0
beam aperture (mm)	0.89	5.85
active length (m)	1	147
M = no. of periods	394	12800

Undulator Basics



1st harmonic (dominating) expressions:

Spectrum:

$$\frac{dN_\gamma}{ds} = 2\pi\alpha M \frac{K^2}{1+K^2}\left(1-2s+2s^2\right)$$

$$s = E_1/E$$

Angular Distribution:

$$\theta = \frac{1}{\gamma}\sqrt{\left(1+K^2\right)\frac{1-s}{s}}$$

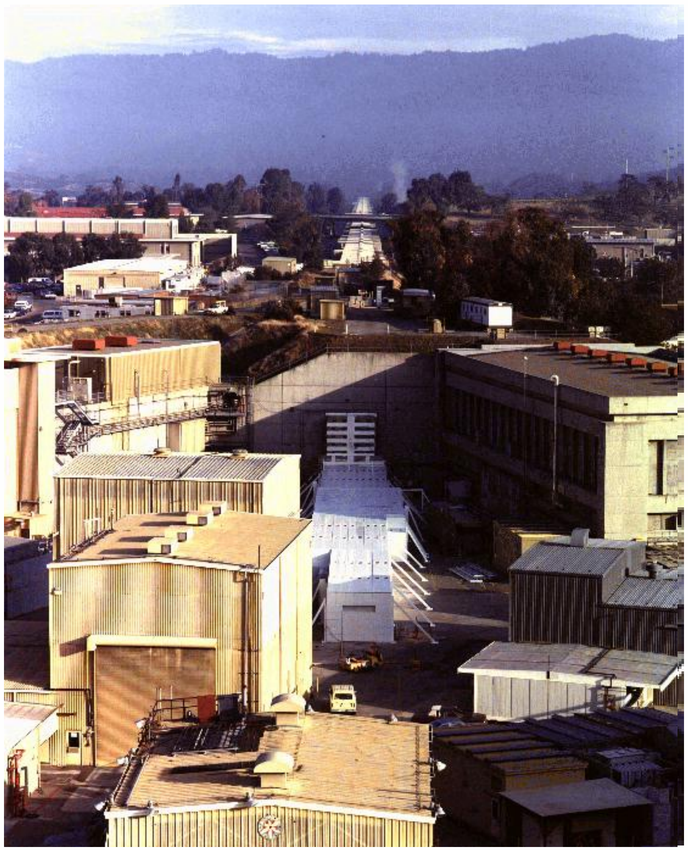
Polarization:

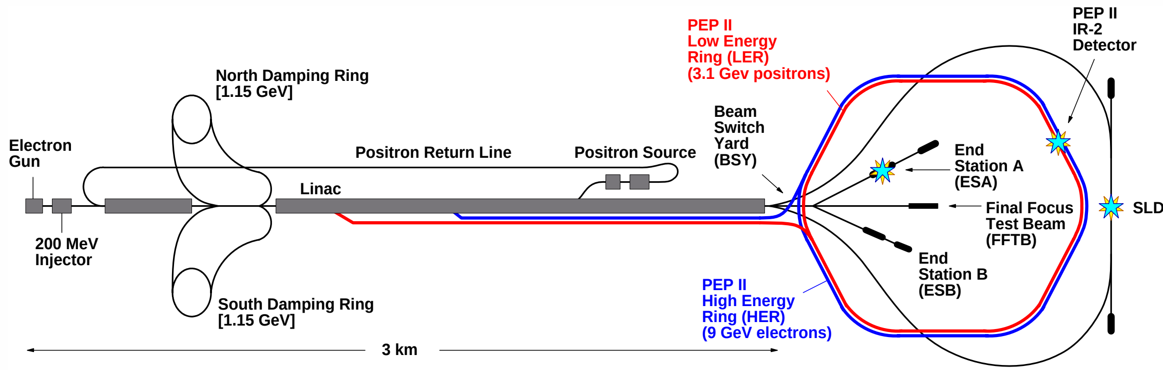
$$P_\gamma = \frac{2s-1}{1-2s+2s^2}$$

E166 Photon Yield: $N_\gamma = \int_0^1 \frac{dN_\gamma}{ds} ds = 0.359$ **= no. of photons per beam electron**

The E166 Experiment at SLAC FFTB

SLAC FFTB:



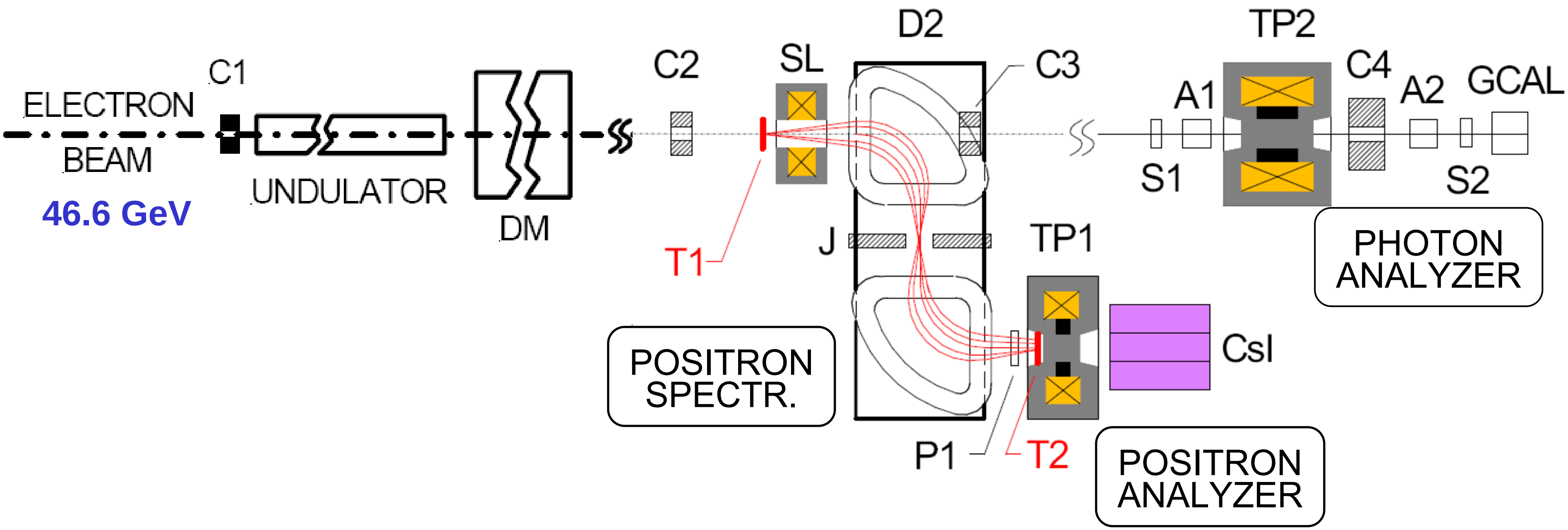


Final Focus Test Beam

- beam energy $E_{\text{beam}} = 46.6\,GeV$
- electrons/bunch $n_e = 0.5 \cdot 10^{10}$
- beam size $\sigma = 40\,\mu m$ σ_z = 50-500 μm
- rep. rate 10Hz

2004/2005	→	**setup and checkout**
2005	→	**4 weeks of data taking**

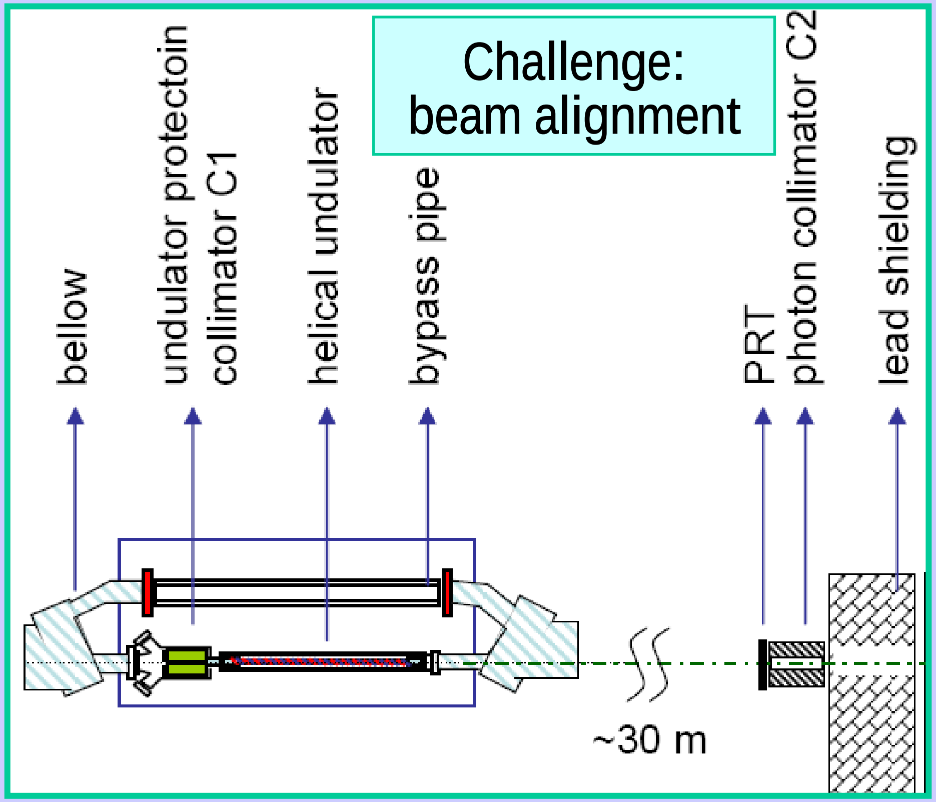
E166 experimental setup

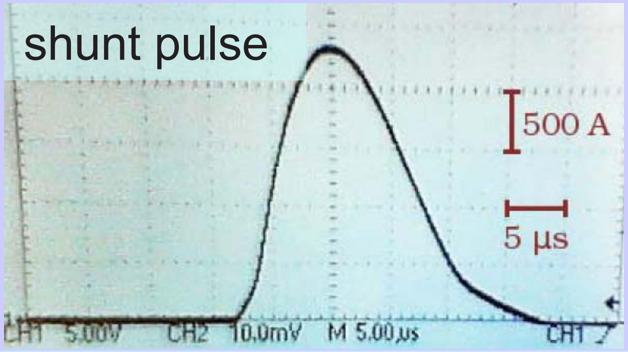


DM:	**electron beam dump magnets**
T1:	$\gamma \rightarrow e^+$ **prod. target (0.2 X_0 W)**
T2:	$e^+ \rightarrow \gamma$ **reconv. target (0.5 X_0 W)**
P1:	e^+ **flux monitor (Silicon)**
CsI:	**CsI calorimeter**
SL:	**solenoid lens**
J:	**movable jaws**

C1 – C4:	**photon collimation**
A1, A2:	**aerogel detectors**
S1, S2:	**silicon detectors**
GCAL:	**Si/W-calorimeter**

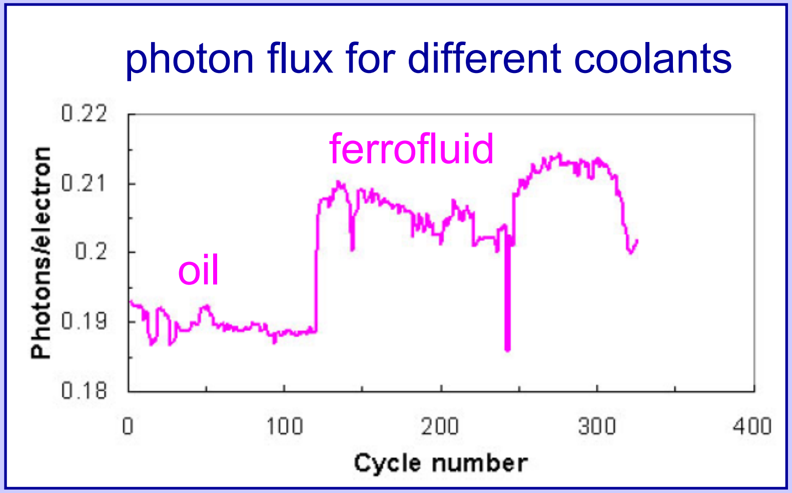
Undulator Operation



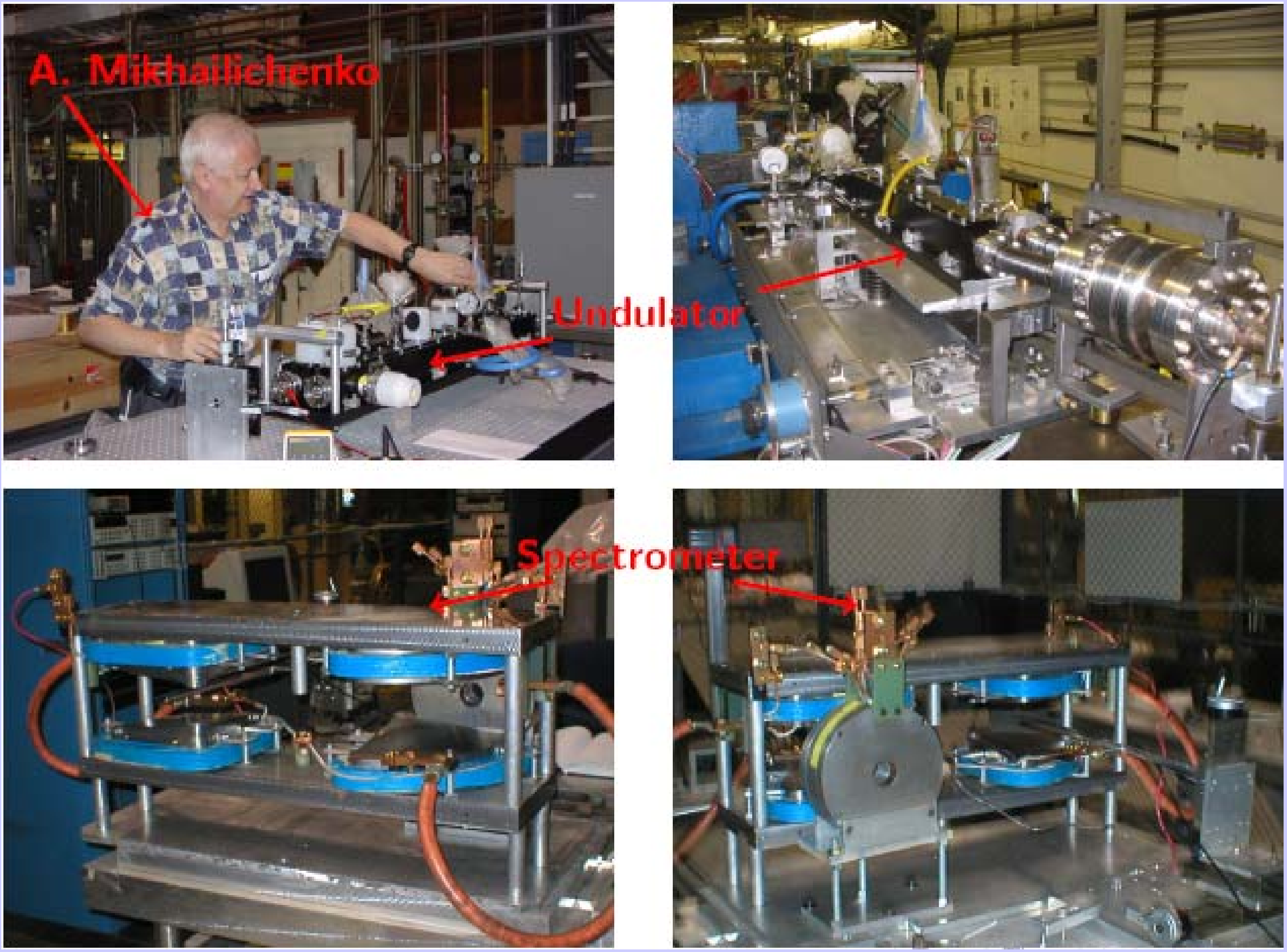


- current: 2.3 kA
- repetition rate 10 Hz
- current density 6.39 kA/mm²
- pulse duration: of about 12 µs.

kicks e⁻ beam ≈ 23µrad

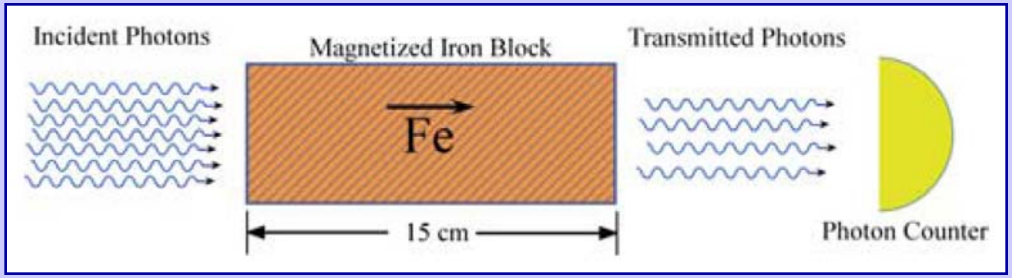


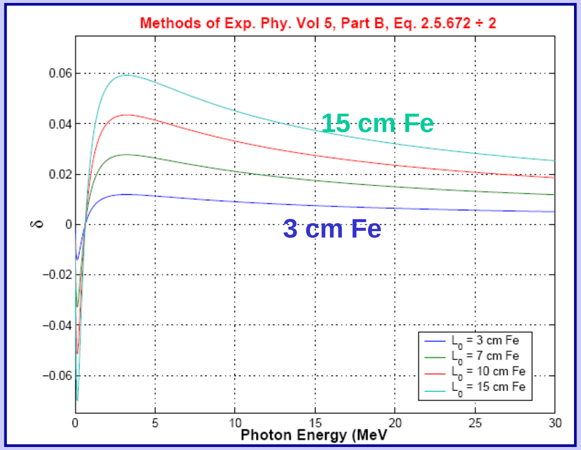
E166 photo gallery



Compton Transmission Polarimetry for Low-Energy Photons

relies on spin dependence of Compton effect in magnetized iron:





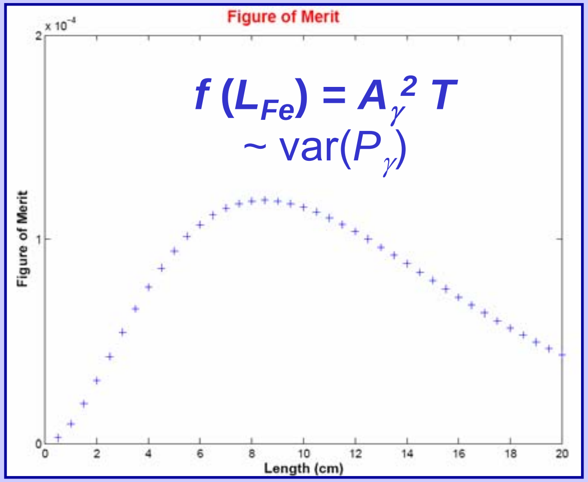
Compton Crosssection $\sigma = \sigma_0 + P_\gamma \, P^{\mathrm{Fe}} \sigma_p$

Transmission $T^{\pm}(L) = e^{-n^{\mathrm{Fe}} L\, \sigma} = e^{-n^{\mathrm{Fe}} L\, \sigma_0} \; e^{\pm n^{\mathrm{Fe}} L\, P^{\mathrm{Fe}} P_\gamma \, \sigma_p}$

Asymmetry $\delta(L) = \dfrac{T^+(L) - T^-(L)}{T^+(L) + T^-(L)} \approx n^{\mathrm{Fe}} L\, P^{\mathrm{Fe}} P_\gamma \sigma_p$

Analysing power $A_\gamma(L) \equiv \dfrac{\delta(L)}{P^{\mathrm{Fe}} P_\gamma} \approx n^{\mathrm{Fe}} L\, \sigma_p$

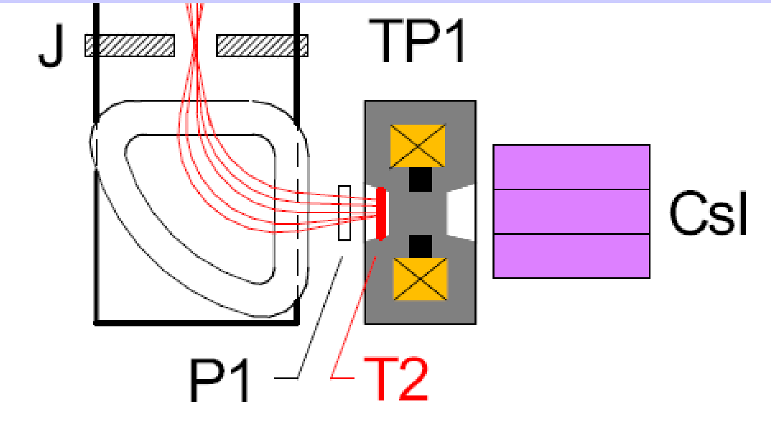
Photon polarisation $P_\gamma = \dfrac{\delta}{P^{\mathrm{Fe}} A_\gamma}$

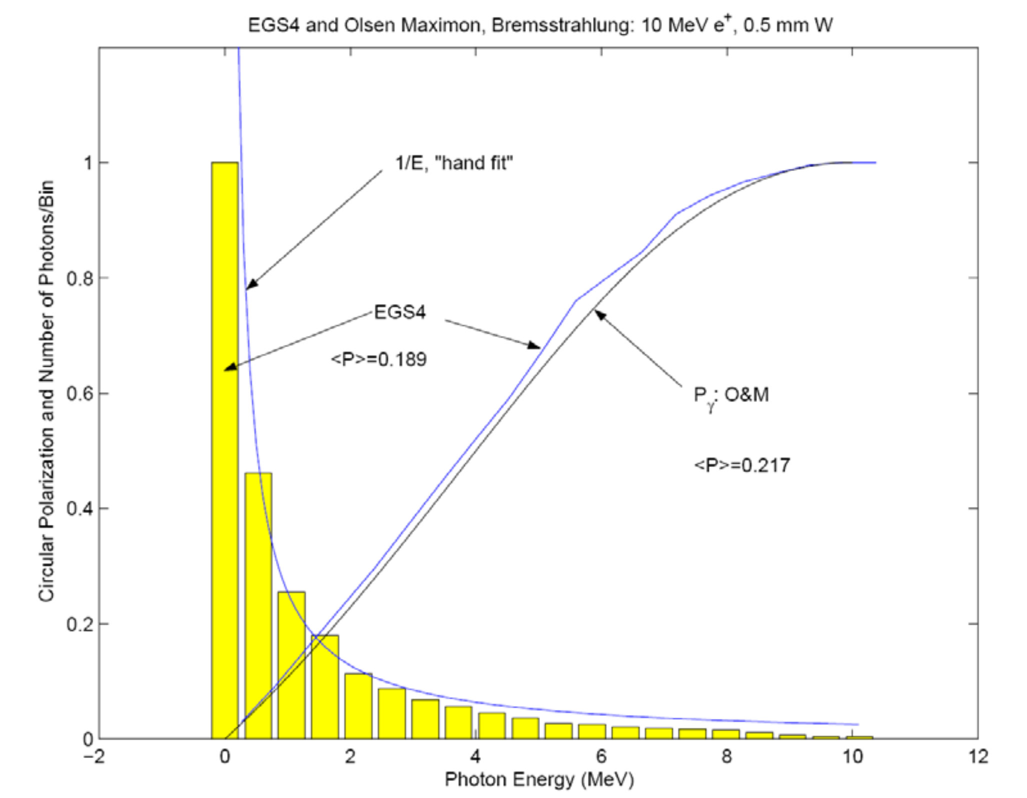


Positron Polarimetry

(a) transfer e^+ polarization to photons via brems/annihilation processes („reconversions“)

(b) infer e^+ polarization from photon polar. by transmission polarimetry

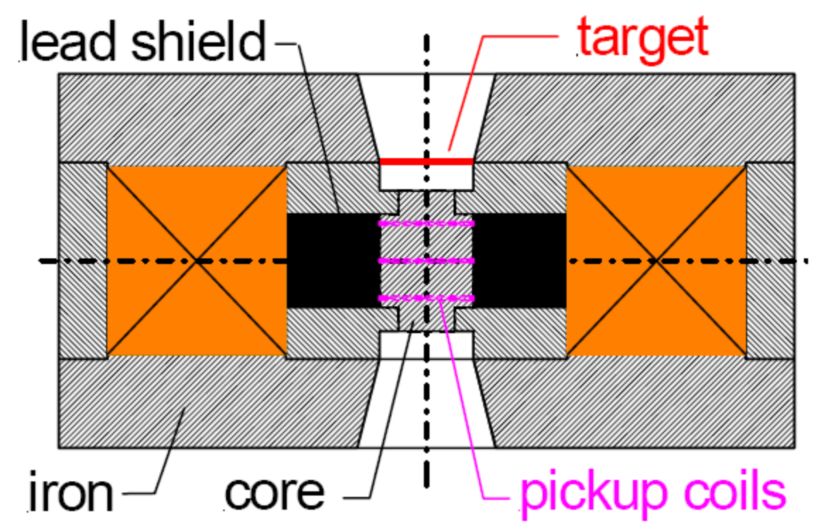


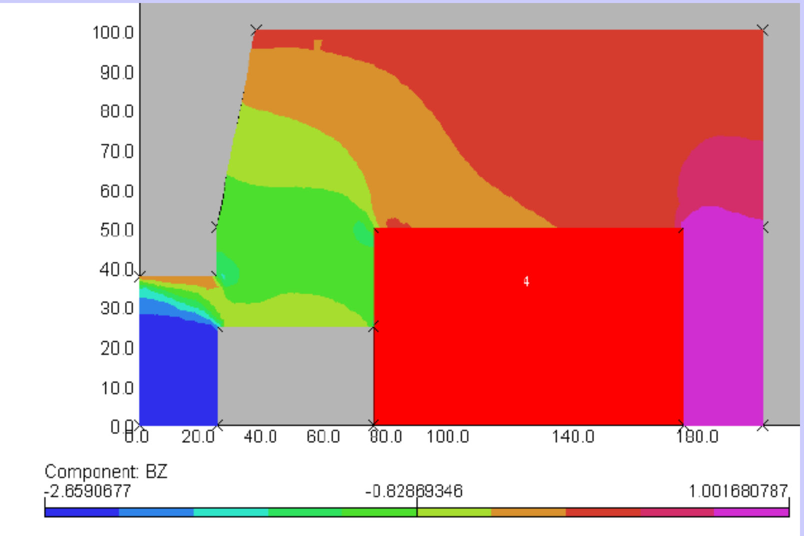


(c) calculate analysing power from detailed simulation of spin dependent processes

(new Geant4 implementations)

Analyzer Magnets





electron polarization of the iron:

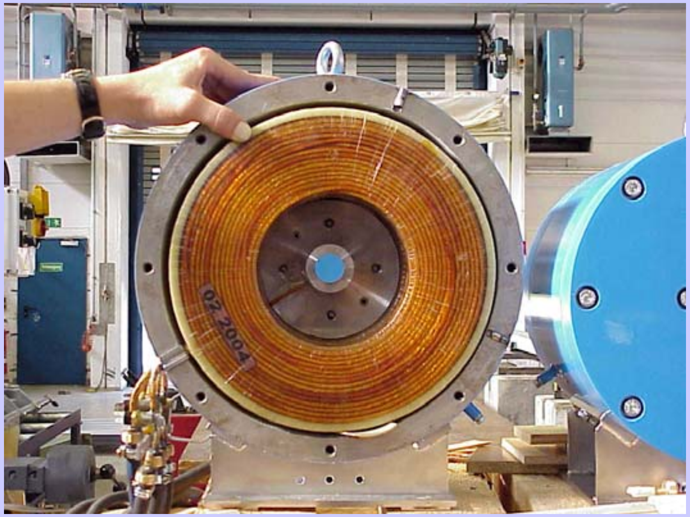
$$P_e = 2 \cdot \frac{g' - 1}{g'} \cdot \frac{M}{n\,\mu_B}$$

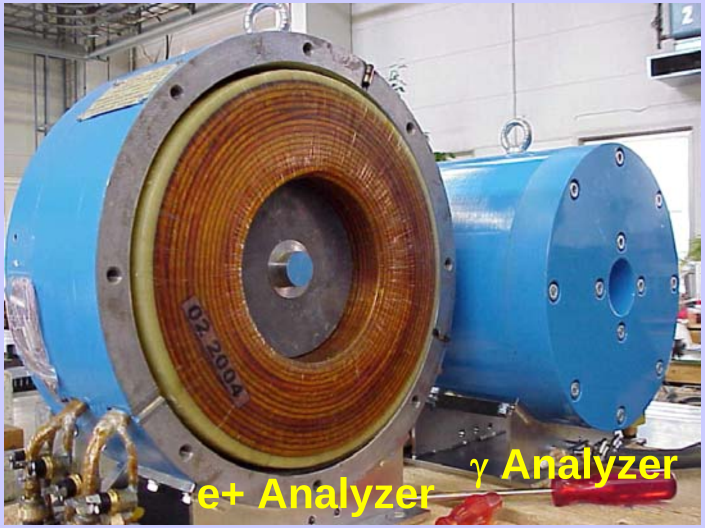
M **= $(B - B_0)/\mu_0$ = magnetization**
n **= electron density**
μ_B = Bohr magneton
g' **= magneto-mechanical factor**

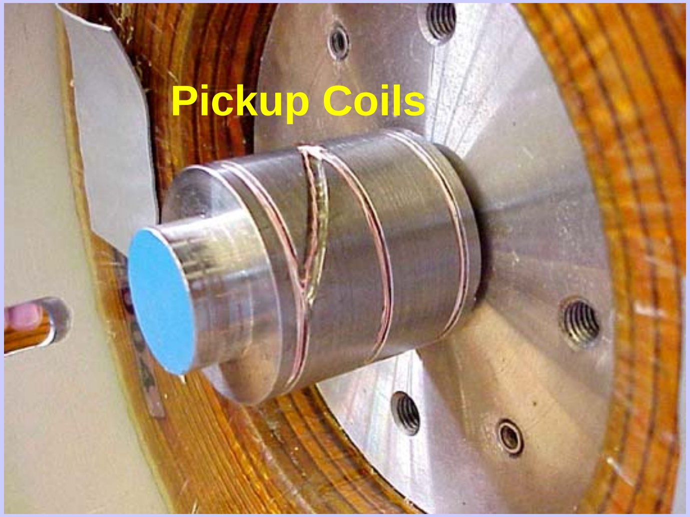
	active volume
Photon Analyzer:	50 mm Ø × 150 mm long
Positron Analyzer:	50 mm Ø × 75 mm long

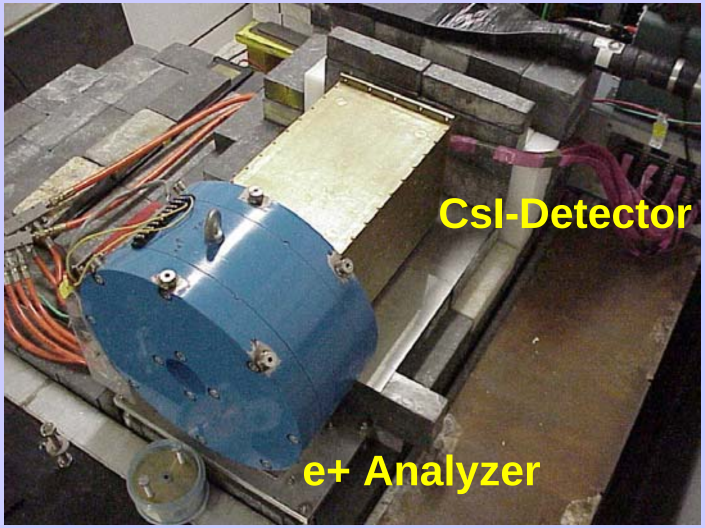
$P_e \approx 0.07$
$\Delta P_e / P_e < 0.05$
(aim of experiment)

Analyzer Magnet Installation









GEANT4 Upgrade
for Polarisation Dependent EM Processes

Polarimetry:
cross sections polarization dependent

- Compton Scattering
- Bhabha Scattering
- Møller Scattering
- Positron annihilation in Flight
- ....

gammas:

- GammaConversion
- ComptonScattering
- PhotoElectricEffect

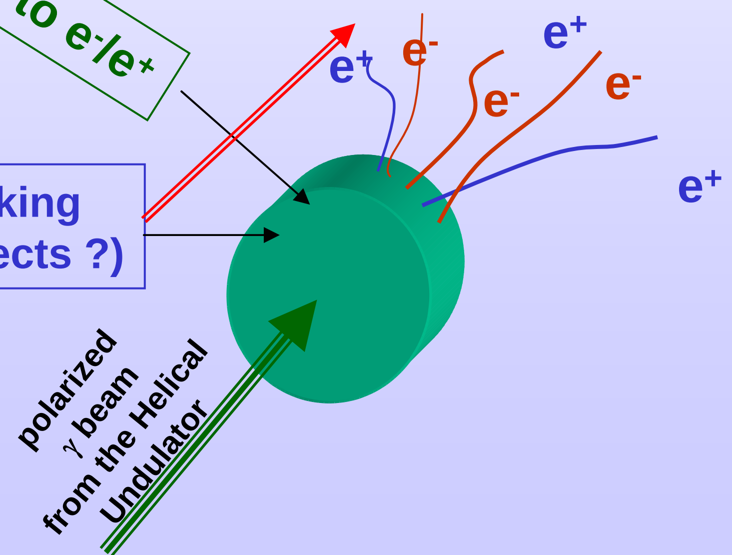
Polarization transfer to e⁻/e⁺

electrons and positrons:

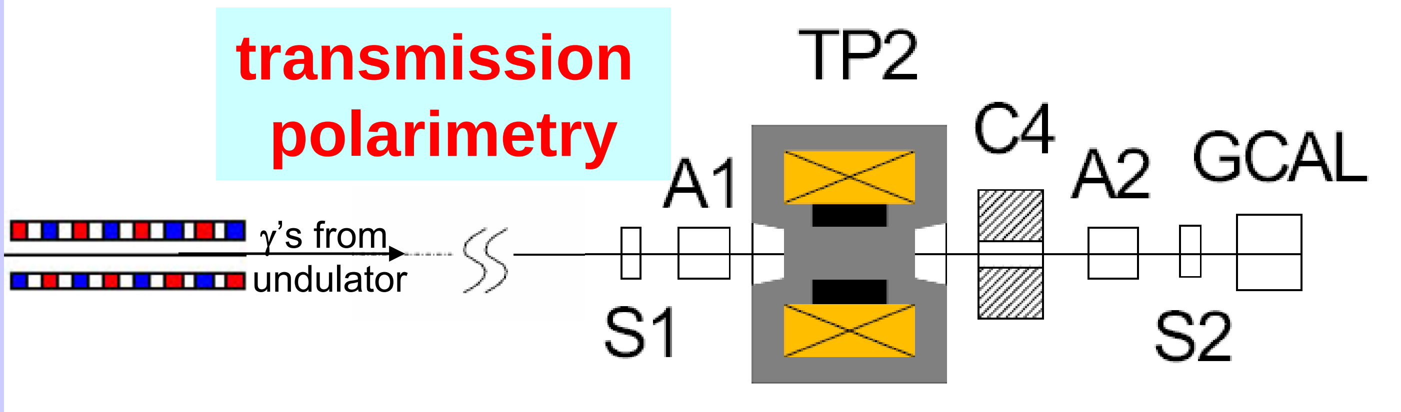
- MultipleScattering
- Ionisation
- Bremsstrahlung

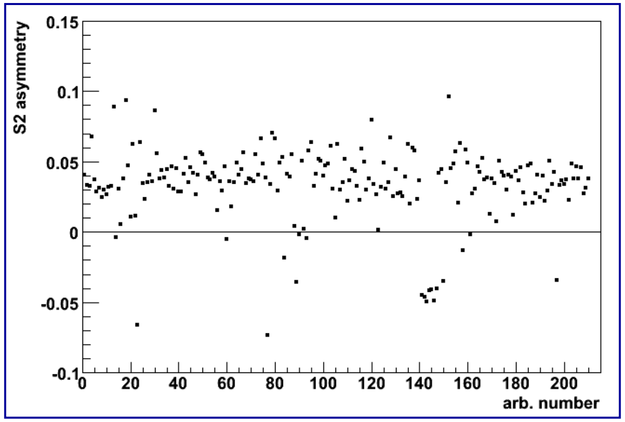
Polarization tracking
(depolarization effects ?)

magnetic field:



Photon Asymmetries





$$\delta = \frac{S^+ - S^-}{S^+ + S^-}$$

detector		asymmetry δ(%)	predicted δ(%)
S2	(silicon)	3.88 ± 0.12 ± 0.63	3.1
A2	(aerogel)	3.31 ± 0.06 ± 0.16	3.6
GCAL	(Si/W)	3.67 ± 0.07 ± 0.40	3.4

conclusion:
measured photon asymmetries are in **agreement with expectations** based on the theor. undulator polarization spectrum and detector response functions.

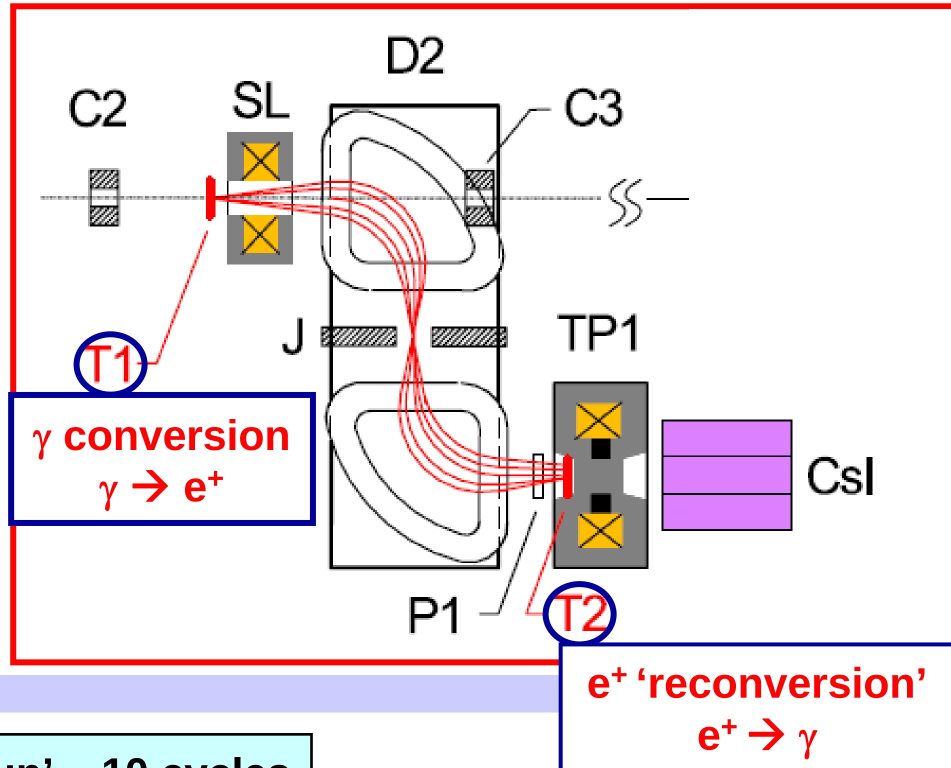
no spectral shape analysis possible!

Positron Analysis

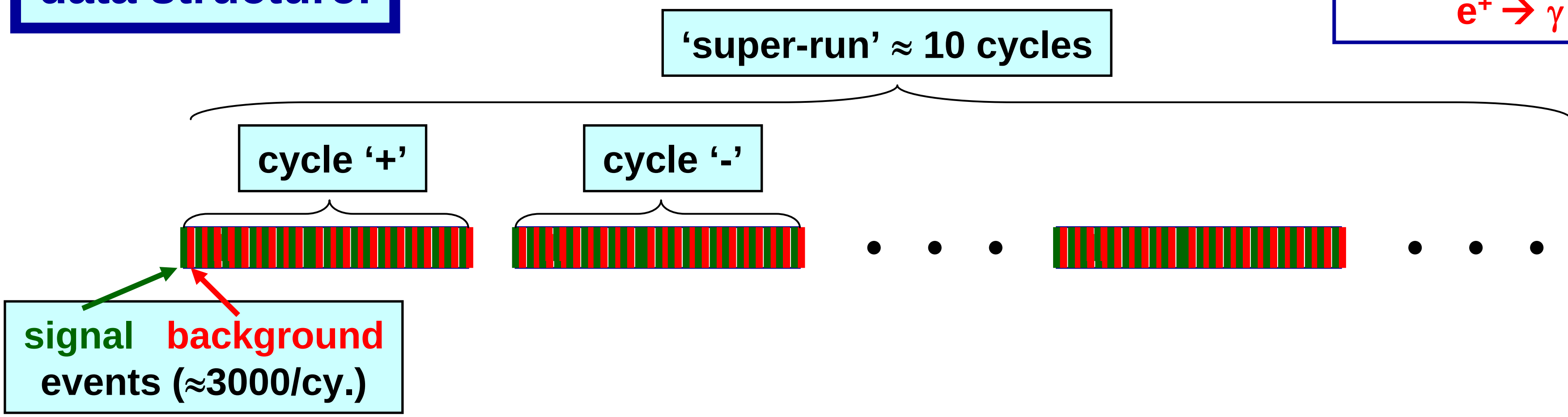
O(1%) asymmetry in CsI expected

⇒ **high statistics req'd**
control systematics

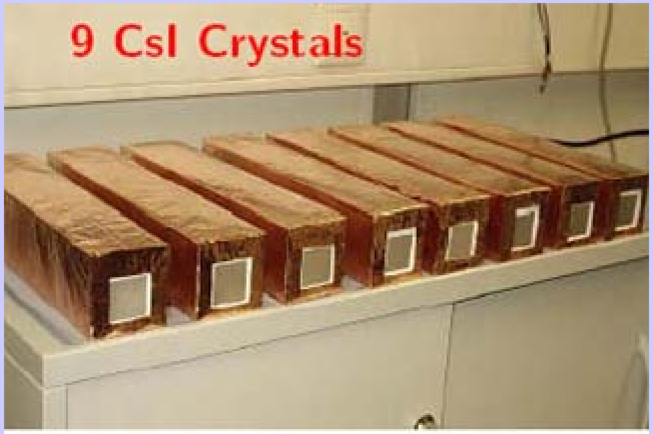
- determine background for each signal:
  undulator 'on' – 'off'
- change magnet polarity between 'cycles'
- normalisation to P1 counter

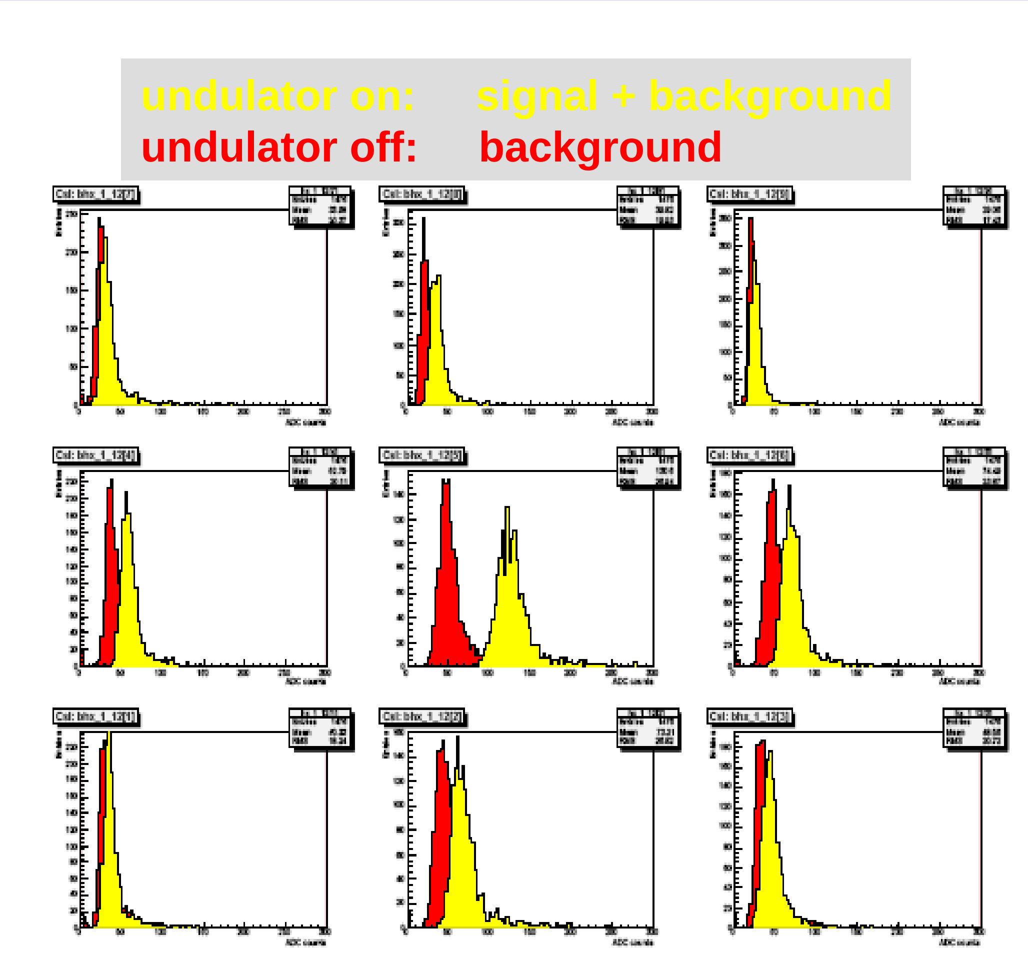


data structure:



Energy Deposition in CsI crystals

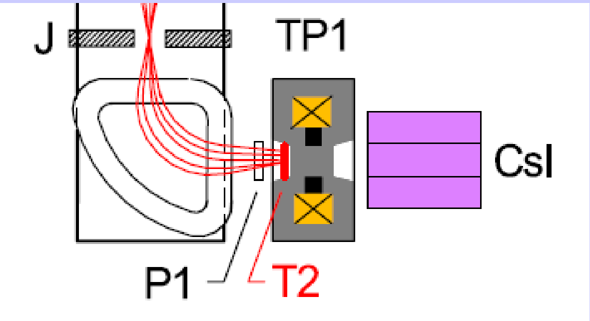


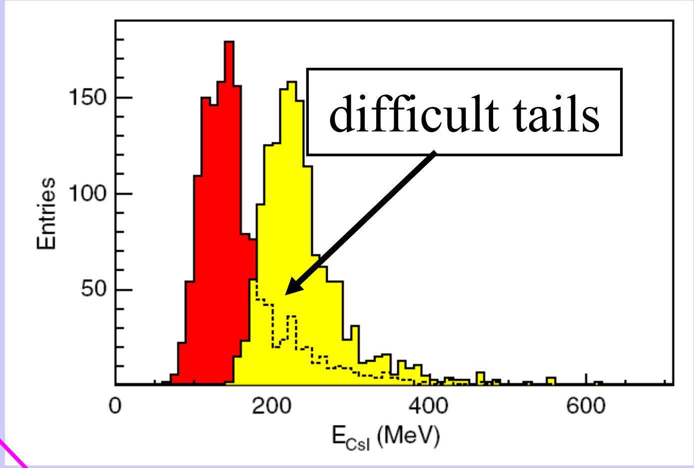


- good signal/background separation in central crystal
- use only central crystal for final results
- outer crystals as cross check and simulation scrutiny

Analysis of positron asymmetries

$$S_{\mathrm{CsI}} = \frac{1}{N_{\mathrm{on}} N_{\mathrm{off}}} \sum_{i=1}^{N_{\mathrm{on}}} \sum_{j=1}^{N_{\mathrm{off}}} \frac{E^{\mathrm{on}}_{\mathrm{CsI},i} - E^{\mathrm{off}}_{\mathrm{CsI},j} \frac{I^{\mathrm{on}}_i}{I^{\mathrm{off}}_j}}{\mathrm{P1}^{\mathrm{on}}_i - \mathrm{P1}^{\mathrm{off}}_j \frac{I^{\mathrm{on}}_i}{I^{\mathrm{off}}_j}},$$



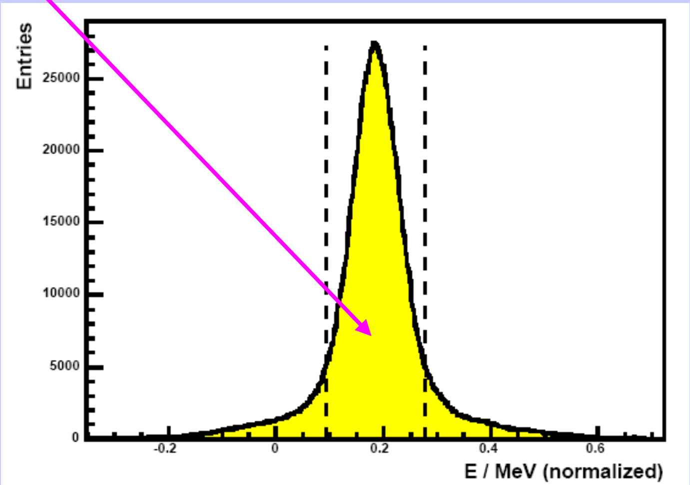


'truncated mean' of each on-off combination within one cycle (with given magnet polarity)

S_{CsI}^{+} and S_{CsI}^{-} for each cycle pair

$\Rightarrow$ 1 asymmetry point

$$\delta_{e^\pm} = (S^-_{\mathrm{CsI}} - S^+_{\mathrm{CsI}})/(S^-_{\mathrm{CsI}} + S^+_{\mathrm{CsI}})$$

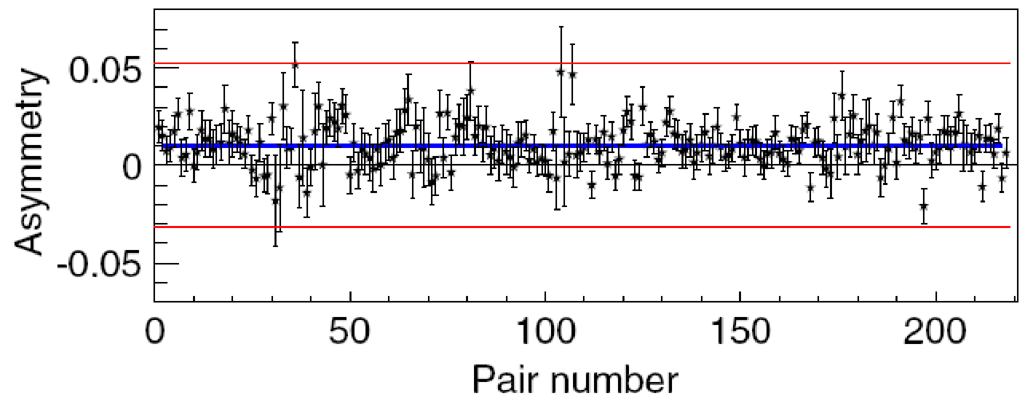


$S_{CsI}(i,j)$ distribution
(all signal-backgr combinations)

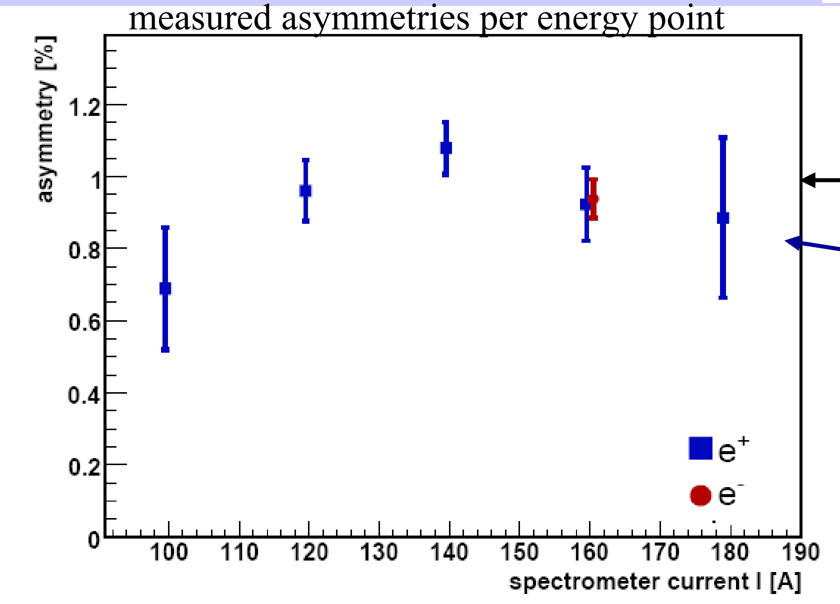
positron asymmetries

$$\delta_{e^\pm} = (S^-_{\rm CsI} - S^+_{\rm CsI})/(S^-_{\rm CsI} + S^+_{\rm CsI})$$

central crystal asymmetries
for e^+ spectrometer setting at 140 A



measured asymmetries per energy point



1% !!

get average δ for
each spectrometer setting

Results

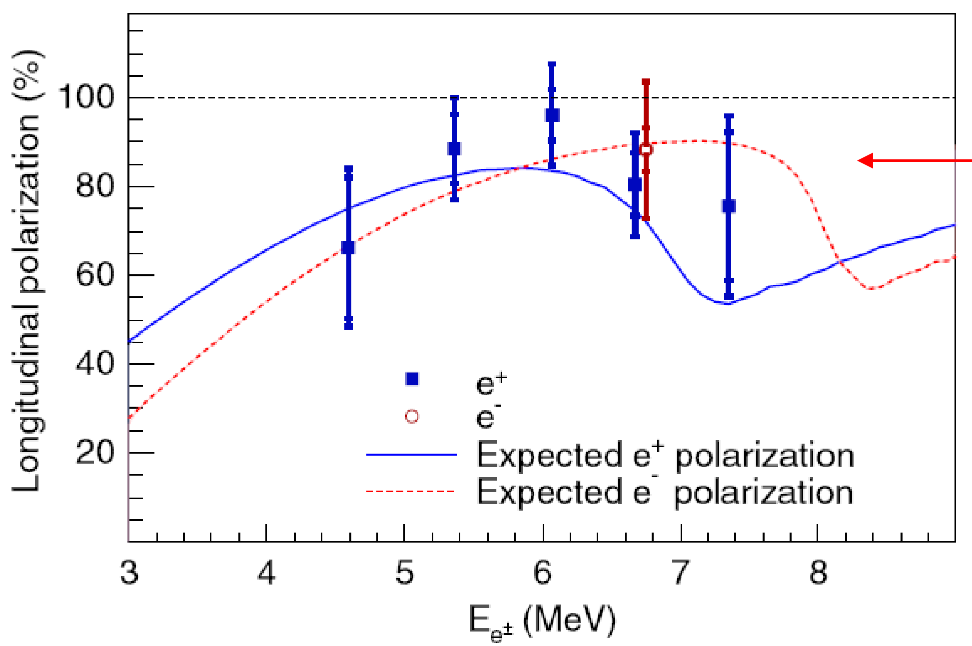
$$P_{e+} = \frac{\delta}{A_{e+} P^{Fe}}$$

A_{e+} = analyzing power from simulations
P^{Fe} = electron polarization of the iron

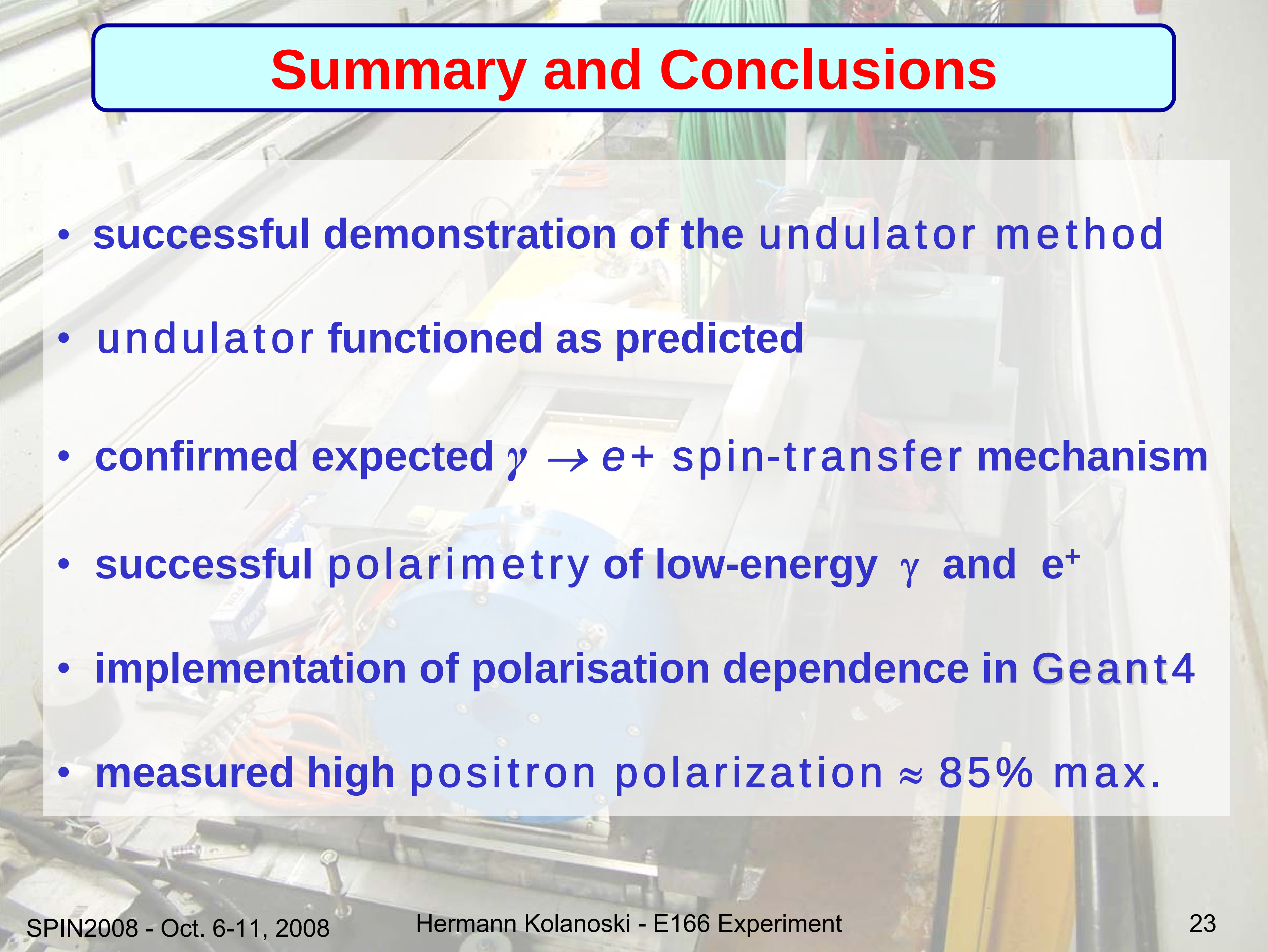
results for the central CsI crystal

$E_{e^\pm}$	$\delta \pm \sigma_\delta(\text{stat})$	A	$P \pm \sigma_P(\text{stat}) \pm \sigma_P(\text{syst})$
4.6 (e^+)	0.69 ± 0.17	0.150	$66 \pm 16 \pm 8$
5.4 (e^+)	0.96 ± 0.08	0.156	$89 \pm 8 \pm 9$
6.1 (e^+)	1.08 ± 0.06	0.162	$96 \pm 6 \pm 10$
6.7 (e^+)	0.92 ± 0.08	0.165	$80 \pm 7 \pm 9$
6.7 (e^-)	0.94 ± 0.05	0.153	$88 \pm 5 \pm 15$
7.4 (e^+)	0.89 ± 0.20	0.169	$76 \pm 17 \pm 12$

δ in % P in %



85%



Summary and Conclusions

- successful demonstration of the undulator method
- undulator functioned as predicted
- confirmed expected $\gamma \rightarrow e+$ spin-transfer mechanism
- successful polarimetry of low-energy γ and e^+
- implementation of polarisation dependence in Geant4
- measured high positron polarization ≈ 85% max.

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Observation of Polarized Positrons from an Undulator-Based Source

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An experiment (E166) at the Stanford Linear Accelerator Center (SLAC) has demonstrated a scheme in which a multi-GeV electron beam passed through a helical undulator to generate multi-MeV, circularly polarized photons which were then converted in a thin target to produce positrons (and electrons) with longitudinal polarization above 80% at 6 MeV. The results are in agreement with Geant4 simulations that include the dominant polarization-dependent interactions of electrons, positrons and photons in matter.

More detailed description of the experiment in a NIM paper under preparation


E166 collaboration
Helical Undulator based polarized positron source for the ILC
50 GeV e⁻
E - 166
10 MeV γ
e⁺
e⁻
International Polarized Positron Collaboration