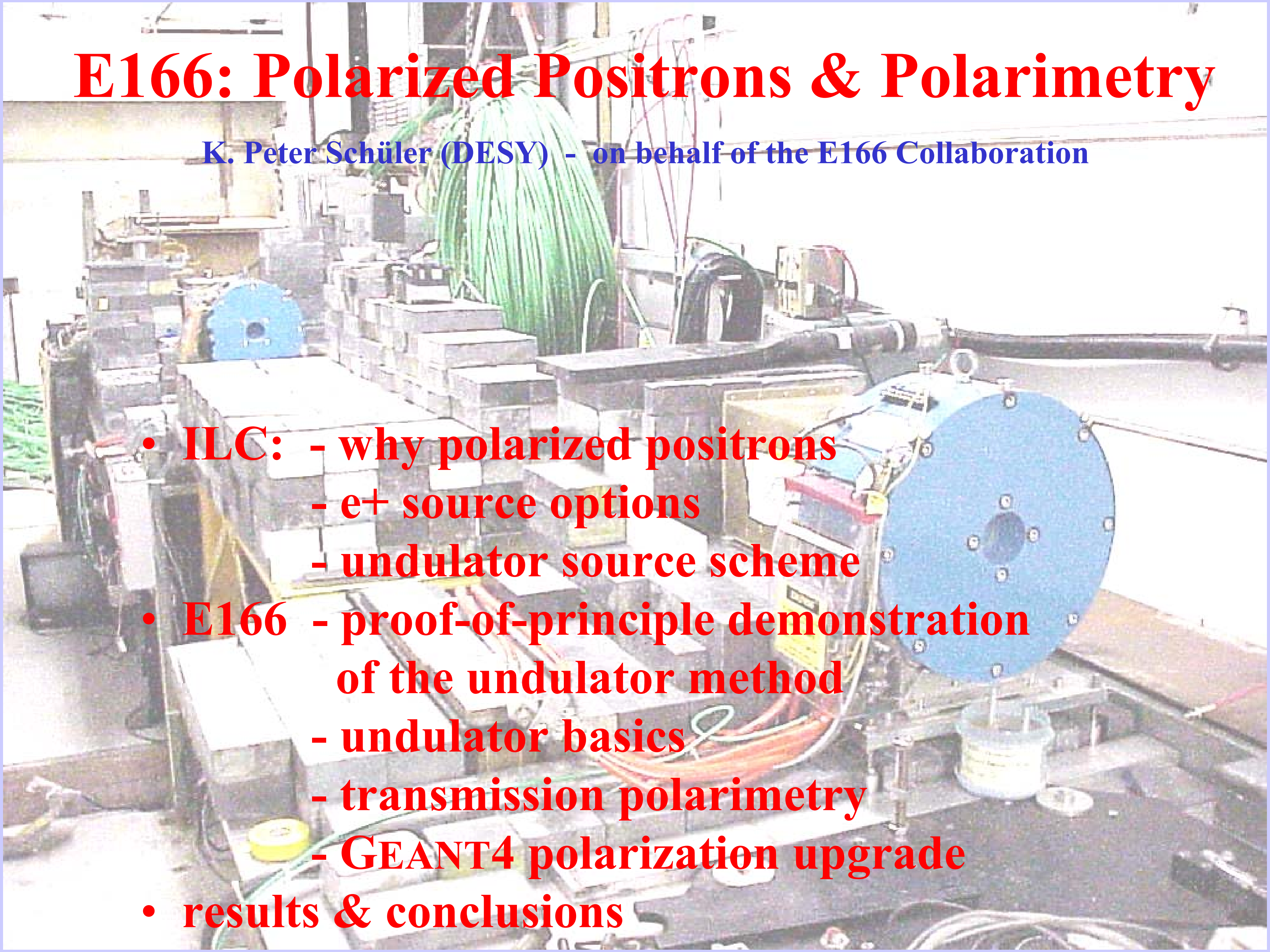


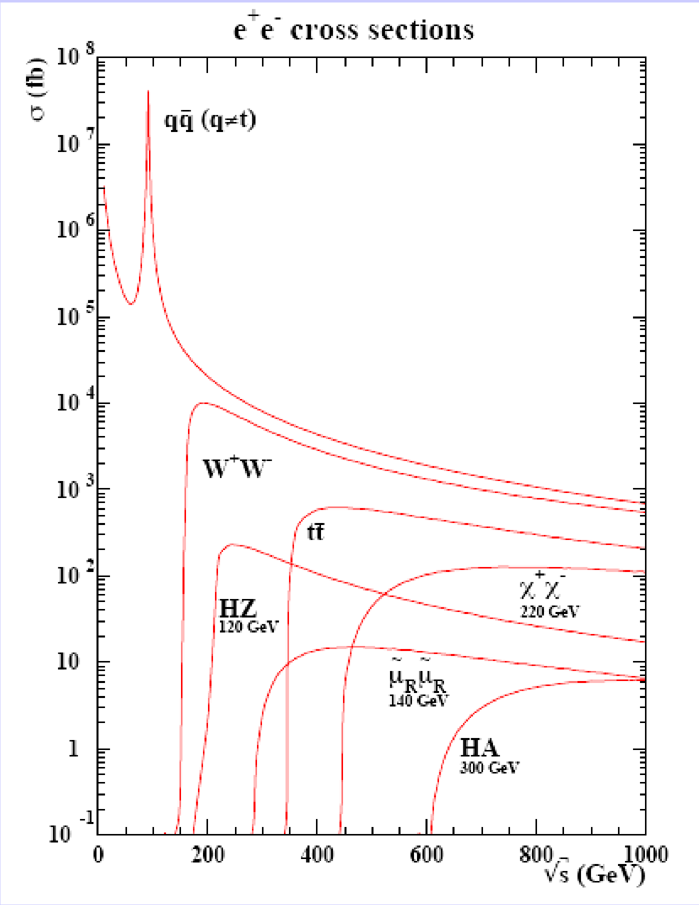
E166: Polarized Positrons & Polarimetry

K. Peter Schüler (DESY) - on behalf of the E166 Collaboration

- ILC: - why polarized positrons
  - e+ source options
  - undulator source scheme
- E166 - proof-of-principle demonstration of the undulator method
  - undulator basics
  - transmission polarimetry
  - GEANT4 polarization upgrade
- results & conclusions

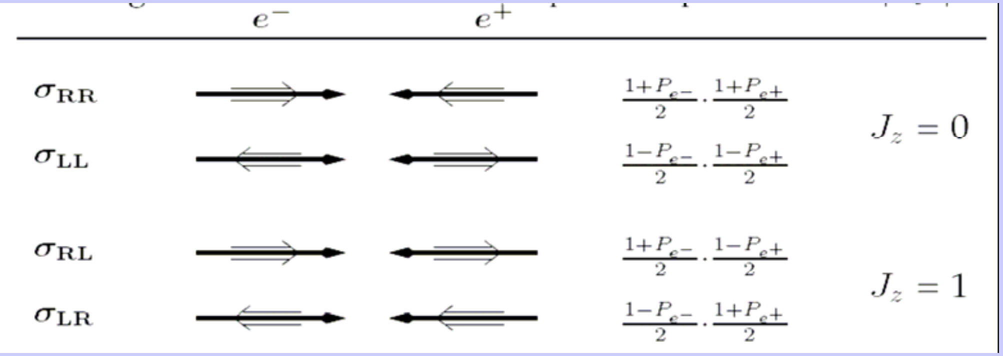
ILC: why polarized positrons?

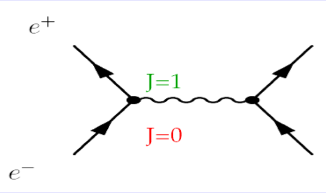
- **SLC as precursor of the ILC very successfully employed polarized electrons, but <u>not</u> polarized positrons.**
- **What does the ILC gain from polarized positrons?**

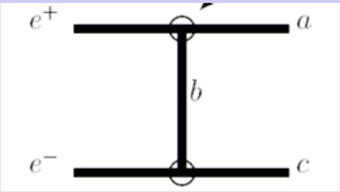


longitudinally polarized beams:

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\{(1+P_{e^-})(1+P_{e^+})\sigma_{RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{LR}\},$$







- **can enhance or suppress processes!**

why polarized positrons?

effective polarization in s-channel (e+e- → γ/Z) annihilation:

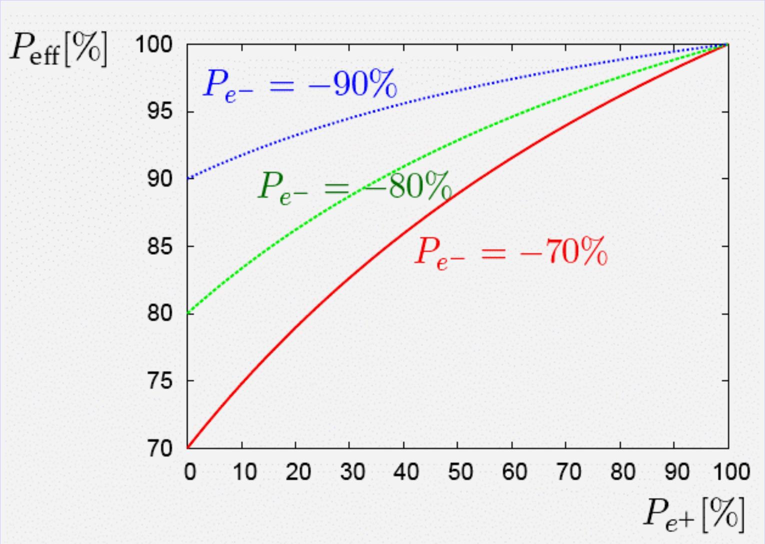
$$\sigma_{P_{e^-}P_{e^+}} = \frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}\sigma_{\mathrm{RL}} + \frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}\sigma_{\mathrm{LR}}$$

$$= (1-P_{e^+}P_{e^-})\,\sigma_0\,[1 - P_{\mathrm{eff}}\,A_{\mathrm{LR}}]$$

$$\sigma_0 = \frac{\sigma_{\mathrm{RL}}+\sigma_{\mathrm{LR}}}{4}$$

$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{LR}}-\sigma_{\mathrm{RL}}}{\sigma_{\mathrm{LR}}+\sigma_{\mathrm{RL}}}$$

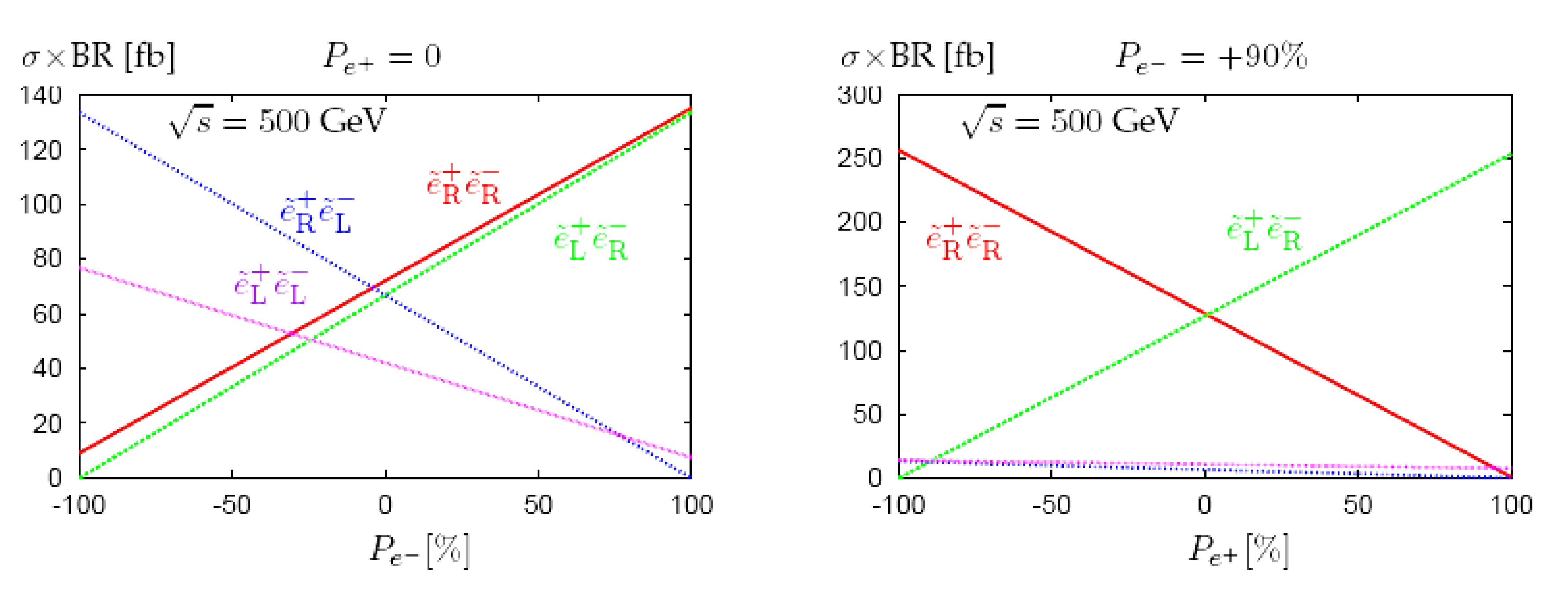
$$P_{\mathrm{eff}} = \frac{P_{e^-}-P_{e^+}}{1-P_{e^+}P_{e^-}}$$



- **positron polarization can significantly increase precision in measurement of A_{LR}**

why polarized positrons?

Supersymmetry: Selectron Pair Production



- positron polarization is required for separation of RR from LR pairs

why polarized positrons?

- **can effectively enhance or suppress processes**
- **improved signal/background ratio**
- **higher effective polarization and precision in A_{LR} asymmetry**
- **unique understanding of non-standard couplings**
- **explore new physics (e.g. extra dim.) with transverse beam pol.**

G. Moortgat-Pick *et al.*, Physics Reports 460 (2008) 131-243

CERN-PH-TH-2005-036, SLAC-PUB-11087, arXiv: hep-ph/0507011

e^+ source options for the ILC

existing/proposed positron sources:

	pulse rep rate (Hz)	bunches per pulse	e+/bunch	e+/pulse	e+/second
DESY	50	1	$1.5 \cdot 10^9$	$1.5 \cdot 10^9$	$7.5 \cdot 10^{10}$
SLC	120	1	$5 \cdot 10^{10}$	$5 \cdot 10^{10}$	$6.0 \cdot 10^{12}$
ILC	5	2820	$2 \cdot 10^{10}$	$5.6 \cdot 10^{13}$	$2.8 \cdot 10^{14}$
CLIC	100	154	$4 \cdot 10^{10}$	$6.2 \cdot 10^{12}$	$6.2 \cdot 10^{14}$

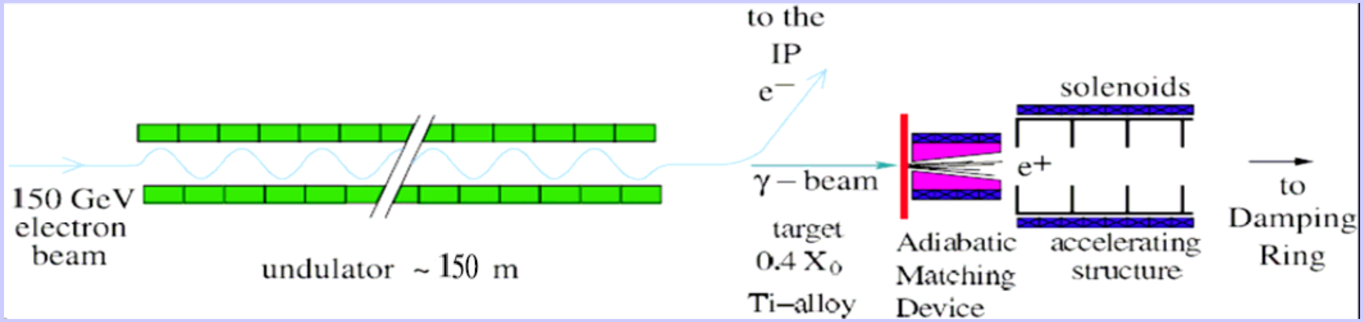
← **ILC**

large amount of charge req'd !

3 Concepts:

- **‚conventional'**
- **laser Compton based**
- **undulator-based**

undulator source



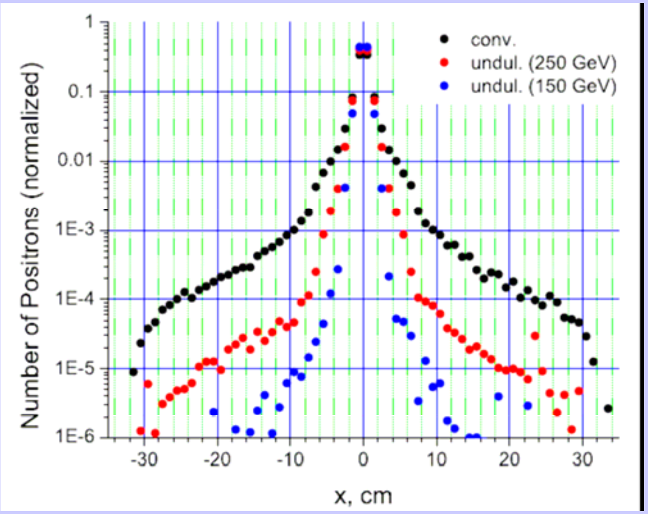
PRO:

- **photoprod. in thin target 0.4 X_0 Ti-alloy → lower e+ beam emittance**
- **less energy deposition in target (1/5) and AMD (1/10)**
- **less neutron induced activation (1/16)**
- **no multiplexing & accumulation req'd**
- **polarized positrons**

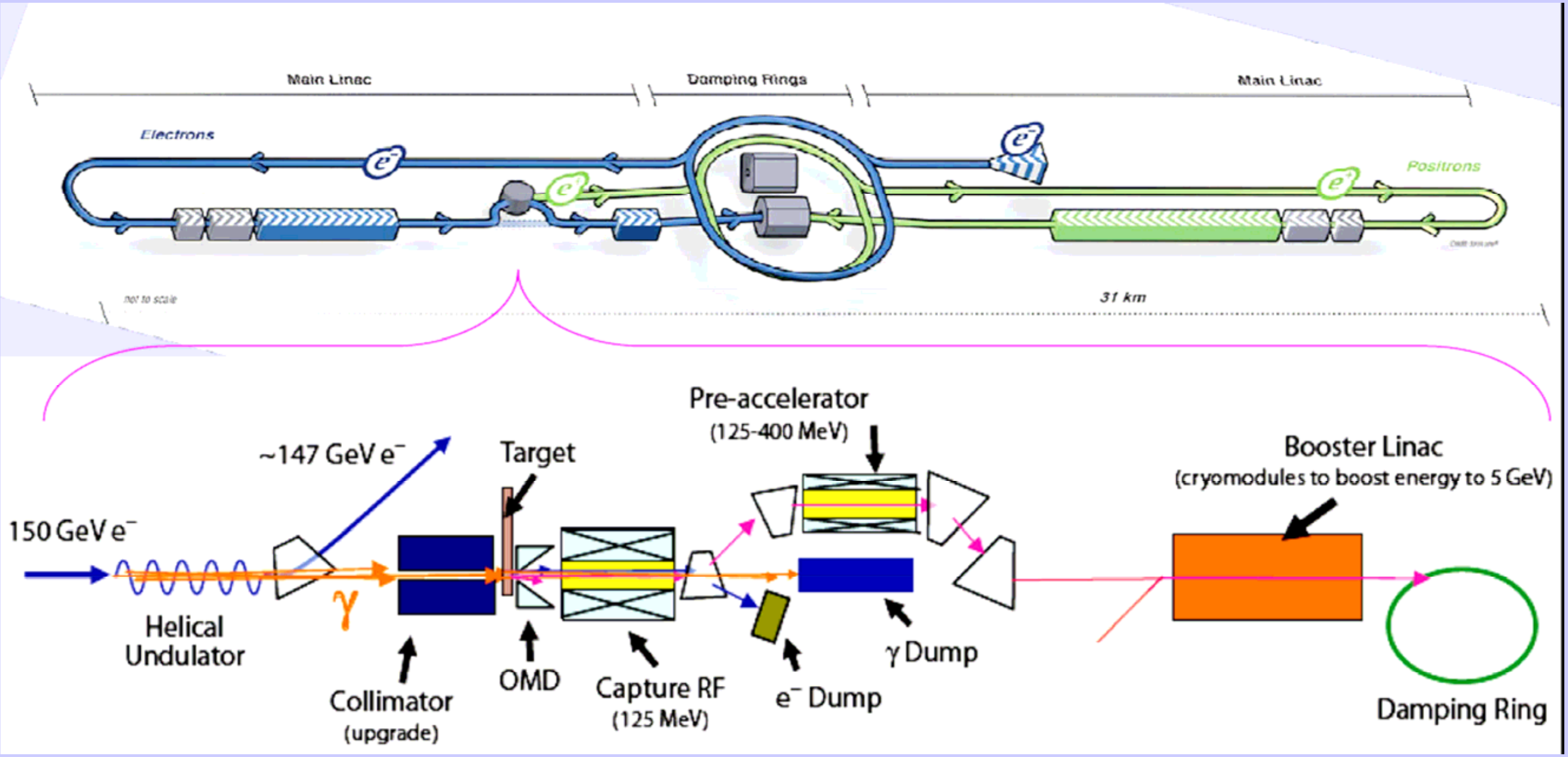
CON:

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

positron beam profile



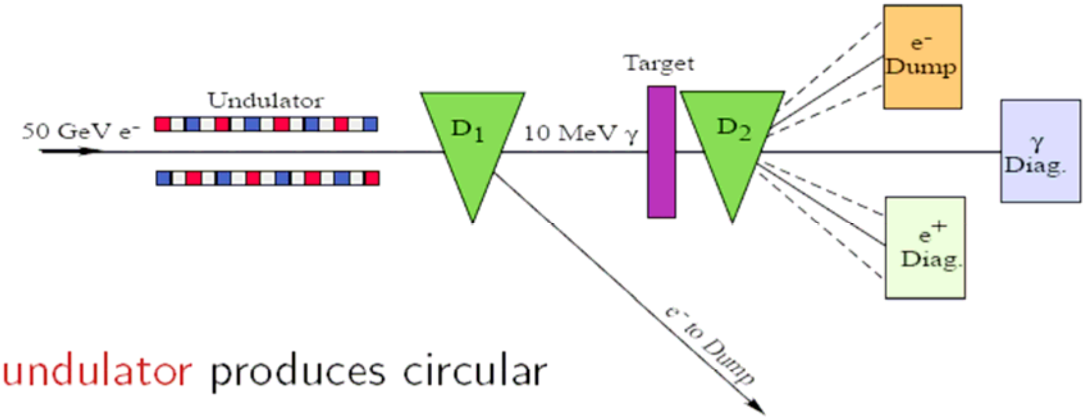
undulator source scheme for ILC



- undulator is chosen baseline scheme for the positron source (although initially at less than full length)
- expect initial e+ polarization of ~ 30%
- Compton based e+ source has alternative status

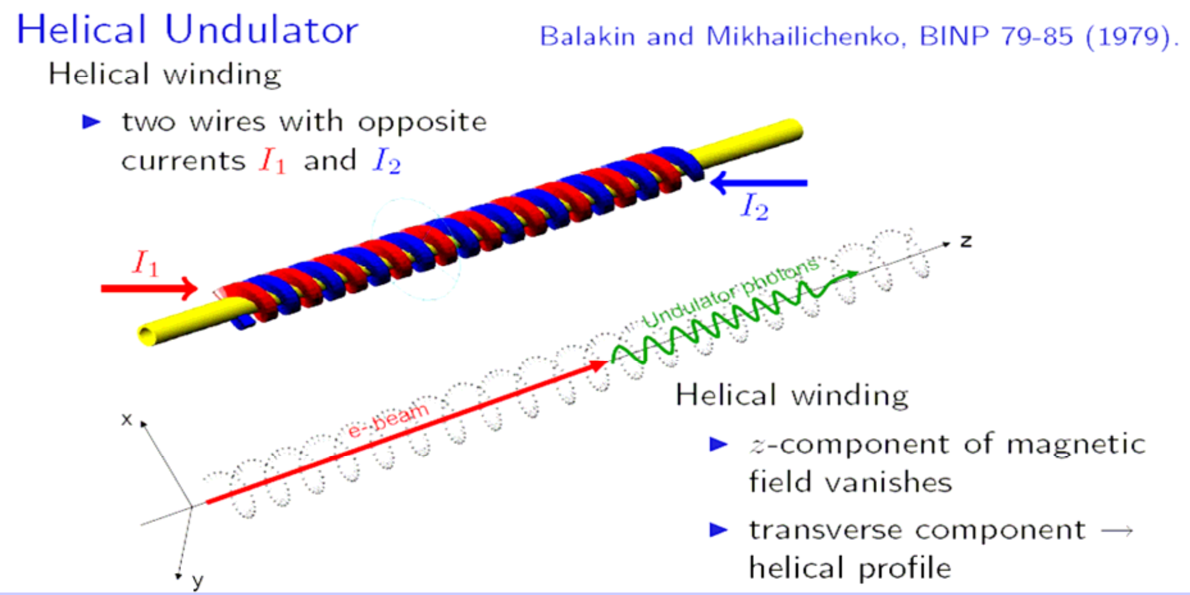
E166 – proof of principle demonstration of the undulator method

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

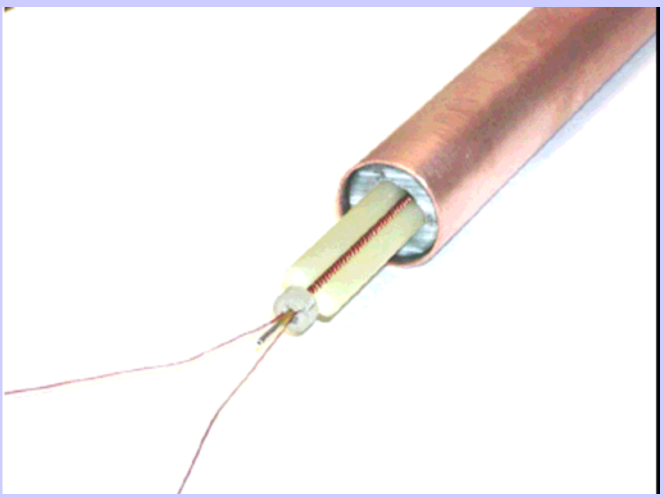


Undulator parameter

$$\omega_0^{max} \approx \frac{2\gamma^2 hc}{\lambda_u} \frac{1}{1+K^2}$$

$$K = \frac{e B_0 \lambda_u}{2\pi\, mc}$$

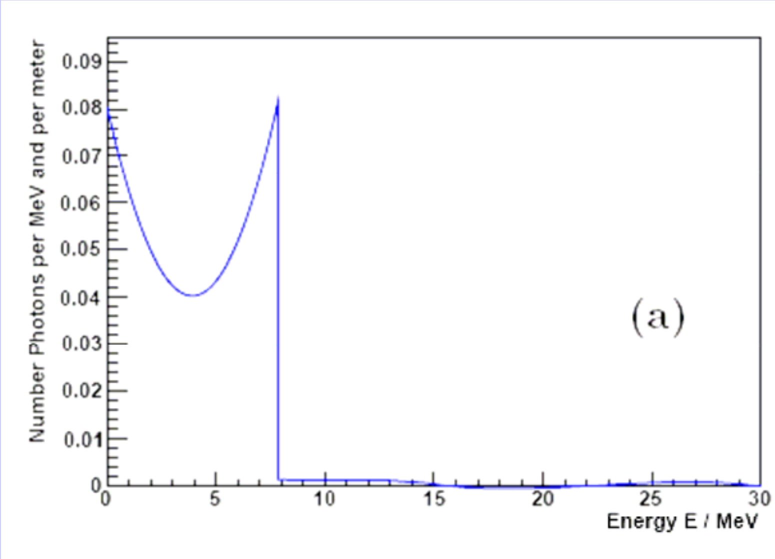
$$\frac{dN}{dL} = \frac{4}{3} \frac{\pi\alpha}{\lambda_u} \frac{K^2}{1+K^2}$$



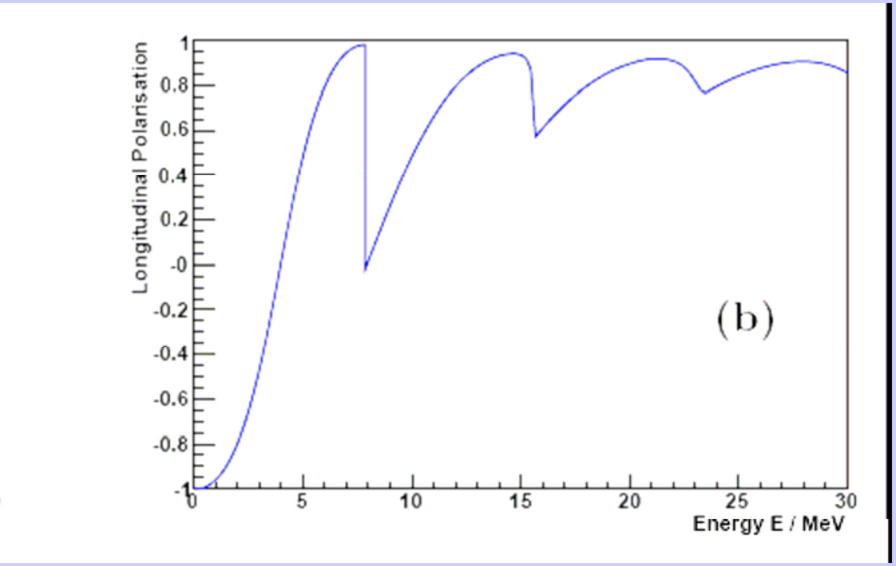
	E166	ILC (RDR)
electron beam energy (GeV)	46.6	150
field (T)	0.71	0.86
period (mm)	2.54	11.5
K value	0.17	0.92
photon energy ω_0^{max} (MeV)	7.9	10.0
beam aperture (mm)	0.89	5.85
active length (m)	1	147
M (no. of periods)	394	12800

undulator basics

E166 Photon Spectrum



E166 Photon Polarization



first harmonic (dominating) expressions:

Spectrum:

$$\frac{dN_\gamma}{ds} = 4\pi\alpha\, M \frac{K^2}{1+K^2} \cdot \frac{1}{2}\left(1-2s+2s^2\right)$$

Angular Distribution:

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

Polarization:

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

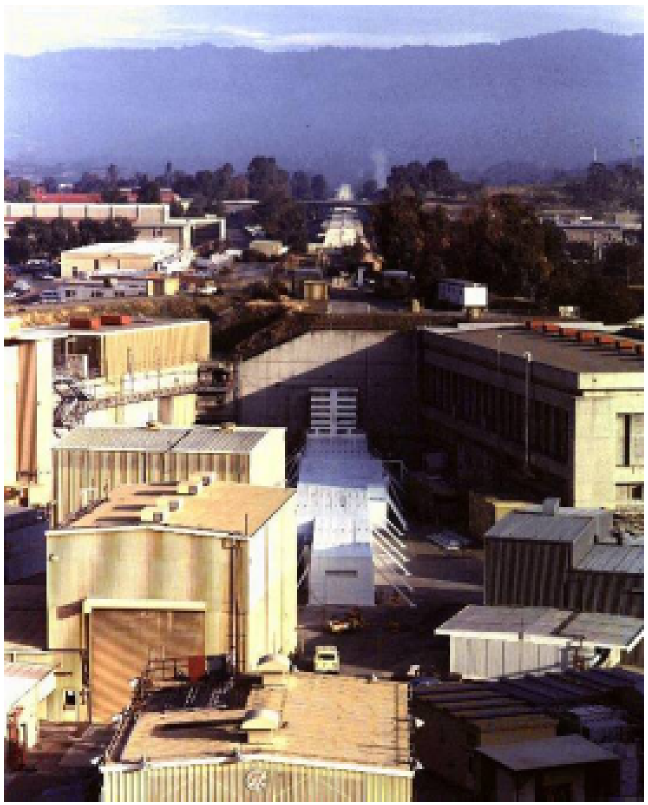
$$s = \omega_0/\omega_0^{max}$$

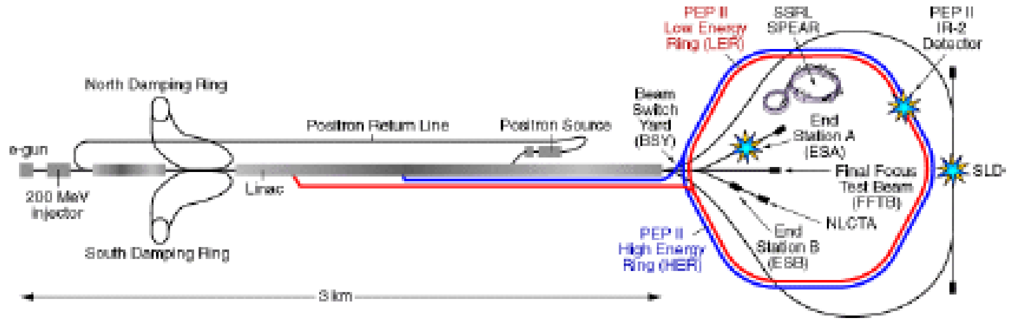
ω_0^{max} = 7.9 MeV

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

The E166 Experiment

SLAC FFTB:





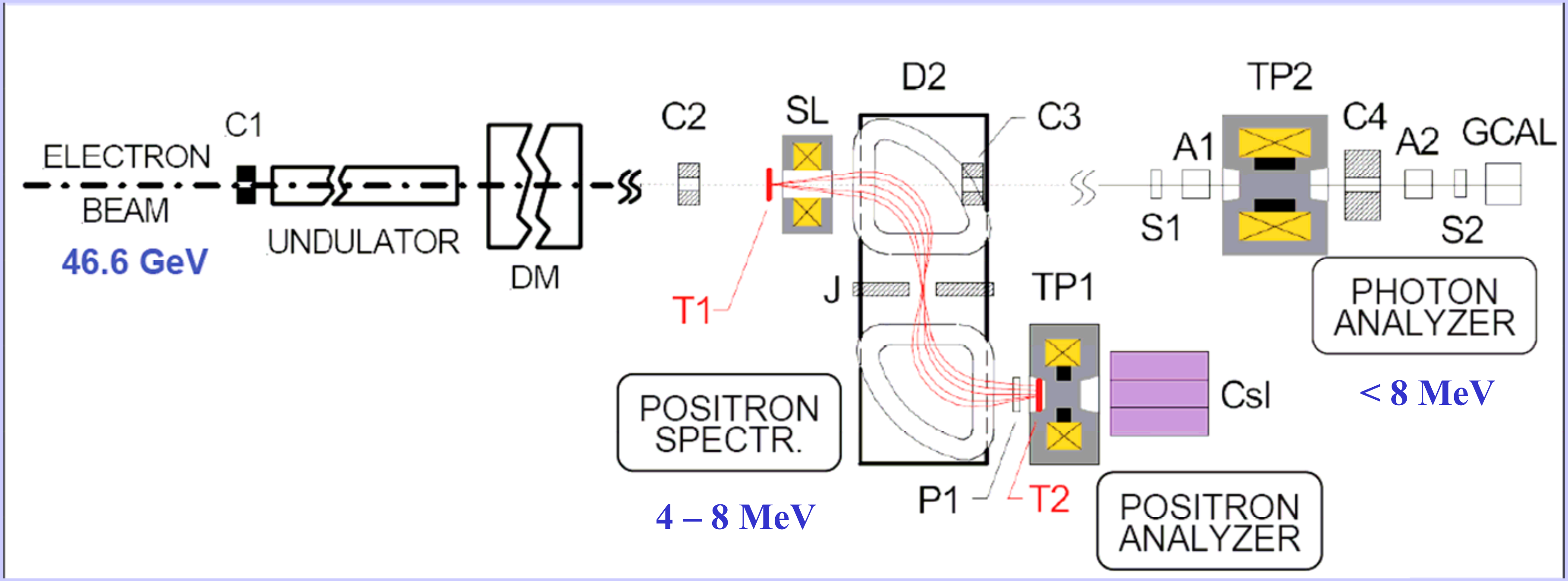
Final Focus Test Beam

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

2004/2005 → setup and checkout

Oct. 2005 → 4 weeks of data taking

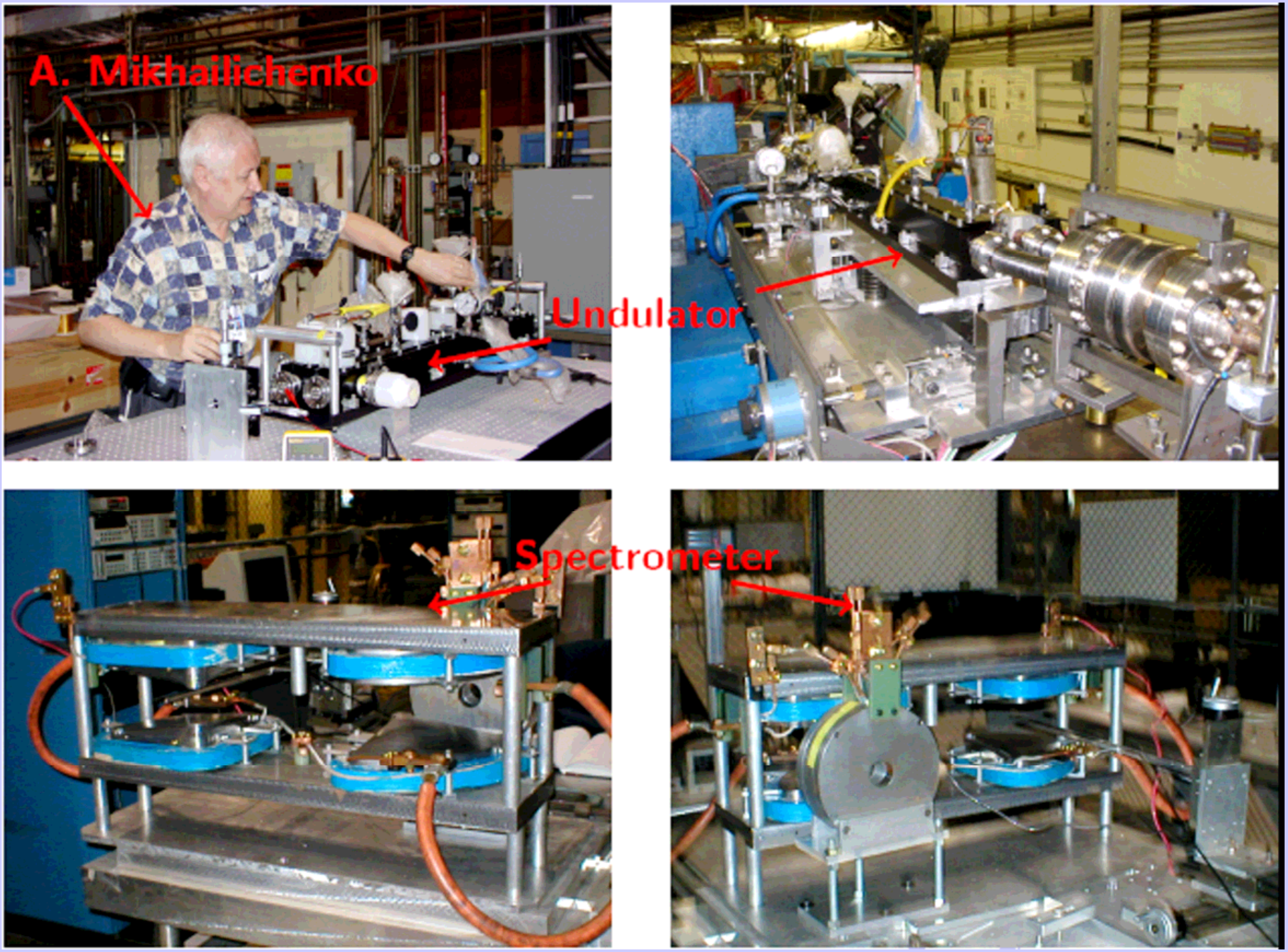
E166 experimental setup



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:	**Cesium Iodide calorimeter**
SL:	**solenoid lens**
J:	**movable jaws**

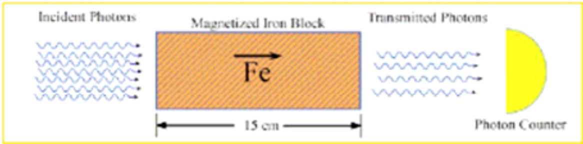
C1 – C4:	**photon collimation**
A1, A2:	**aerogel detectors**
S1, S2:	**silicon detectors**
GCAL:	**Si/W-calorimeter**

E166 photo gallery



transmission polarimetry

1. **Compton Transmission Polarimetry for Low-Energy Photons relies on spin dependence of Compton effect in magnetized iron:**



$$\sigma_{tot} = \sigma_{phot} + \sigma_{comp} + \sigma_{pair} \quad \text{with} \quad \sigma_{comp} = \sigma_0 + P_\gamma P_e \sigma_{pol}$$

Transmission

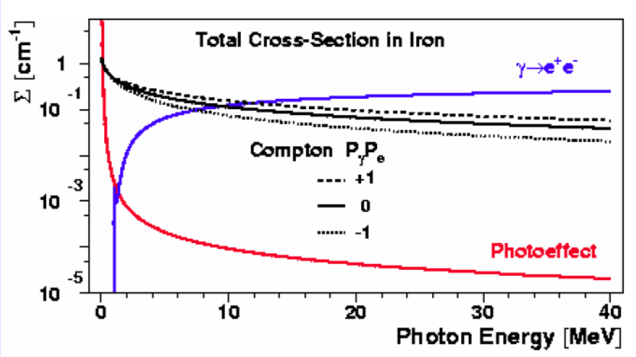
$$T^{\pm}(L) = e^{-nL\sigma} = e^{-nL(\sigma_{phot}+\sigma_{pair}+\sigma_0)} e^{\pm nL P_\gamma P_e \sigma_{pol}}$$

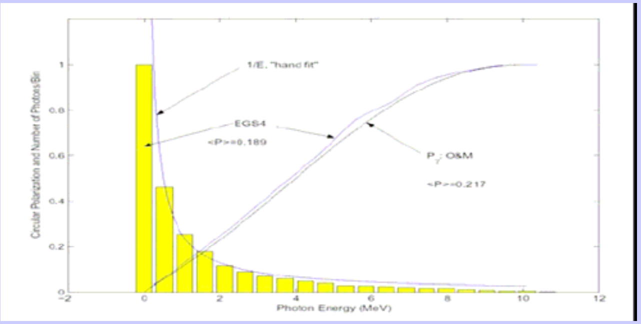
Asymmetry

$$\delta(L) = \frac{T^+ - T^-}{T^+ + T^-} \approx nL P_\gamma P_e \sigma_{pol}$$

Photon Polarization

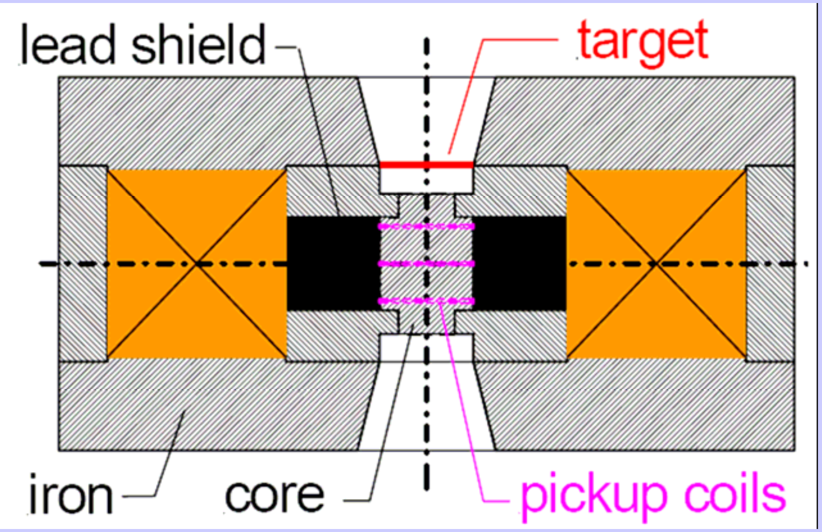
$$P_\gamma = \frac{\delta}{nL\sigma_{pol} P_e} = \frac{\delta}{A_\gamma P_e} \qquad A_\gamma = \text{Analyzing power}$$

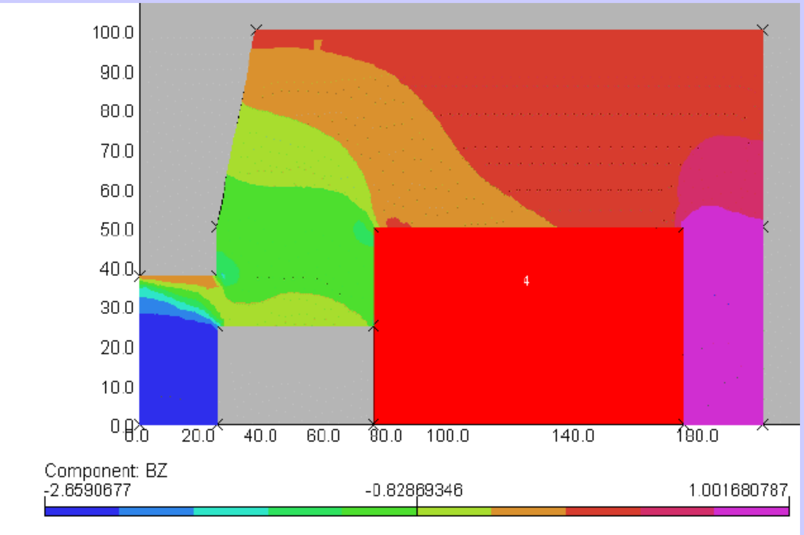




2. **Positron Polarimetry: (a) transfer e+ polarization to photon via brems/annihilation process (b) then infer e+ polarization from measured photon pol. as in method 1.**

analyzer magnets: overview





electron polarization of the iron:

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

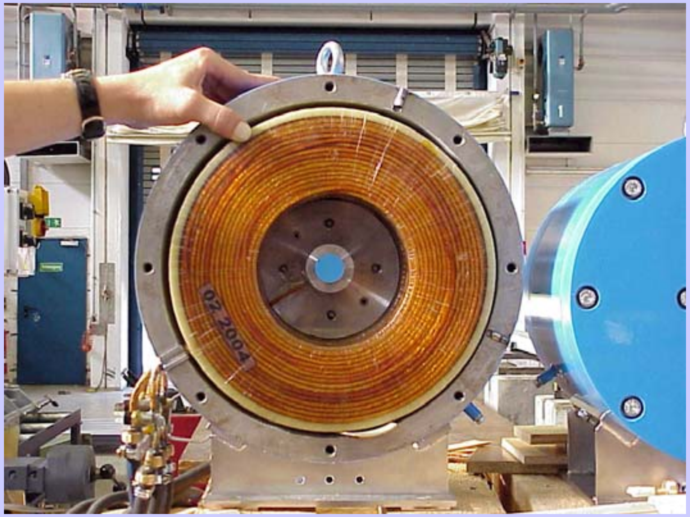
M = $(B - B_0)/\mu_0$ = magnetization
n = electron density
μ_B = Bohr magneton
g‘ = magneto-mechanical factor

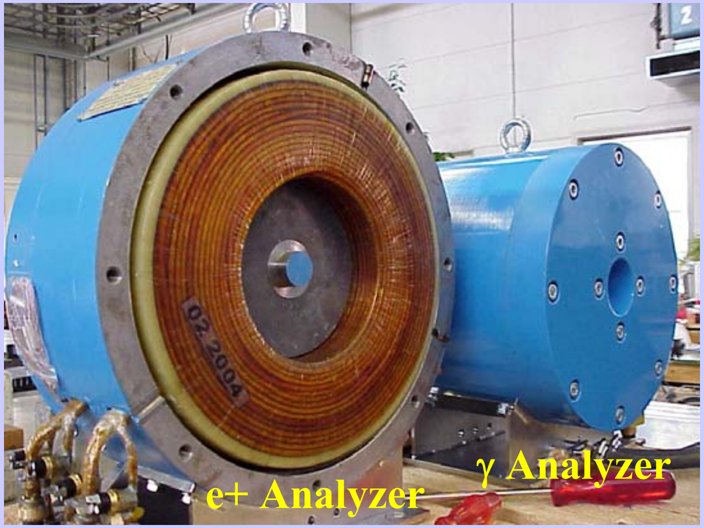
	active volume
Photon Analyzer:	**50 mm dia. x 150 mm long**
Positron Analyzer:	**50 mm dia. x 75 mm long**

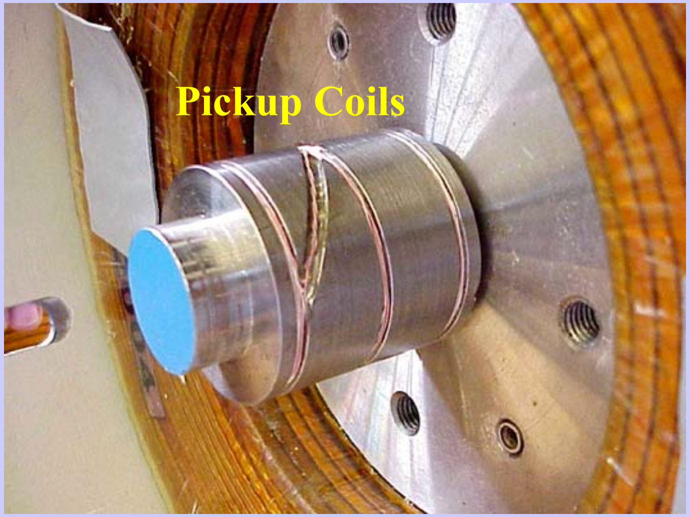
$P_e \approx 0.07$

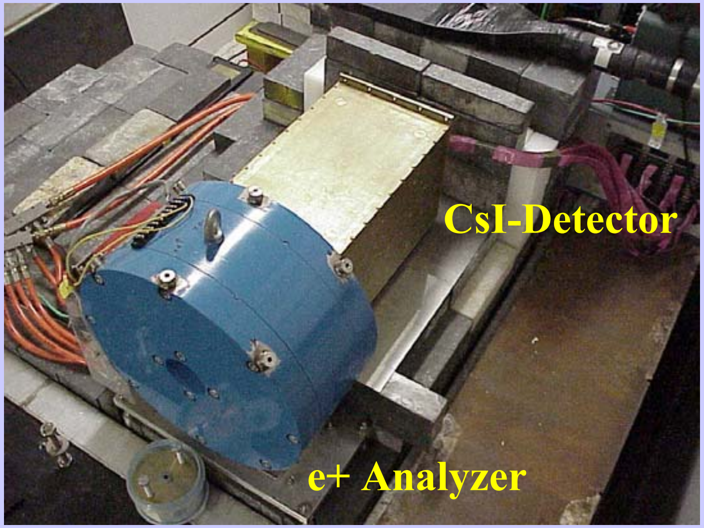
$\Delta P_e/P_e \sim 0.03$

analyzer magnets









electron polarization of the iron

$P_e = M_s / (\rho_e \mu_B) = 0.03727\ (B-B_0)$ (with $B-B_0$ in Tesla)
$M_s = (M_s/M)\ M$
$M_s/M = 2\ (g'-1)/g' = 0.958 \pm 0.002$

radius [mm]	$\langle B_z \rangle$ [Tesla]	$\langle B_z \rangle - B_0$ [Tesla]	$\langle P_e \rangle$
Positron Analyzer			
$r = 0$	2.071	1.974	0.0736
$0 < r < 5$	2.046	1.949	0.0726
$0 < r < 10$	2.025	1.928	0.0719
$0 < r < 15$	2.001	1.904	0.0710
$0 < r < 20$	1.977	1.880	0.0701
$0 < r < 22.5$	1.963	1.866	0.0695
Photon Analyzer			
$r = 0$	2.040	1.940	0.0723

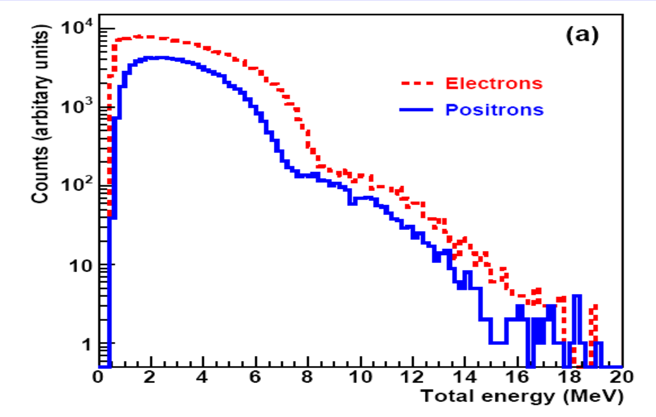
$P_e \sim 0.07$

$\Delta P_e/P_e \sim 2\%$

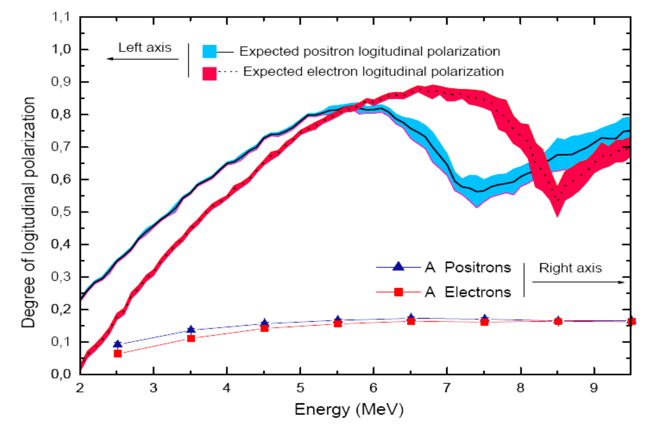
Simulations

GEANT4 upgrade for spin-dependent e/m processes:

- **gammas:**
  - gamma conversion
  - Compton scattering
  - photo-electric effect
- **electrons & positrons:**
  - multiple scattering
  - ionization
  - bremsstrahlung
- **polarization tranfer**
  - **$\gamma \rightarrow$ e+/e-**
  - **e+/e- $\rightarrow \gamma$**
- **polarimetry**
  - Compton scattering
  - Bhabha scattering
  - Moller scattering
  - positron annihilation in flight

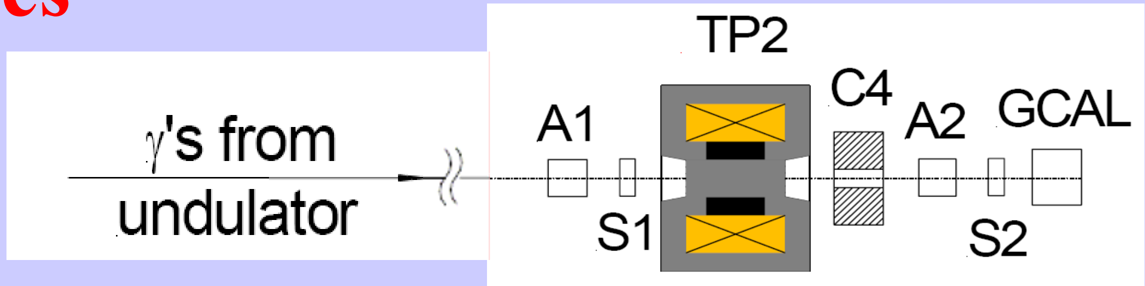


e+/e- spectra at production target

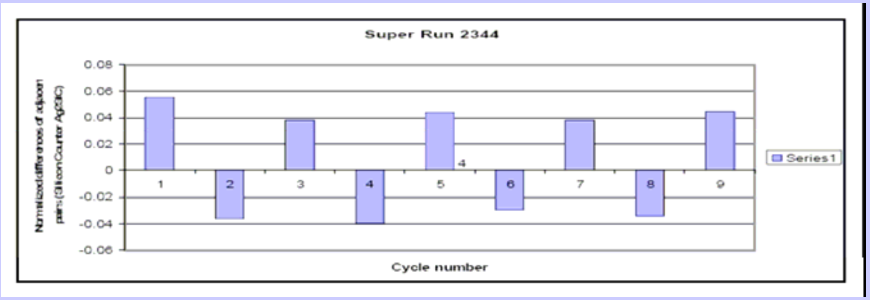


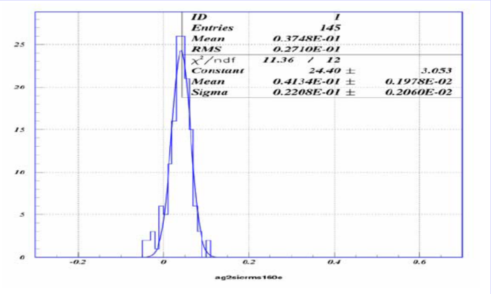
e+/e- polarization & analyzing power

photon asymmetries



$$\delta_\gamma = \frac{S_\gamma^- - S_\gamma^+}{S_\gamma^- + S_\gamma^+}$$

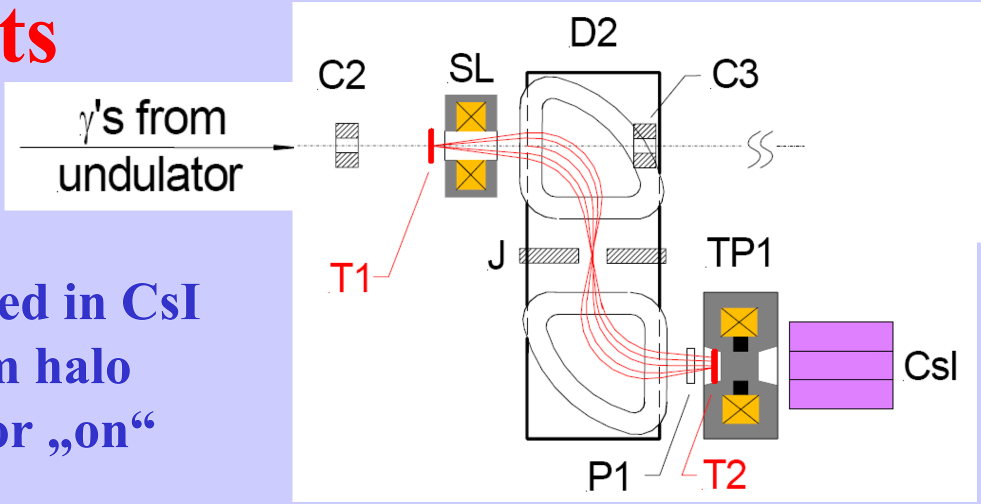




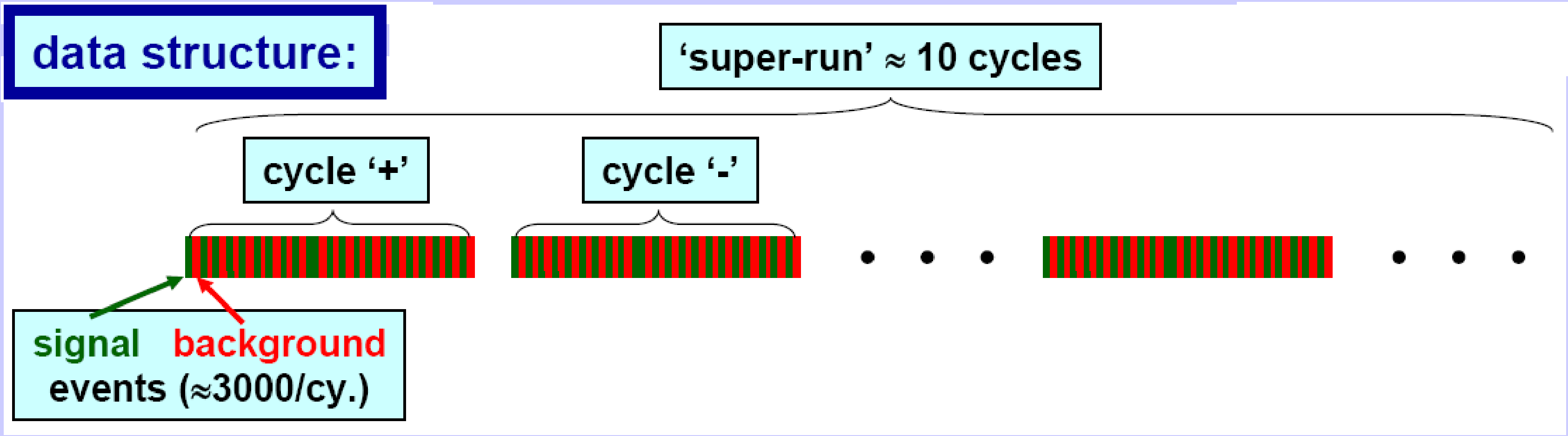
detector		asymmetry δ (%) measured	predicted
S2	(silicon)	3.88 ± 0.12 ±0.63	3.1
A2	(aerogel)	3.31 ± 0.06 ±0.16	3.6
GCAL	(Si/W-calo)	3.67 ± 0.07 ±0.40	3.4

- reasonable agreement with simulation results based on theoretical undulator polarization spectrum and detector response functions
- but no detailed spectral shape analysis possible

positron measurements

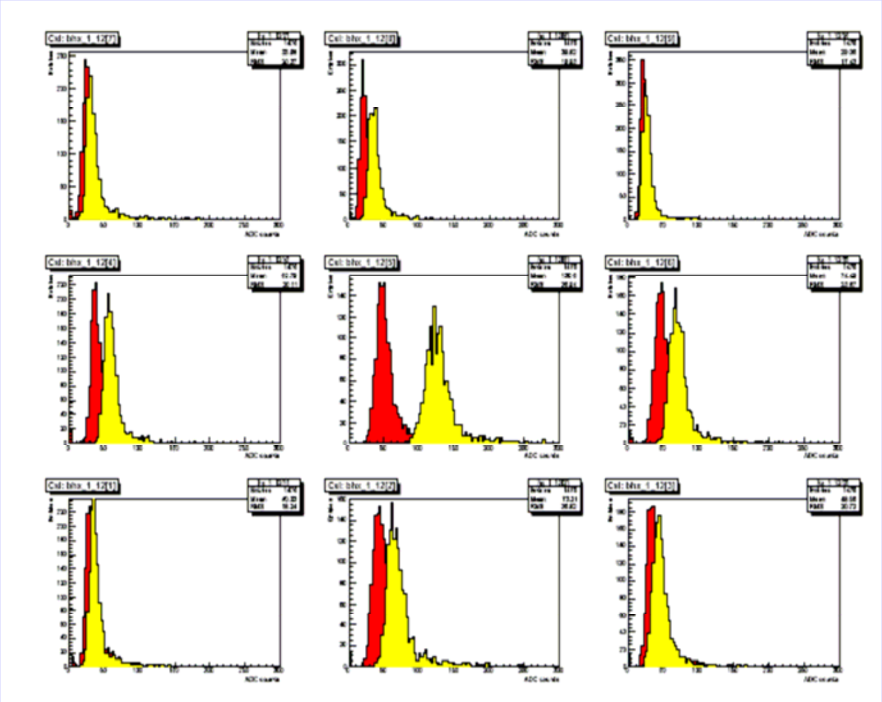


- exp. asymmetry of ~1% expected in CsI
- large background from e- beam halo req's equal amount of undulator „on" and „off" statistics
- normalization to P1 detector avoids false asymmetries from flip-correlated beam shifts



energy deposition in CsI crystals

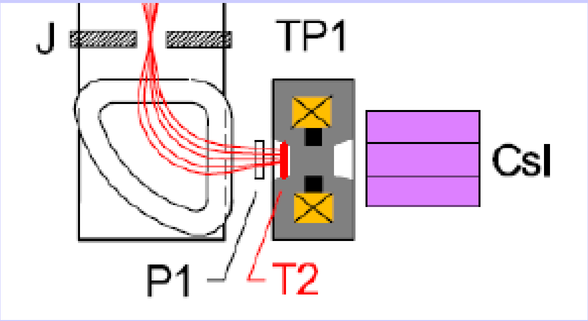
undulator on: signal + background
undulator off: background



- good signal/background separation in central crystal
- background from e- beam halo hitting the undulator
- undulator on/off measurements taken on alternating machine pulses for effective background subtraction

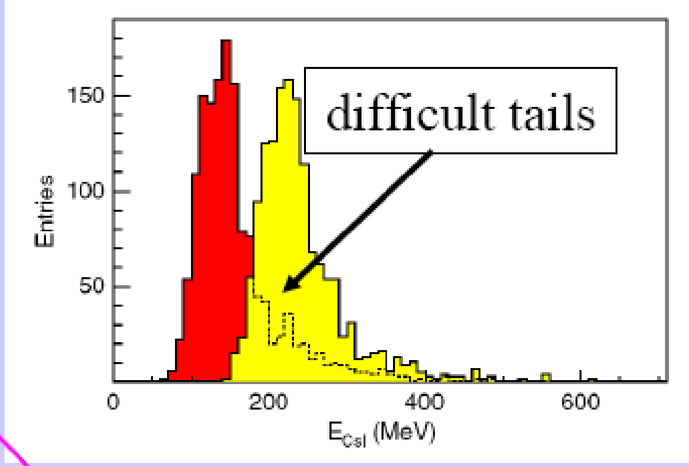
positron asymmetries

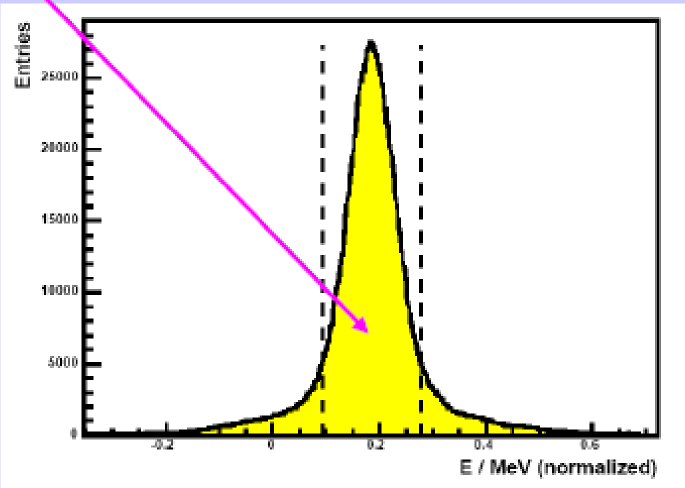
$$S_{\mathrm{CsI}} = \frac{1}{N_{\mathrm{on}} N_{\mathrm{off}}} \sum_{i=1}^{N_{\mathrm{on}}} \sum_{j=1}^{N_{\mathrm{off}}} \frac{E^{\mathrm{on}}_{\mathrm{CsI},i} - E^{\mathrm{off}}_{\mathrm{CsI},j} \frac{I^{\mathrm{on}}_i}{I^{\mathrm{off}}_j}}{\mathrm{P1}^{\mathrm{on}}_i - \mathrm{P1}^{\mathrm{off}}_j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



‘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

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

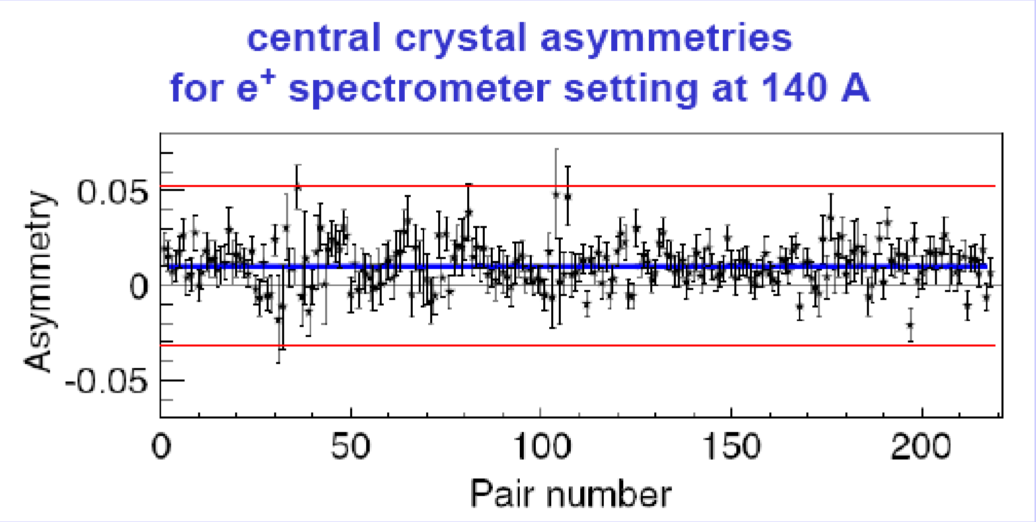


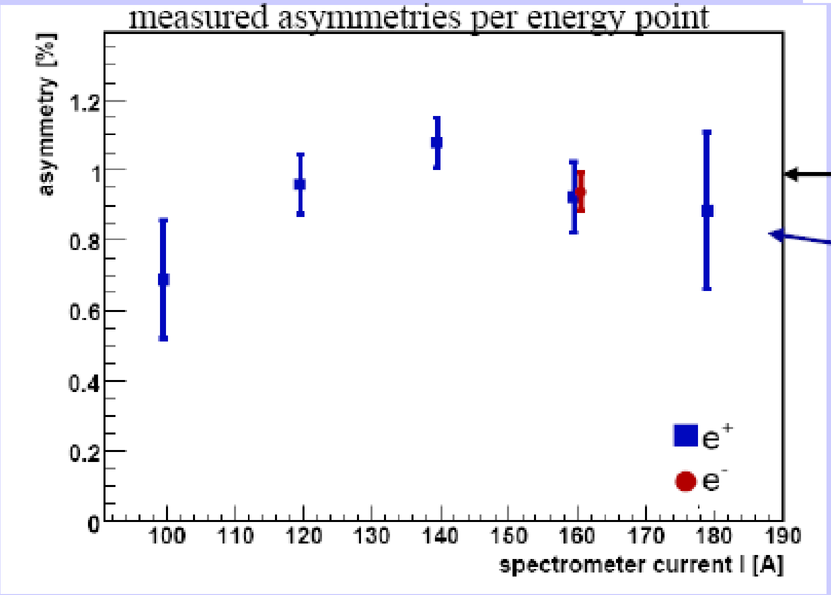


$S_{CsI}(i,j)$ distribution
(all signal-backgr combinations)

positron asymmetries

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





1% !!

get average δ for
each spectrometer setting

results: beam polarization

results for the central CsI crystal

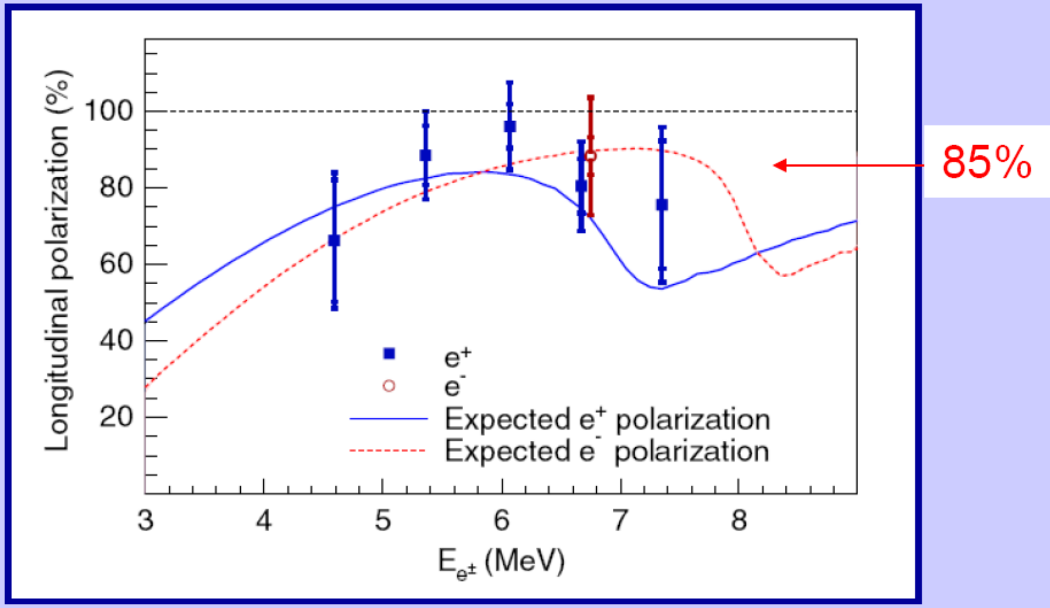
$E_{e^\pm}$	$\delta \pm \sigma_\delta(\text{stat})$	A	$P \pm \sigma_P(\text{stat}) \pm \sigma_P(\text{syst})$
4.6 (e^+)	0.69 ± 0.17	0.150	66 ± 16 ± 8
5.4 (e^+)	0.96 ± 0.08	0.156	89 ± 8 ± 9
6.1 (e^+)	1.08 ± 0.06	0.162	96 ± 6 ± 10
6.7 (e^+)	0.92 ± 0.08	0.165	80 ± 7 ± 9
6.7 (e^-)	0.94 ± 0.05	0.153	88 ±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

δ in % P in %

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

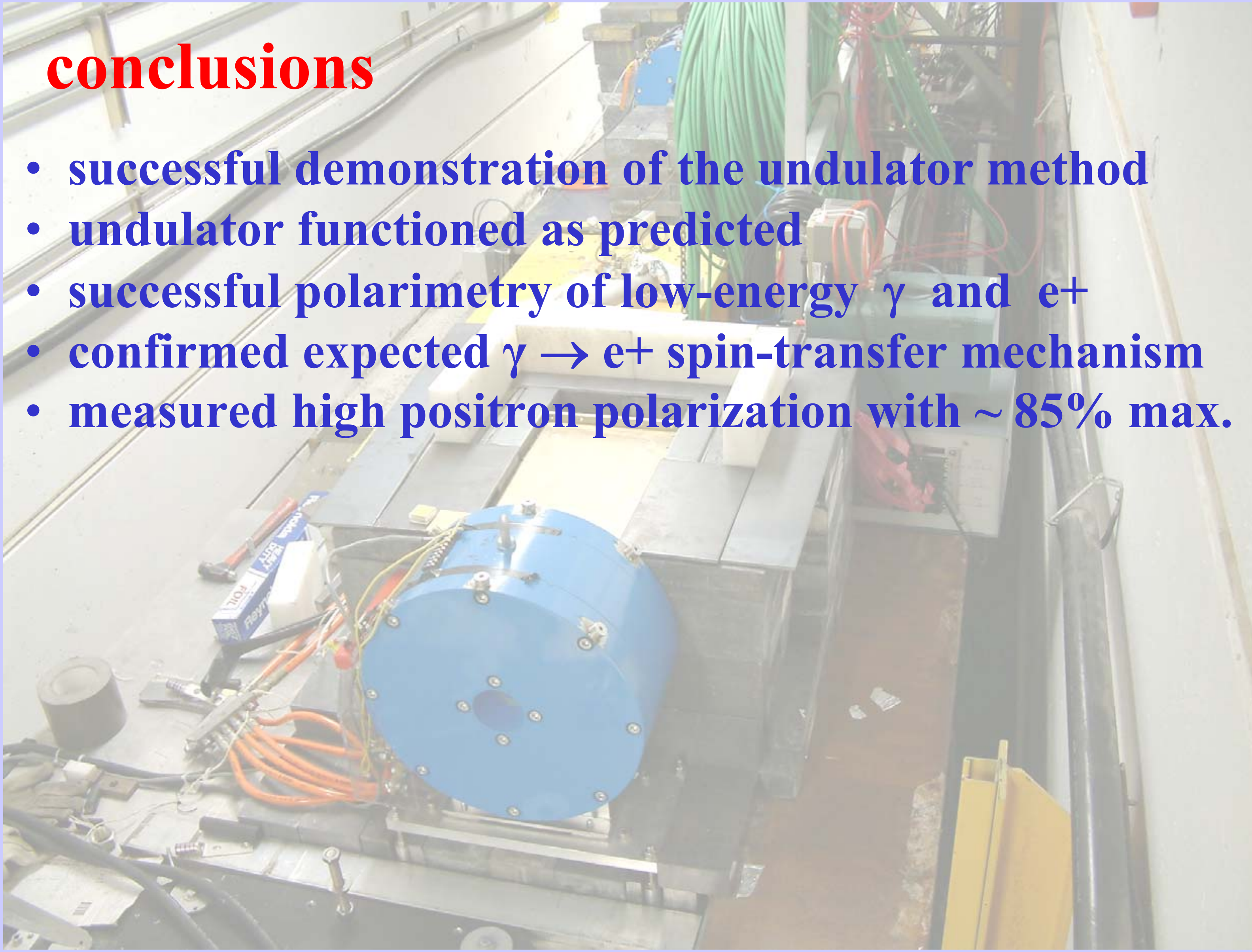
A_{e^+} = **analyzing power from simulations**

$P_{e^-}^{Fe}$ = **electron polarization of the iron**



conclusions

- successful demonstration of the undulator method
- undulator functioned as predicted
- successful polarimetry of low-energy γ and e+
- confirmed expected $\gamma \rightarrow$ e+ spin-transfer mechanism
- measured high positron polarization with ~ 85% max.



published results

- **PRL 100, 210801 (2008), G. Alexander et al.:**

PRL **100,** 210801 (2008) PHYSICAL REVIEW LETTERS week ending 30 MAY 2008

Observation of Polarized Positrons from an Undulator-Based Source

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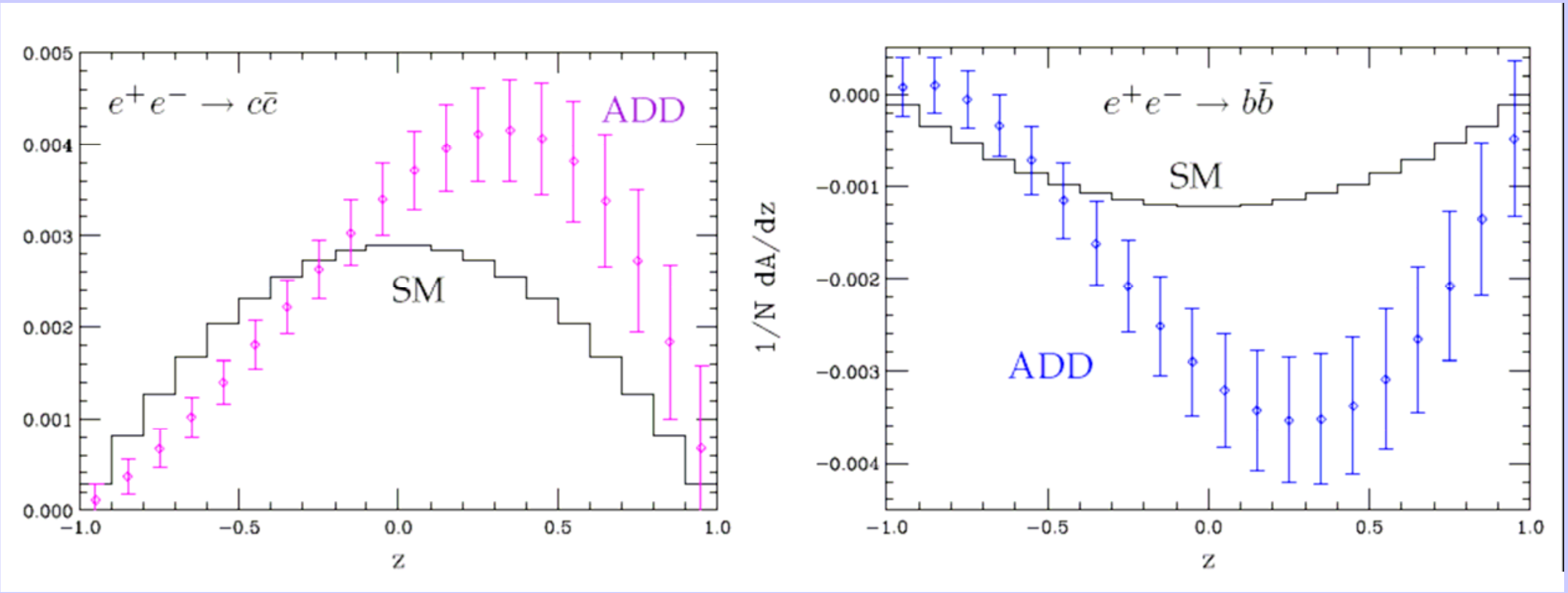
(Received 8 March 2008; published 29 May 2008)

- **long paper (66 pages) about to be submitted to NIM**

why polarized positrons?

Transverse Beam Polarization:



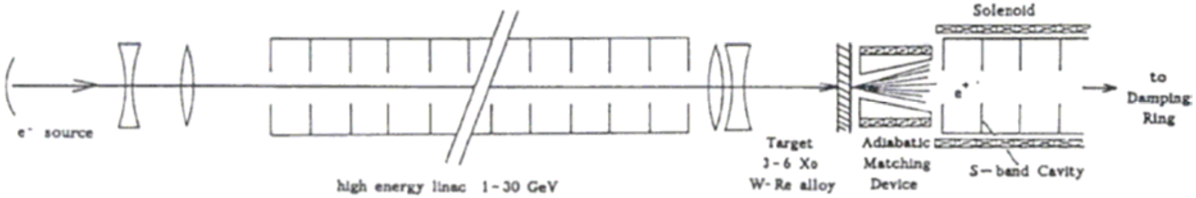
- **Gravity in Extra Dimensions:** **expect significant asymmetric deviations from SM in the azimuthal distributions**

T. G. Rizzo, JHEP 0302 (2003) 008 [arXiv:hep-ph/0211374];

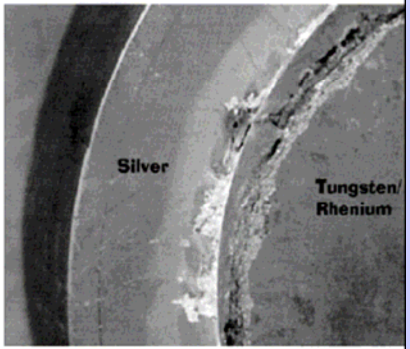
JHEP 0308 (2003) 051 [arXiv:hep-ph/0306283].

conventional positron source

(as used for SLC at SLAC)



- 30 GeV electron beam hits W-Re target
- pulsed at 120Hz, 1 bunch/pulse
- heat load 24kW



thick W-Re target: strong multiple scattering, less efficient e+ capture

PRO: established technology (although not at req'd level)

CON: pushing technical limits of target materials;
req's multiple targets and beamlines;
very high activation levels
no polarization option

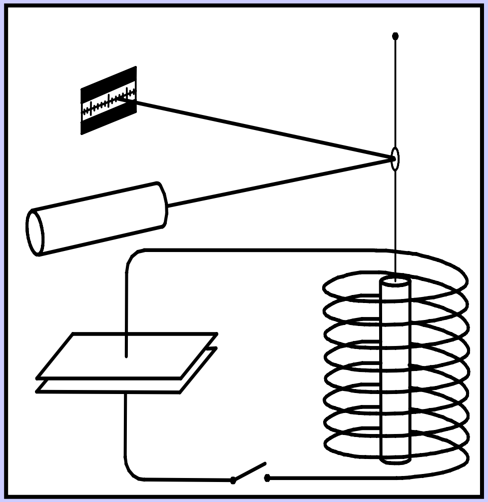
spin and magnetization

$$P_e = \frac{M_S}{\rho_e \mu_b} = \frac{M_S}{M}\frac{M}{\rho_e \mu_b} = 2\frac{g'-1}{g'}\frac{M}{\rho_e \mu_b}$$

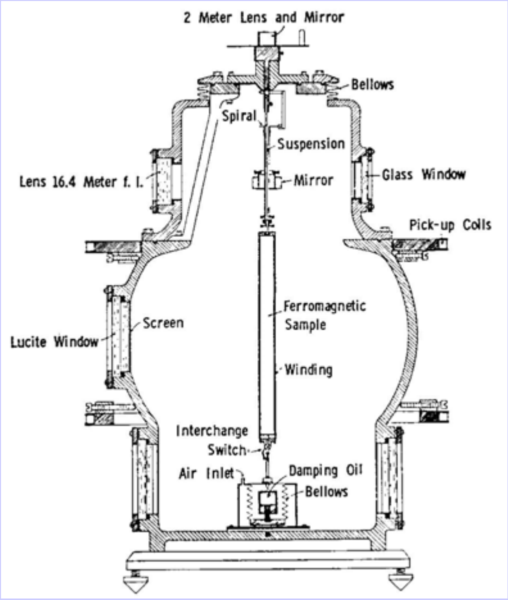
g' = magneto-mechanical factor: obtained from Einstein - de Haas type experiments, related to gyromagnetic ratio: $\gamma = (g'/2) \cdot (e/m)$

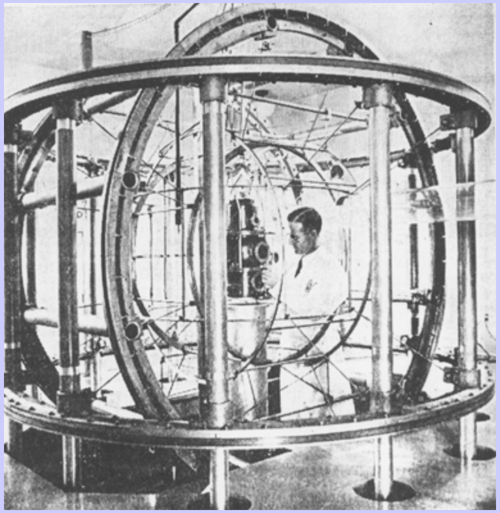
Note: $g' = 2 \rightarrow M_s / M = 1$ **(pure spin magnetization)** $\gamma = e/m$

$g' = 1 \rightarrow M_s / M = 0$ **(pure orbit magnetization)** $\gamma = ½\,(e/m)$



the principle





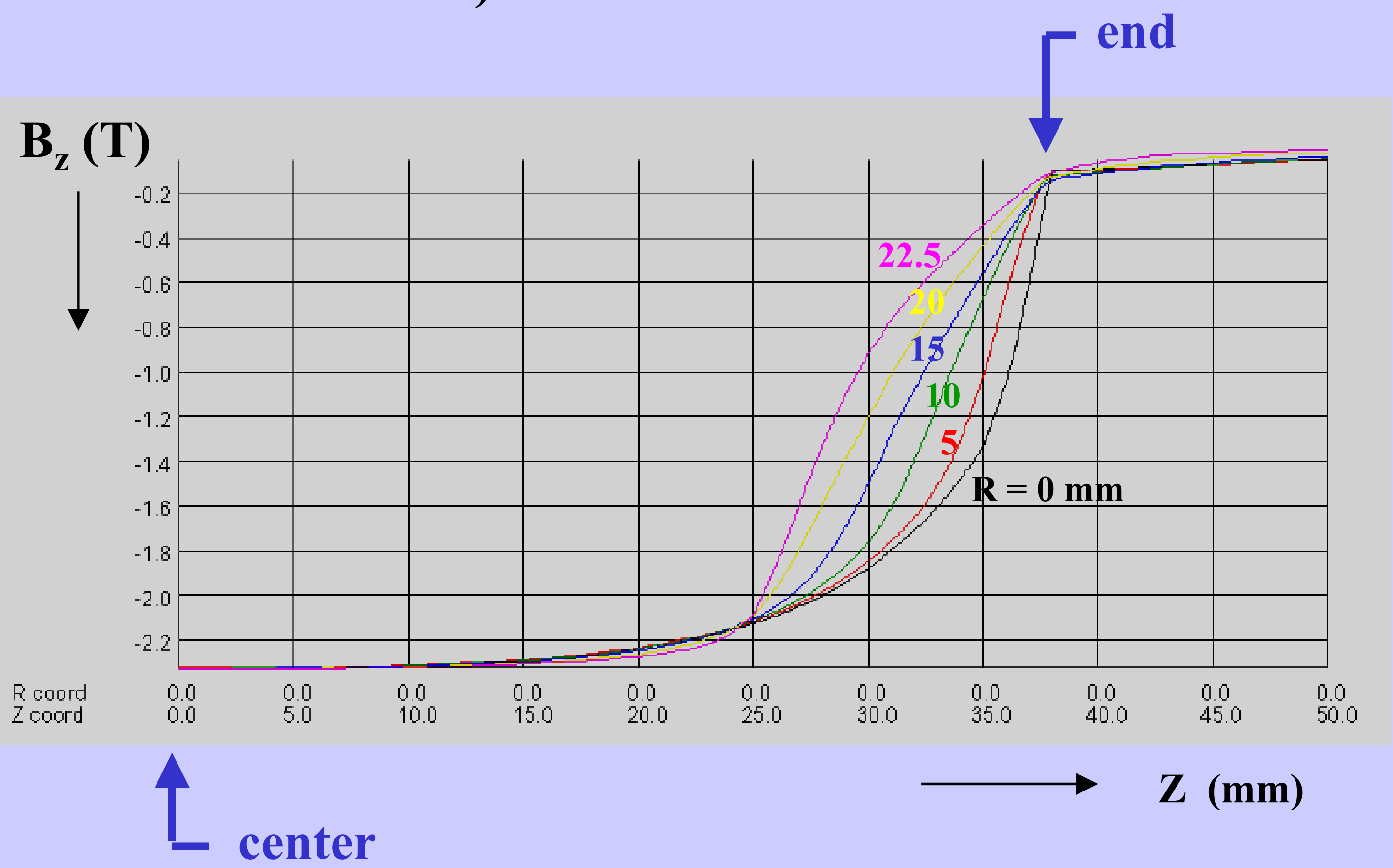
… and its ultimate implementation (Scott 1962)

$g' = 1.919 \pm 0.002$ for pure iron

i.e. orbital effects contribute about 4%

field distribution modeling

(Vector Fields OPERA-2d)

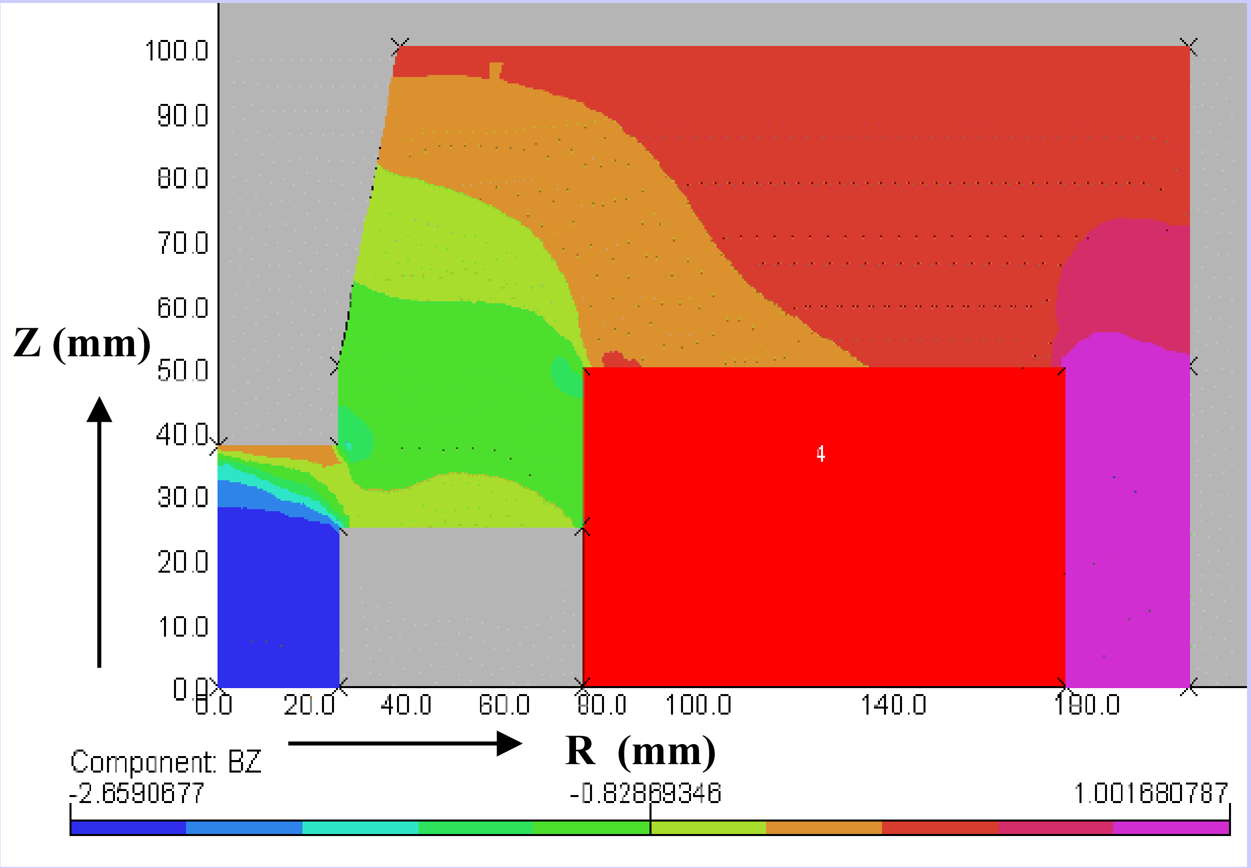


longitudinal field distribution: B_z (R,Z)

field drops gradually towards the ends: $L_{eff} / L < 1$

field distribution in 2d

(Vector Fields OPERA-2d)



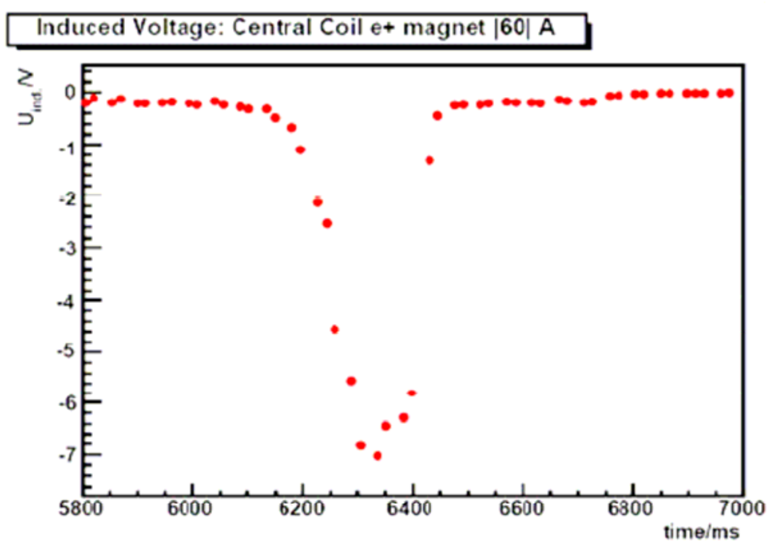
longitudinal field distribution: B_z (R,Z)

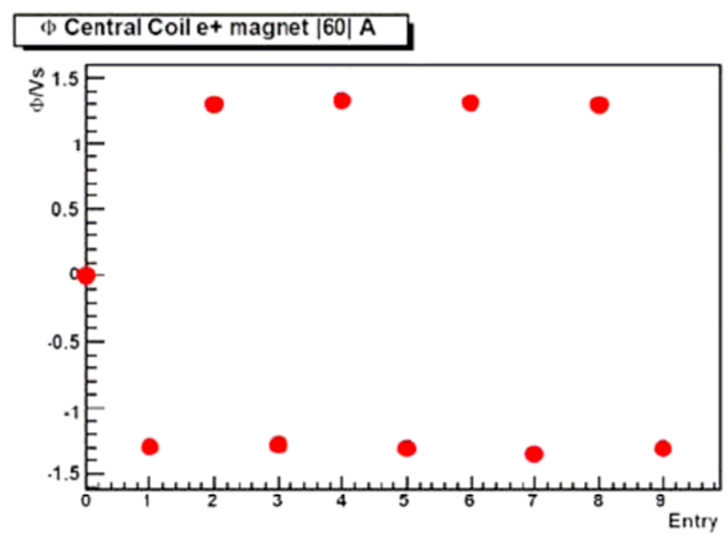
(shown for one quadrant)

flux measurements:

measure voltage transients in pickup coils upon current reversals

Positron Analyzer (-60 → +60 amps)

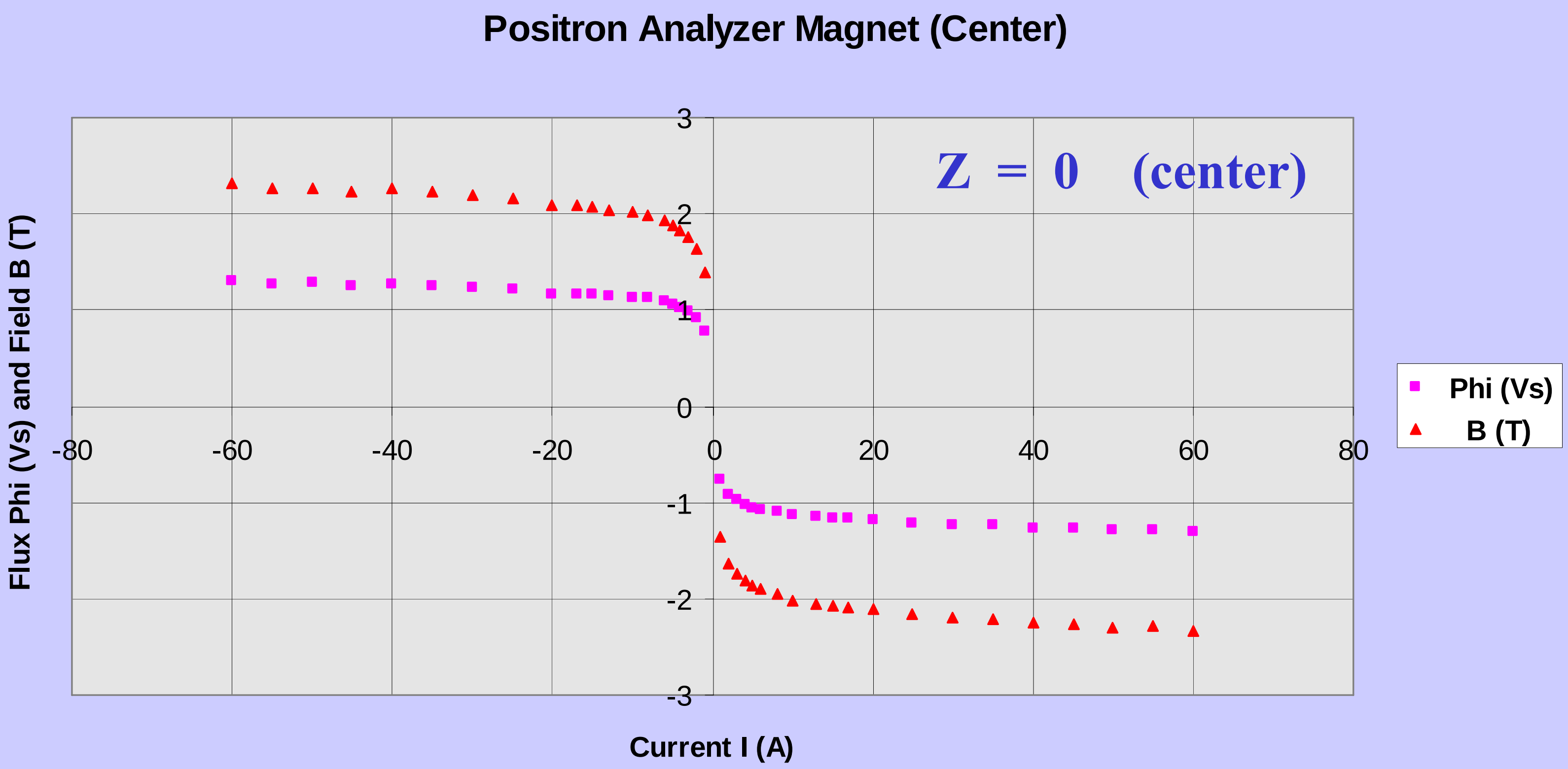




voltage transient

$$\Phi = \int U dt = \int B dA$$

flux and field measurements: results



Note: polarimetry was always done at full saturation over the central region (±60A)