Beam Polarization at the ILC: the Physics Impact and the Accelerator Solutions

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LCWS08, University of Illinois at Chicago

November 19, 2008

Talk is given on behalf of all enthusiasts working for polarized beams, in particular:
J. List, K. Moffeit, M. Woods, G. Moortgat-Pick, D. Kaefer, P.Schuler, K. Moenig, A. Hartin, A. Schaelicke, A. Ushakov, C. Rimbault, and participants of the "Workshop on polarimetry and energy measurement" in Zeuthen, April 2008.

Talks presented at LCWS08/ILC08

Jenny List:
- **Precision of Polarisation and Beam Energy Measurements at the ILC**
- **Upstream polarimeter**

Daniela Kaefer:
- **Compton Cherenkov detector development**

Anthony Hartin:
- **Depolarization from the upstream to the downstream polarimeter**

Cecile Rimbault:
- **Implementation and study of depolarizing effects in GINEA-PIG++ beam-beam interaction siulation**

Ken Moffeit:
- **Positron Spin Rotation at lower energy than the damping ring**

Sabine Riemann:
- **Fast or slow positron spin flipping**

Gudrid Moortgat-Pick:
- **Precision Electroweak Measurements During Calibration Running at E_{cm}=91GeV**

Outline

- Introductive remarks
- Production of intense polarized beams
- Polarimetry
  - **precision requirements**
  - **Measurement of polarization**
  - **Problems and concerns**
- Summary including recommendations from April workshop on polarization and energy measurements

Introductive remarks

- In general, with e- **<u>and</u>** e+ polarization
  - **Knowledge of initial state**
  - **Enhancement and suppression of processes**
  - **Choice of initial helicity states ⇔ additional degrees of freedom**
    - higher precision
    - less ambiguities
  - **Disentangling of new physics**

- **Polarization is essential for precision tests**
  - **Minimum: polarized electrons, unpolarized positrons**
  - **powerful: polarized electrons and polarized positrons**

Detailed summary of physics goal with polarized electrons <u>and</u> polarized positrons:

- **POWER Report** **[Phys.Rept. 460 (2008) 131]**
- **Physics RDR**

Production of intense beams

- Production of polarized electrons
- Production of (polarized) positrons

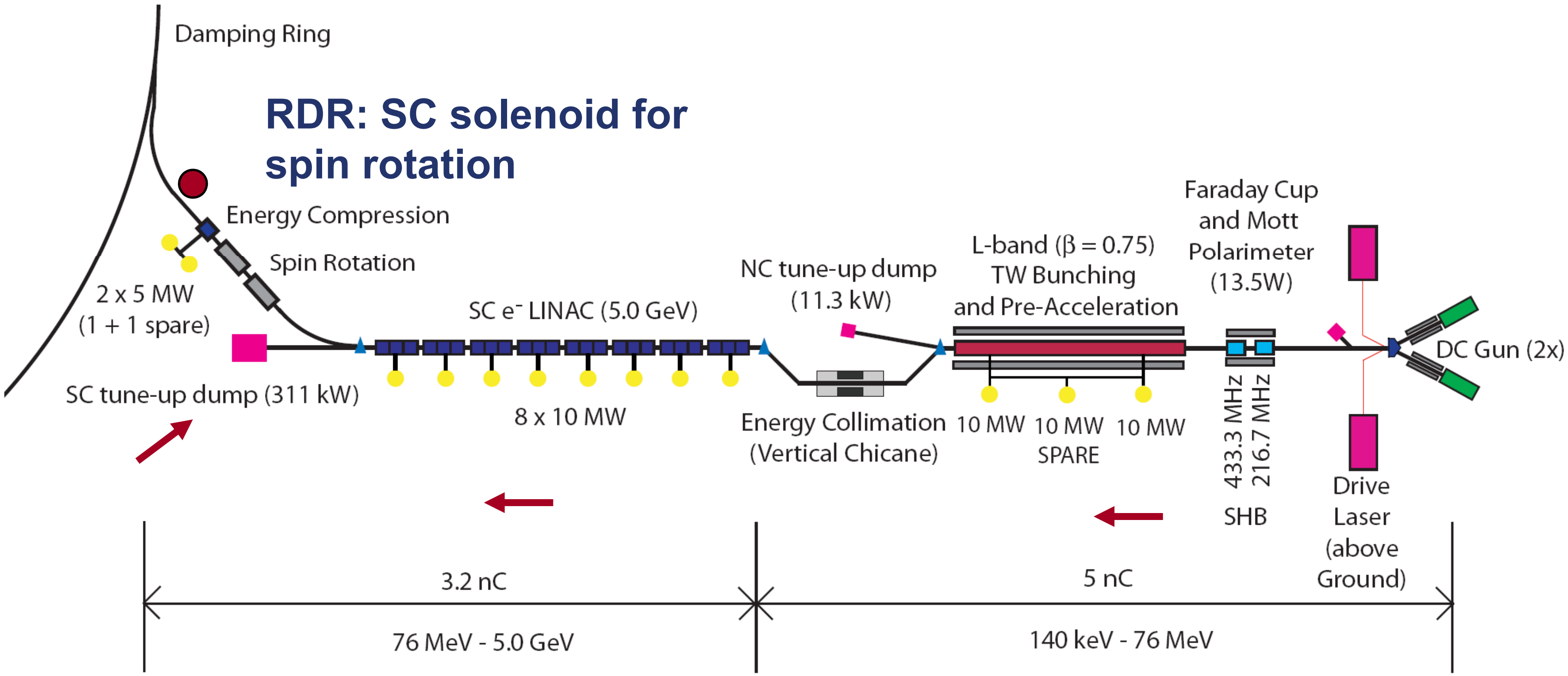
Electron Source System

Spin rotation requirements:

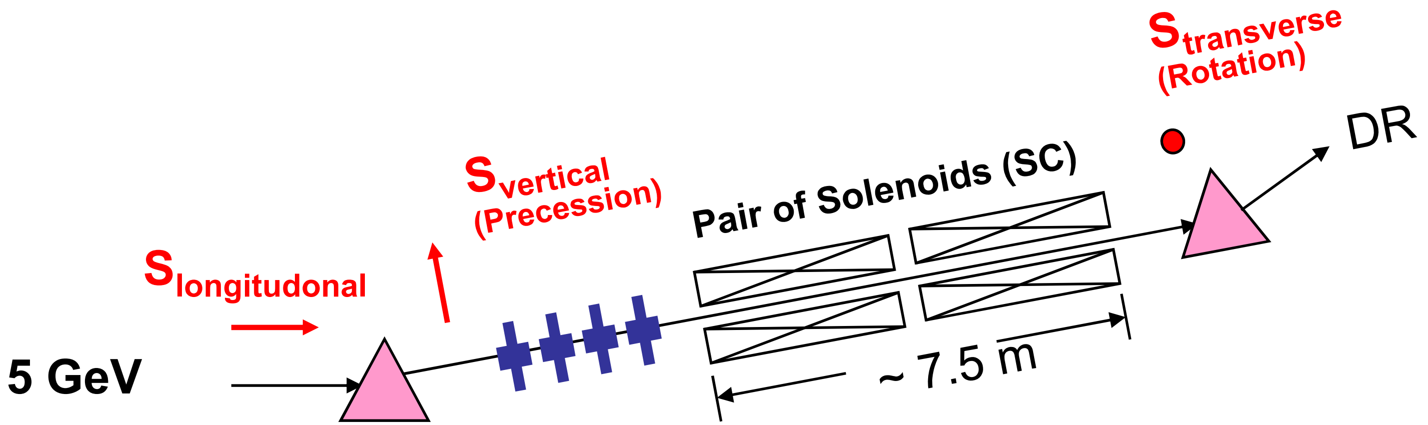
- before damping ring: rotate spin to the vertical
- after damping ring: rotate spin to have the desired polarization (e.g. longitudinal polarization) at the IP, .

Fast spin flip done with laser

RDR: SC solenoid for spin rotation



Baseline Spin Rotation System



Bend of n * 7.9312°

Odd Integer

$$\theta_{spin} = \frac{\int B_z dl}{B_0 \cdot \rho}$$

$$\theta_{spin} = \frac{E[GeV]}{0.44065} \cdot \theta_{bend}$$

Dipole and solenoid strength are set by spin manipulation requirements

Dipole: 7.9312°
→ ~ 2 kG

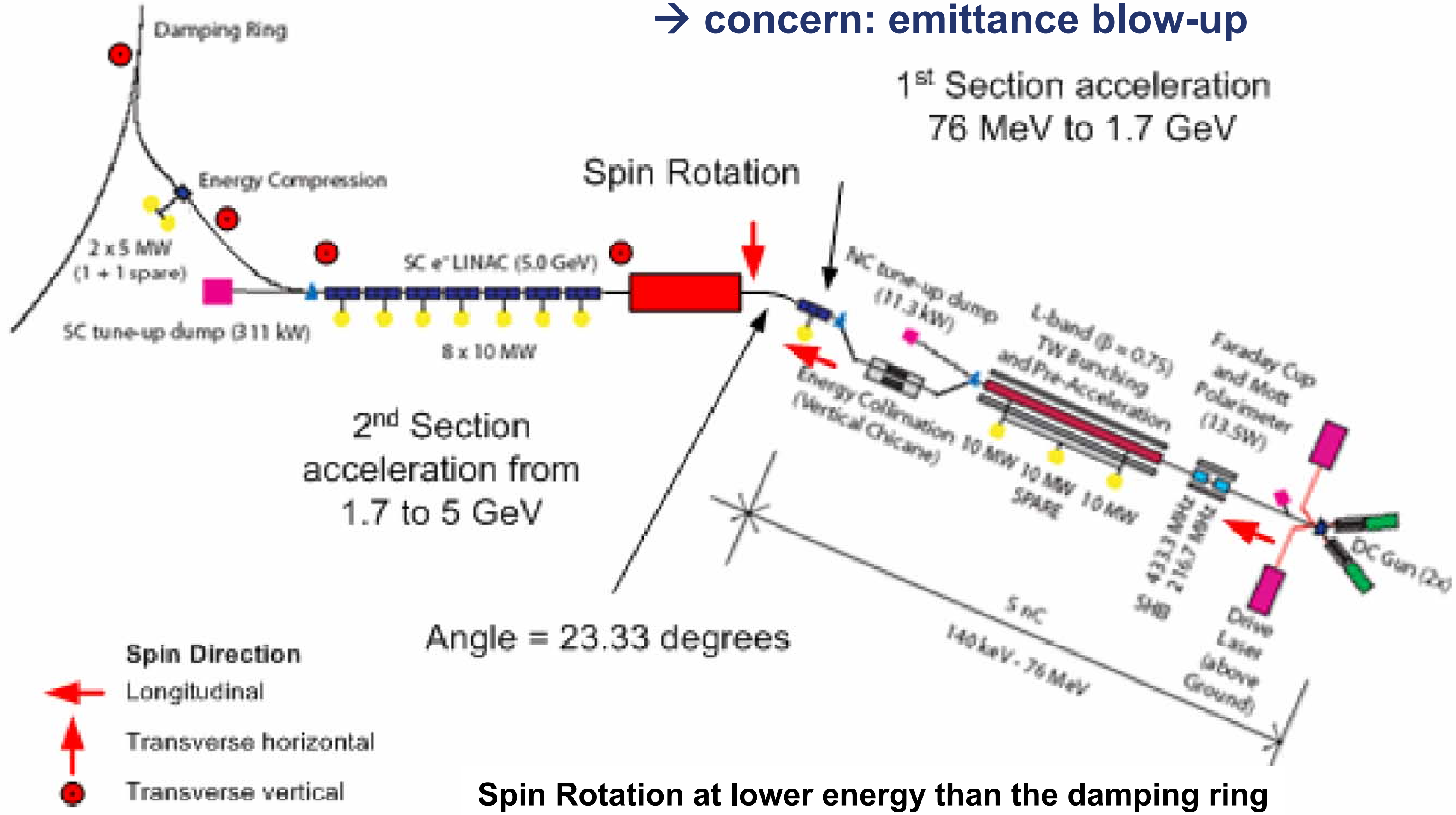
Solenoid: 26.2 T
→ 2x3.5 m; 38.5 kG

Design is based on paper by Moffeit, Woods, Schuler, Moenig and Bambade (2005), SLAC-TN-05-045

Spin Rotation – Alternatives

Example: Spin rotation at 1.7 GeV
→ less stringent requirements for solenoid

Proposal: spin rotation using Wien filter near gun
→ concern: emittance blow-up

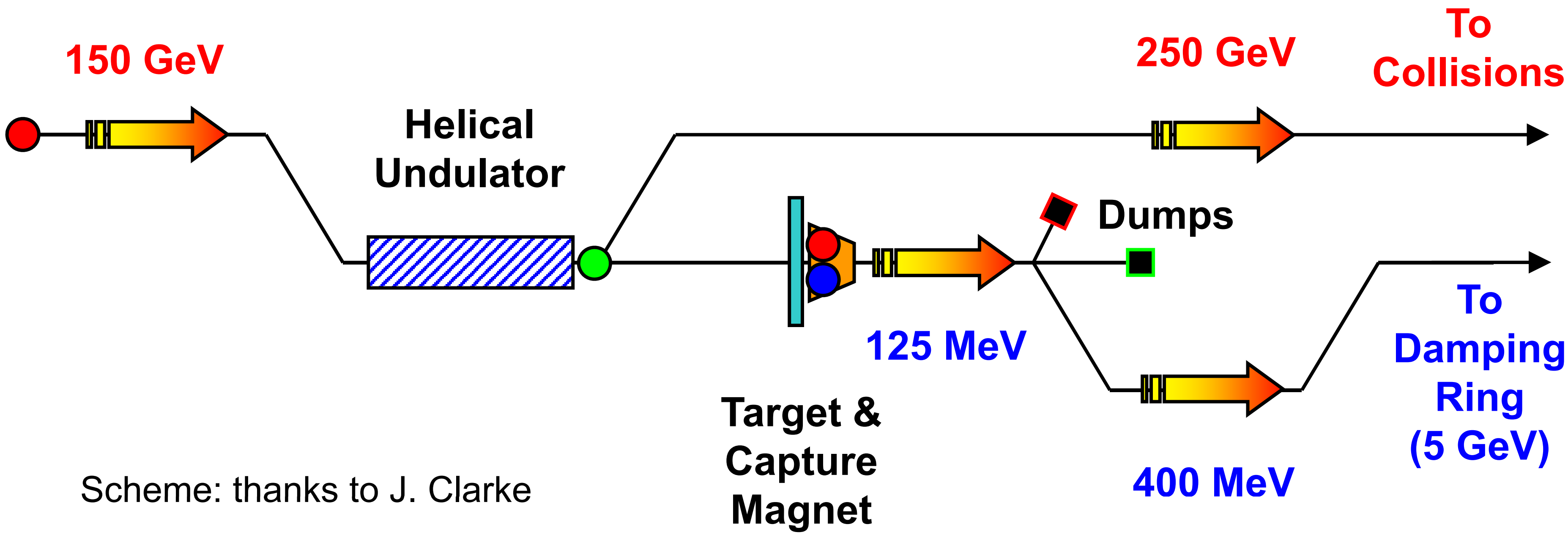


Spin Rotation at lower energy than the damping ring
K. Moffeit, M. Woods and D. Walz, ILC-NOTE-2008-040

Production of Positrons

RDR

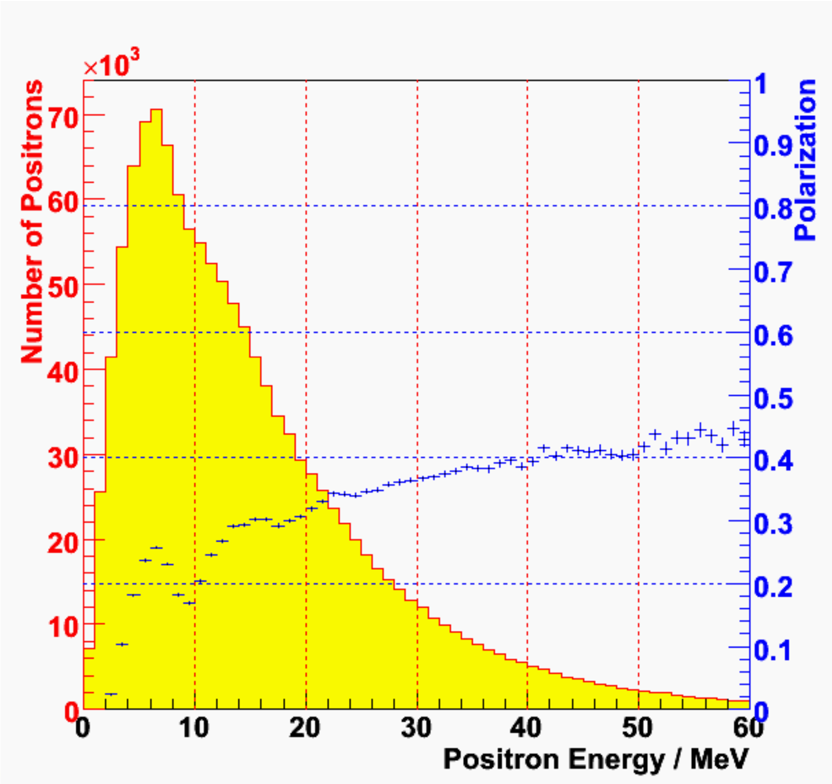
- 150 GeV electrons pass helical undulator → circularly polarized photons
- Photons hit thin Ti alloy target → e+e- pairs
- e+ spin rotation before DR, and after DR before ML
- Minimal machine: undulator at the end of main e- linac
- Alternative scheme: photonproduction with Compton backscattering

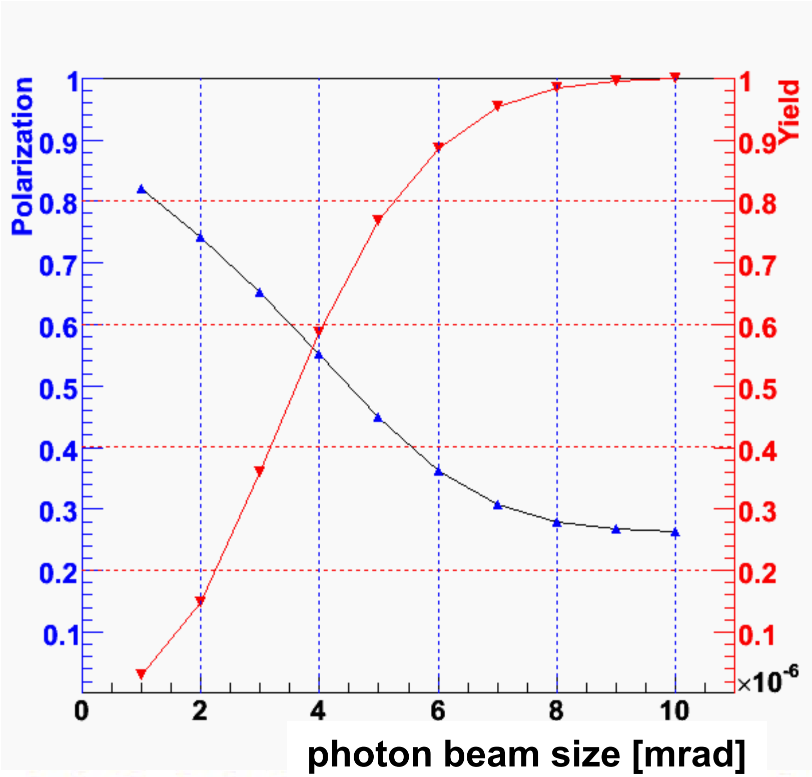


Scheme: thanks to J. Clarke

Positron polarization

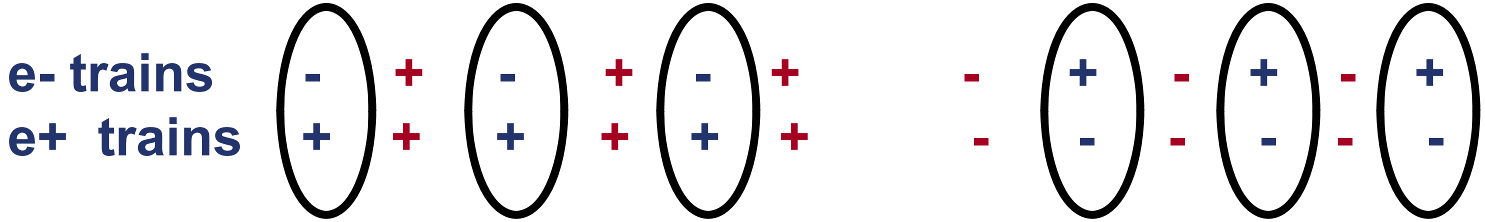
- Distance between target and undulator: ~500m
- Average positron polarization >30 %
- Spin rotation before/after DR is in the RDR





Problem: e^+ helicity reversal

e+ helicity flip less frequent than e- helicity reversal



'interesting' SM processes

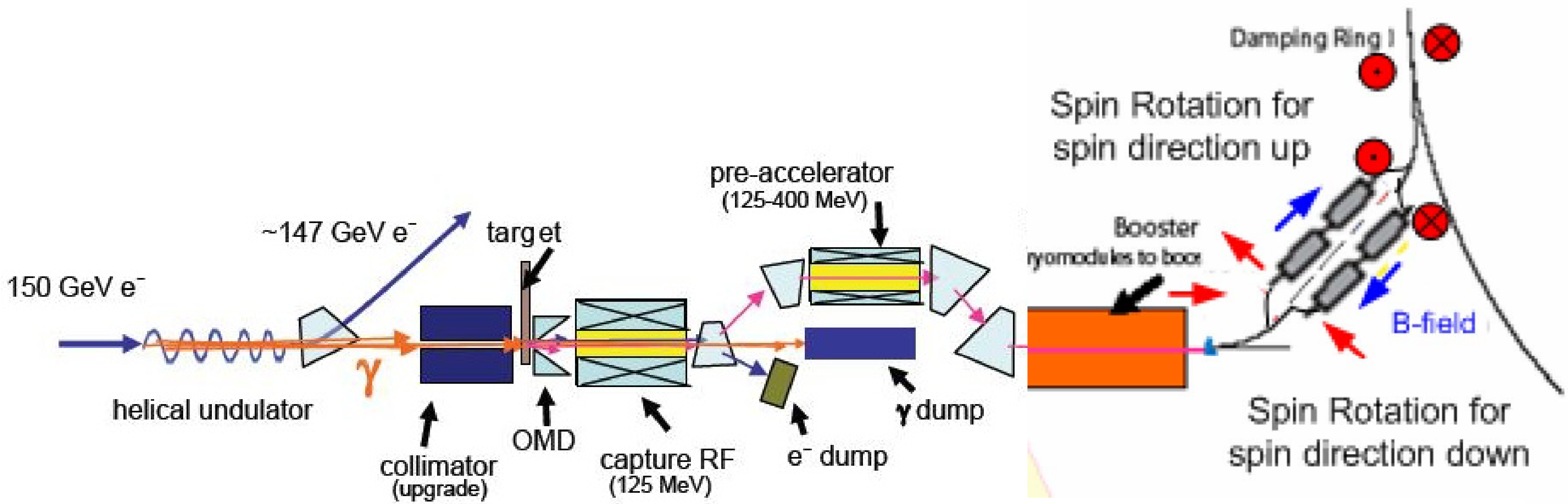
- 50% spent to 'inefficient' helicity pairing σ_{--} and σ_{++} (J=0)
- Have to combine σ_{-+} and σ_{+-} measured in different runs with different luminosities

  ➔ Large systematic uncertainties due to
  - **luminosity variations**
  - **polarization variations**
  - **variations of detector efficiencies**
  - **...**

➔ need rapid helicity reversal also for positrons

Spin rotation and fast flip for e+ at 5 GeV

Scheme suggested by K. Moffeit et al., SLAC-TN-05-045



parallel spin rotation beam lines for randomly selecting e+ polarization; pair of kicker magnets is turned on between pulse-trains

"Compton source":

fast helicity flip by reversing polarization of laser

e+ spin rotation and helicity reversal at 400 MeV

New proposal: K. Moffeit, M. Woods,Walz, ILC-NOTE-2008-040
→ spin rotation and fast helicity reversal at ~400 MeV

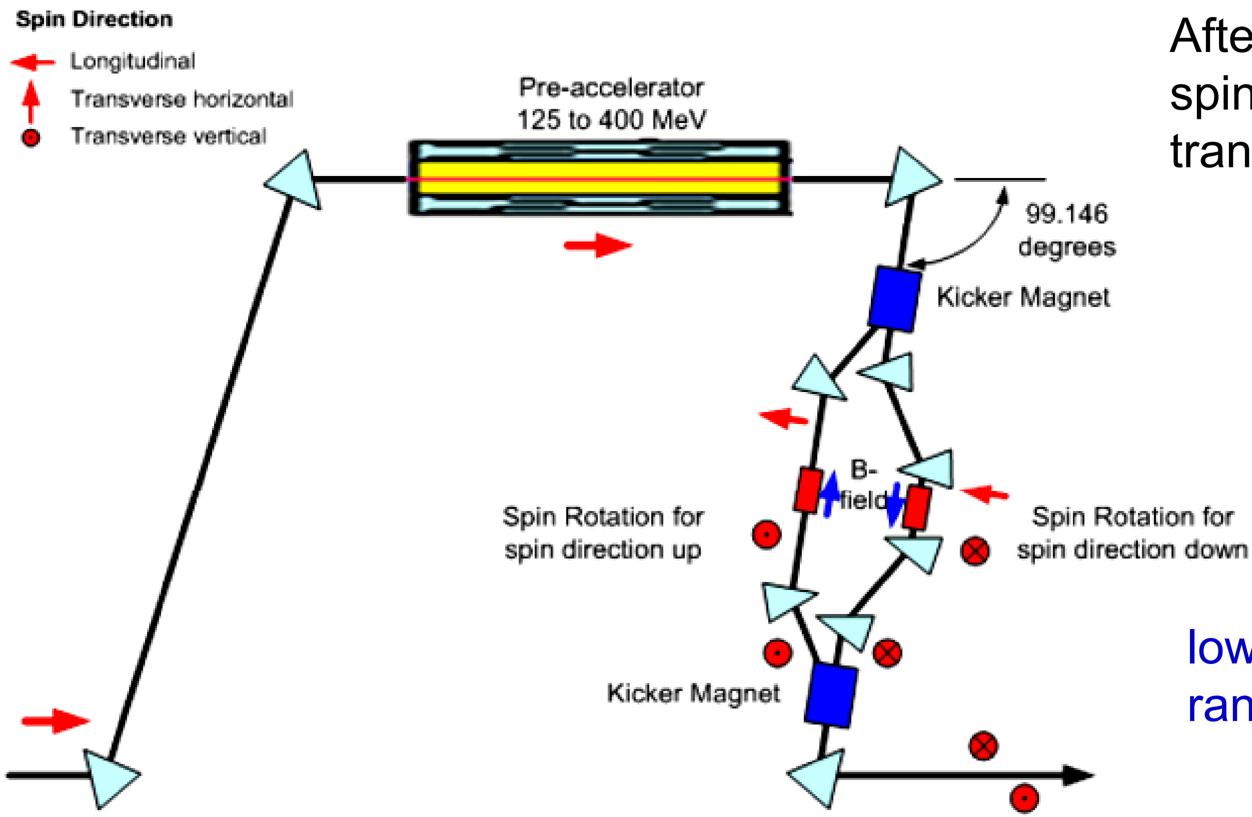


Figure 5: Layout of proposed positron spin rotation systems in the Chicane for the Pre-accelerator. Kicker magnets and parallel spin rotator beamlines allow fast polarization reversals for the positron beam.

After bend of 99.146 degrees spins are horizontally transverse.

Kicker → 2 parallel lines with solenoids to rotate spin to the vertical

low systematic errors ⇔ random kicks to parallel lines

Required precision

Physics between 200 GeV and 500 GeV
Luminosity: Year 1-4: L_{int} = 500 fb^{-1}
Electrons: P > 80%
Energy stability and precision below 0.1%

➔ ee→HZ	at 350 GeV (mH≈120 GeV)	few 10^4
ee→ tt	at 350 GeV	10^5
ee → qq (μμ)	at 500 GeV	$5 \cdot 10^5$ ($1 \cdot 10^5$)
ee → WW	at 500 GeV	10^6

➔ statistical uncertainties at per-mille level !!

$$\Delta\sigma \propto \frac{1}{\sqrt{N}} \oplus \frac{\Delta L}{L} \oplus \frac{\Delta E}{E} \oplus \frac{\Delta P}{P} \longrightarrow O(10^{-3})$$

Polarimetry

- Basics
- Upstream Polarimeter
- Downstream Polarimeter
- Polarimetry with annihilation data

Details: see talks of Jenny List, Daniela Kaefer

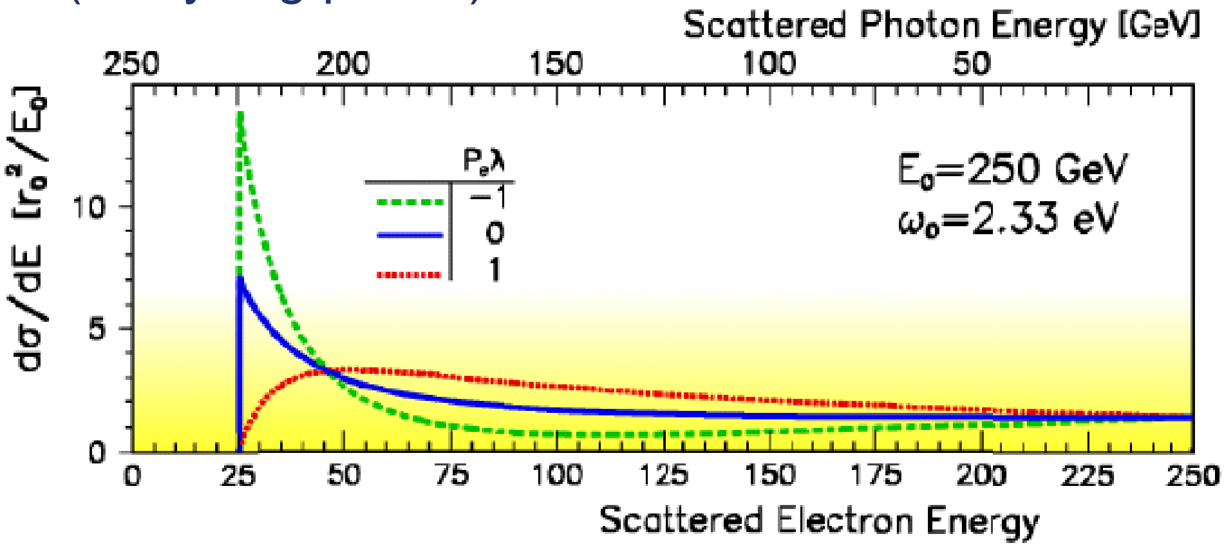
Polarimetry: Basics

- Compton scattering of laser photons on beam electrons or positrons
- Energy spectrum of scattered e- (e+), dσ/dE, depends on
  - **Circular polarization of laser, P_γ (Left, Right)**
  - **Longitudinal polarization of Pe-, Pe+**
- Measure asymmetry A for scattered e+, e-

$$A(P_\gamma, P_e) = \frac{d\sigma_R(E) - d\sigma_L(E)}{d\sigma_R(E) + d\sigma_L(E)}$$

- P=100% ⇔ A = AP (analyzing power)

$$P_e = \frac{1}{AP \cdot P_\gamma} A$$



Upstream polarimeter

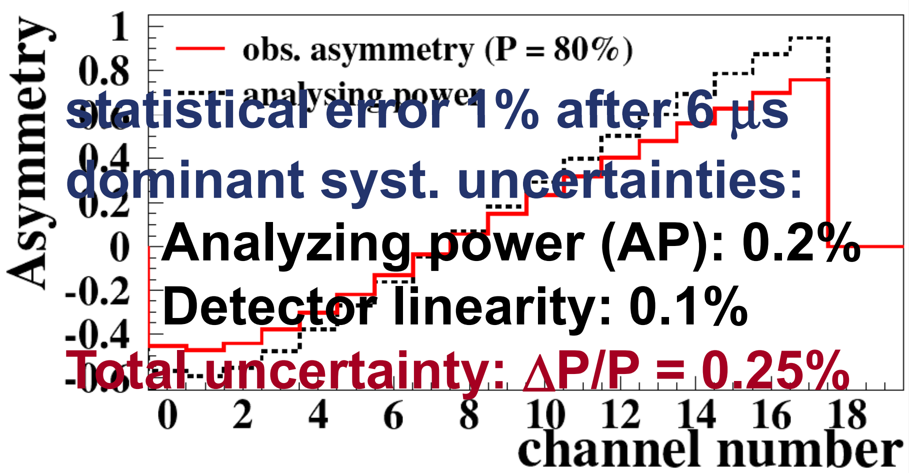
- Spectrometer chicane (4 dipoles) → energy (=position) distribution
- position of Compton edge is indep. on E_b ⇔ const. B field

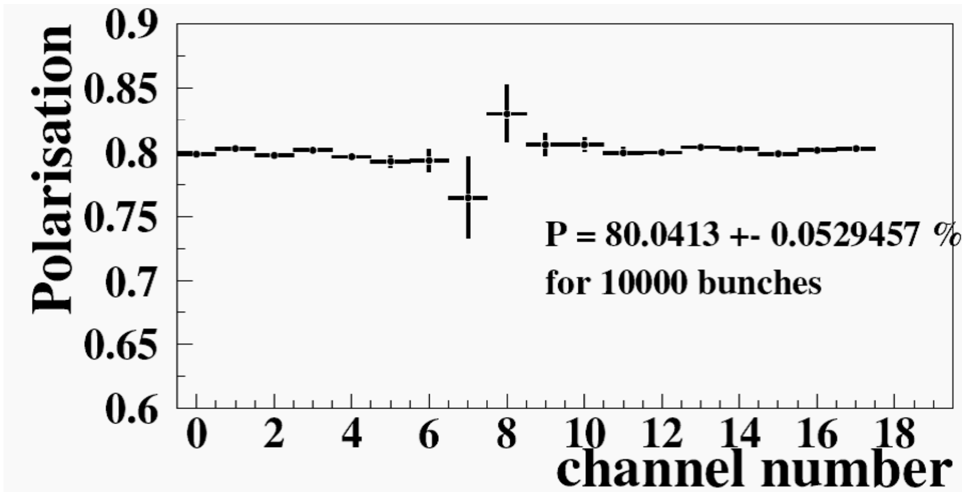
➔ **Uniform acceptance for all E_b (precise detector calibration)**

➔ **Laser - has same frequency for all E_b**

- Compton IP moves horizontally by ≈10cm with E_b

➔ **laser and vacuum chamber are designed accordingly**





statistical error 1% after 6 μs

dominant syst. uncertainties:

Analyzing power (AP): 0.2%

Detector linearity: 0.1%

Total uncertainty: ΔP/P = 0.25%

Upstream polarimeter

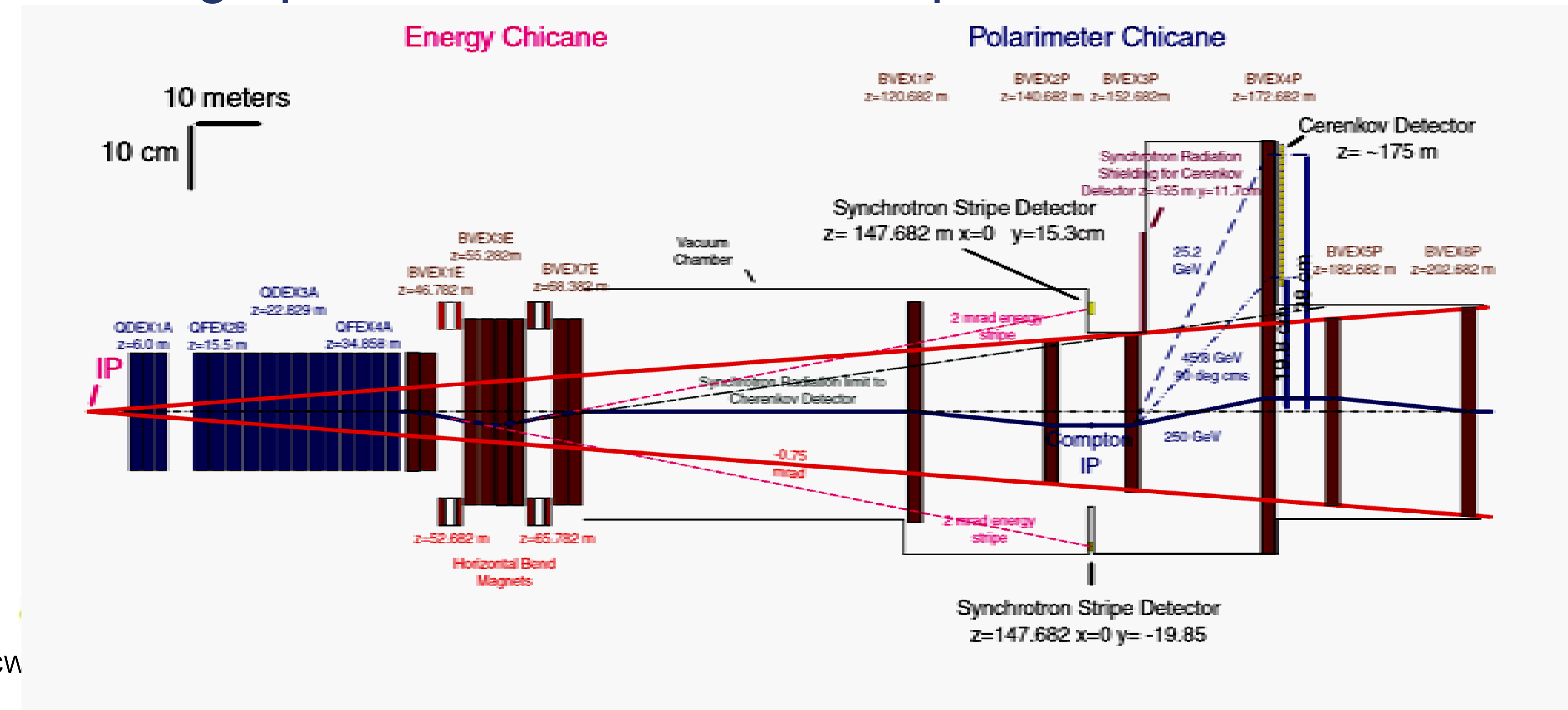
- Polarimeter is 1.8 km upstream of IP,
  offset x=1.5m wrt IP and IR magnets
- Polarization measurement before interaction
  → depolarization effects need to be calculated
  - **unavoidably uncertainties due to unknown beam parameters**
- Clean environment ➔ each bunch can be measured
  - **Fast: O(10^3) Compton events per bunch,**
    small statistical error, «1% per sec
  - **➔ Monitor time dependence of polarization**
  - **➔ variation in analyzing power allows internal cross checks**

Downstream polarimeter

- Same principle as upstream but measures polarization after collisions

  → have access to depolarization effects
- 2 additional dipoles
- Disrupted beam, SR (large background!!)

  → high power laser ⇔ smaller rep. rate



Downstream polarimeter

- Location: 150 meters downstream of IP; on axis with IP and IR magnets
- Polarization measurement after beam crossing
  → disrupted beam; only measurement of one/three bunches per train for 1(3) lasers
- Depolarization of outgoing beams
  - **can be measured:**
    - compare polarization measurement w/wo collisions
    - with collisions depolarization is twice the depolarization without collisions
    - can be corrected by adjusting the extraction line transfer matrix to that of the interacting particles
    - This works for (large) BMT depolarization, but not for (small) Sokolov-Ternov depolarization
    - Absolute value can be adjusted relatively easily
    - Sign is more difficult and important if
      - Collisions not exactly head-on
      - Spins not perfectly aligned
    - Studies have to be done

Depolarization at IP

- depolarization can occur due to
  - **beam-beam effects**
  - **misalignment (e.g. ground motion induced misalignment)**
  - **total depolarization at IP is < 0.3% at 500 GeV**
- Precession of longitudinal spin to transverse directions
  - **Transverse direction shows preference to ±y, but varies train-train**
  - **Need to understand impact on physics with transverse beams (TGC, extra dimensions,…)**
- Propagate disrupted beam down to extraction line; simulate polarization at downstream polarimeter
- Need to include crab cavity, (anti)DID, and understand impact of undulator at end of linac…. ➔ **still lot of work to do**
- Further details see talk of A. Hartin

Depolarization in GP++

- Comparisons with CAIN, good agreement for basic cases.
- At nominal case of the ILC total luminosity-weighted depolarization is $\Delta P_{lw} \sim 0.23 \pm 0.01$ %
- Depolarization is sensitive to horizontal beam size variations: uncertainty of 10% on beamsize → uncertainty on depolarization is larger than 20%
- Details see talk of Cecile Rimbault

Complementarity of polarimeters

Upstream

- Clean environment
- Stat. error 1% after 6μs
- Machine tuning (polarimeter is also upstream of tune-up dump)

Downstream

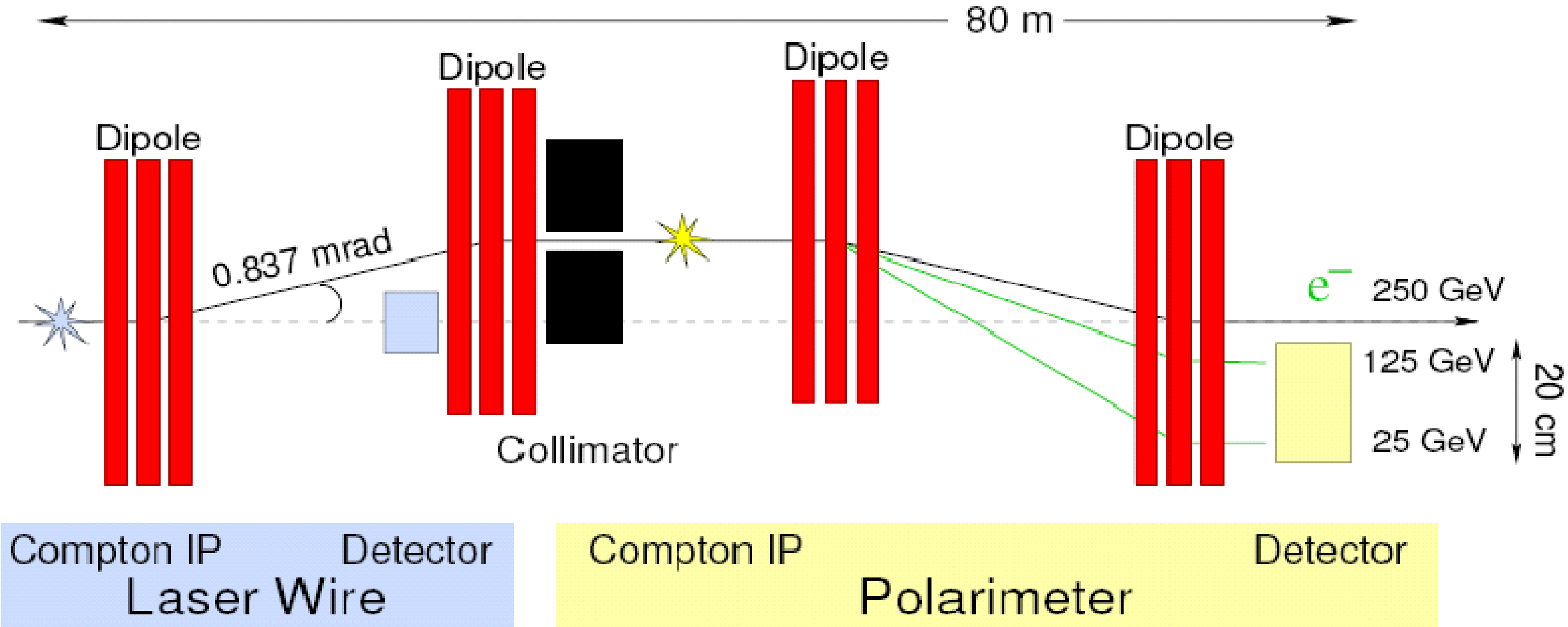
- High background
- Stat. error 1% after ~1min
- Access to depolarization at IP

Combination

- **Cross checks ⇔ redundancy for high precision**
- **With collisions: depolarization at IP**
- **Without collisions: control spin transport in BDS**

Concerns

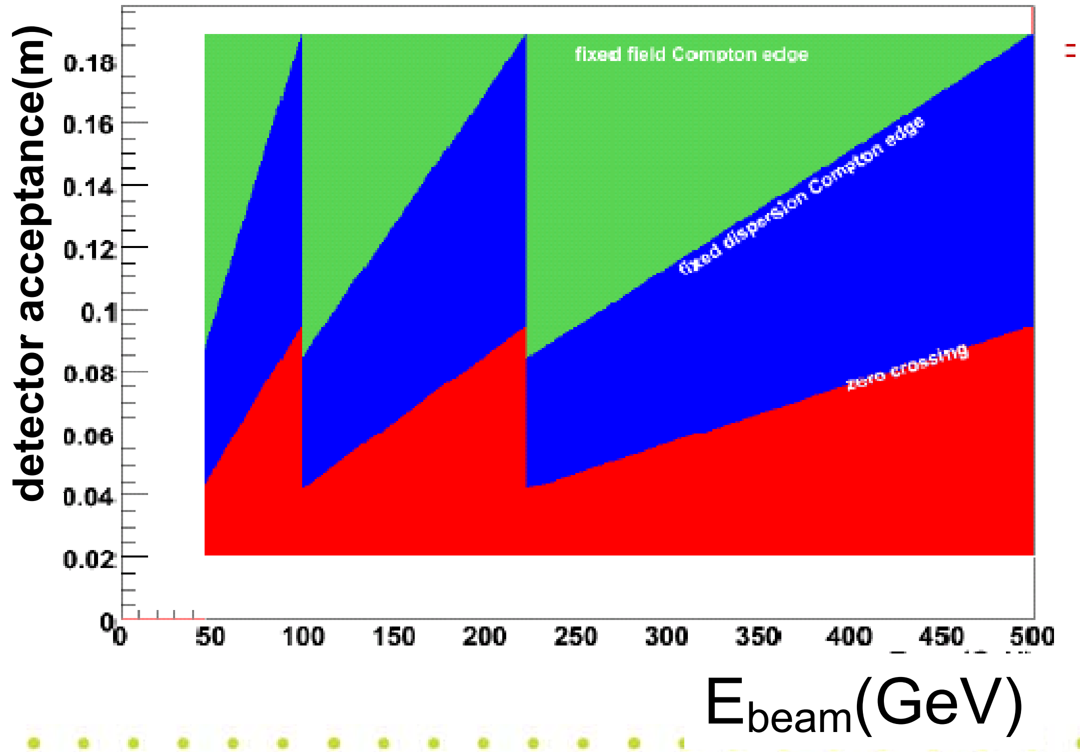
- Other instrumentation in the polarimeter chicane?
  - laser wire emittance diagn.,
  - MPS (machine protection system) Collimator



Concerns (cont.)

- Scaling B field of chicane with E_b and constant dispersion of Compton electrons/positrons ?

→Uniform acceptance for all E_b is lost → reduced precision



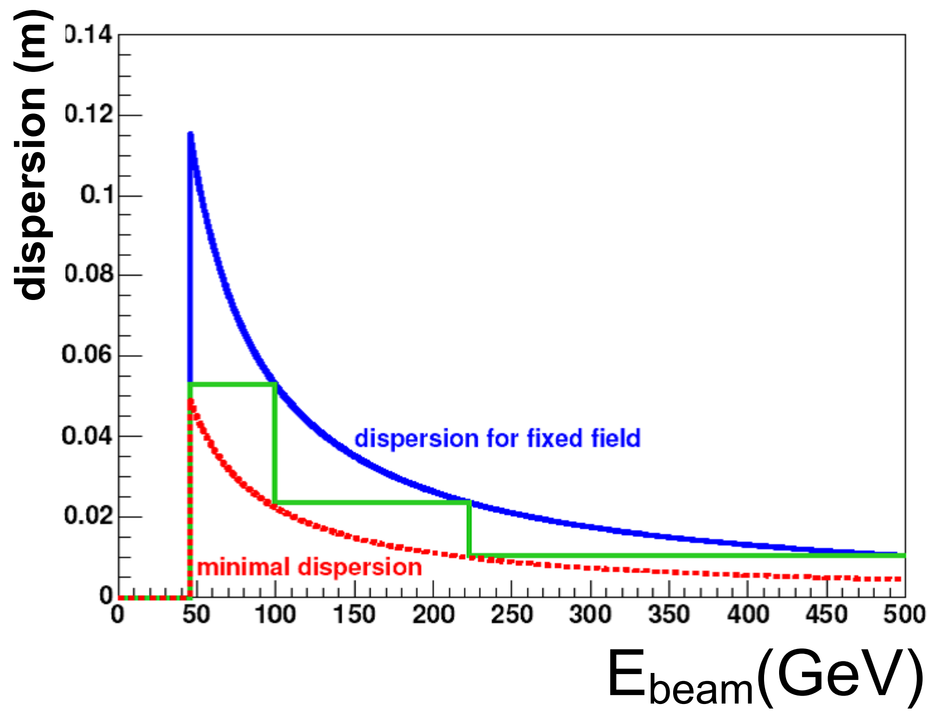
Concerns (cont.)

Scaling B, fixed dispersion?

- dispersion at high E_b can blow up emittance → dispersion is defined by emittance constraints (→maximal dispersion)
- Detector constraints (→ minimal dispersion)
- dispersion for low E_b is too high for laserwire detector

➔ No universal dispersion for all E_b

➔ scaling B is in contradiction with later low energy running where we need precise polarimetry



Polarimetry with annihilation data

Blondel scheme

- Can perform 4 **independent** measurements (s-channel)

$$\sigma_{\pm\pm} = \tfrac{1}{4}\sigma_u\left[1 + P_{e^+}P_{e-} + A_{LR}\left(\pm P_{e^+} \pm P_{e-}\right)\right]$$

=0 (SM) if both beams 100% polarized

$$\sigma_{\mp\pm} = \tfrac{1}{4}\sigma_u\left[1 - P_{e^+}P_{e-} + A_{LR}\left(\mp P_{e^+} \pm P_{e-}\right)\right]$$

- determination of P_{e+} and P_{e-}, σ_u and A_{LR} simultaneously ($A_{LR}\neq 0$); for $P_e(+) = P_e(-)$:

$$P_{e^\pm} = \left[\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--})}{(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--})} \cdot \frac{(\mp\sigma_{+-} \pm \sigma_{-+} - \sigma_{++} + \sigma_{--})}{(\mp\sigma_{+-} \pm \sigma_{-+} + \sigma_{++} - \sigma_{--})}\right]^{1/2}$$

→ need polarimeters at IP for measuring polarization differences between + and – helicity states

→ Have to understand correlation between $P_e(+) = P_e(-)$

Polarimetry with annihilation data

- Measurement takes months at high energies !!
- For threshold scans etc. statistics may not be sufficient
- Have to deliver lumi to ‘inefficient’ channels σ_{--} and σ_{++}
- have to understand correlation between $P_e(+)$ and $P_e(-)$, need the polarimeters to monitor time dependencies
- Scheme works only with e+ polarization

- **essential for GigaZ !**

GigaZ

- Has not highest priority in ILC schedule
- Is important for checks of
  - **electroweak symmetry breaking ($\sin^2\theta_W$)**
  - **understanding of LHC results ?**
- Need all four combinations $\sigma_{+-/-+}$ $\sigma_{\pm\pm}$ to determine simultaneously A_{LR} and effective polarization
- Z pole calibration data may be used for precision physics (integrated over years)

  → **Looks promising (see Gudi's talk)**

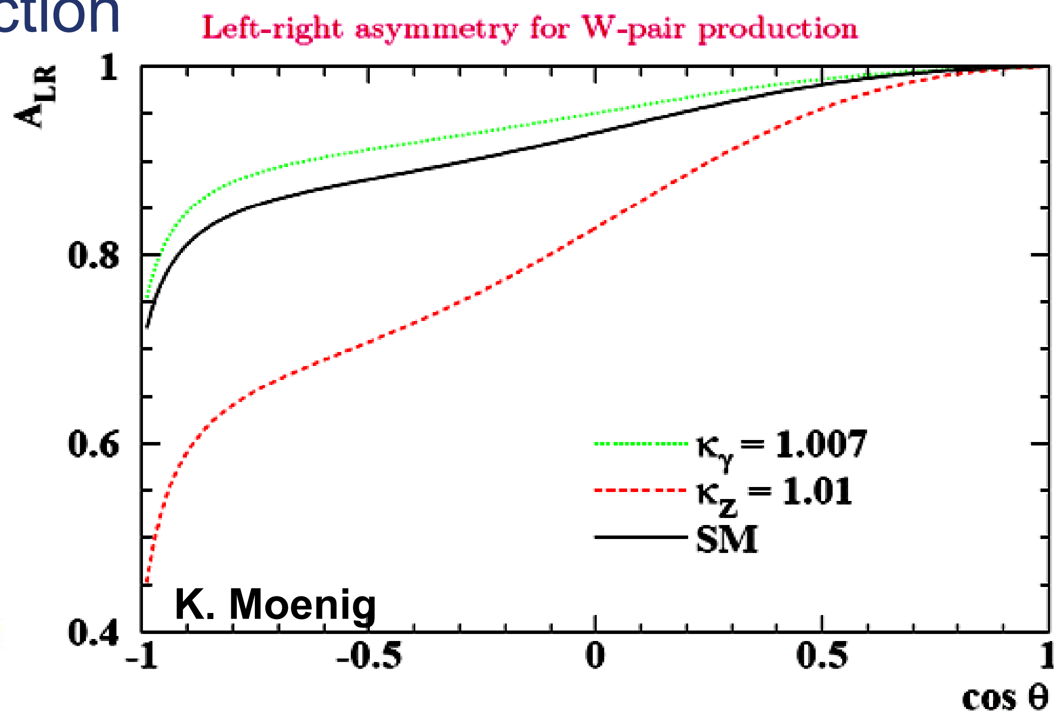
No positron polarization….

Electron polarization only: $$\sigma_{+(-)} \sim \sigma_u \left[1 + A_{LR} P_e\right]$$

2 observables for 3 unknowns, independent measurements of impossible

Include WW production – dominated by ν exchange in t-channel in forward direction

→ Quasi-independent determination of anomalous couplings and P_e



Fast flipping: s-channel A_{LR} with pol e+ beams

Left-Right asymmetry

$$A_{LR} \cong \frac{N_{-+} - N_{+-}}{N_{-+} + N_{+-}} \cdot \frac{1 - P_{e^-} P_{e^+}}{-P_{e^-} + P_{e^+}}$$

P_{eff}

Error propagation

→ →
$$\frac{\Delta P_{eff}}{P_{eff}} \cong F \frac{\Delta P_e}{P_e}$$

(80%,30%): F= 0.5
(80%,60%): F=0.25

Measurements with equal + - and - + pairing only (no - - , no ++) for $\mathbf{P_{e+} > 0}$:

$$\sigma_u = \frac{1}{2} \cdot \frac{N_{+-} + N_{-+}}{L \cdot (1 + |P_{e-} P_{e+}|)}$$

enhancement ~$(1+P_{e-}P_{e+})$

→ (80%, 30%): ~25% gain in stat. but add. uncertainty $\Delta\sigma_u$ ~0.3•ΔP/P[%]
→ (80%, 60%): ~50% gain in stat. but add. uncertainty $\Delta\sigma_u$~0.44•ΔP/P[%]
→ (80%, 0%), e+ pol destroyed: add. uncertainty $\Delta\sigma_u$~0.12%

Conclusion for precision measurements

- Need all cross checks and redundancy to achieve required precision for physics measurements

→Upstream: cleanest measurement with high time resolution

→Downstream: access to depolarization effects in collisions

→annihilation data: small errors if corrections are known from polarimeters and high statistics, need positron polarization

→Systematic uncertainties have to be controlled (fast helicity reversal)

Summary

- Beam polarization and polarimetry are essential for the physics program (precision!!)
- The baseline design provides polarized positrons that should be used for physics
- Important: knowledge of depolarization effects

➔ Polarization needs your support

All important issues were discussed on the EWPS in April08 in Zeuthen; the workshop had a common session with the Positron Source Collaboration.

The recommendations of this workshop were sent to the GDE (see ILC-NOTE-2008-047)

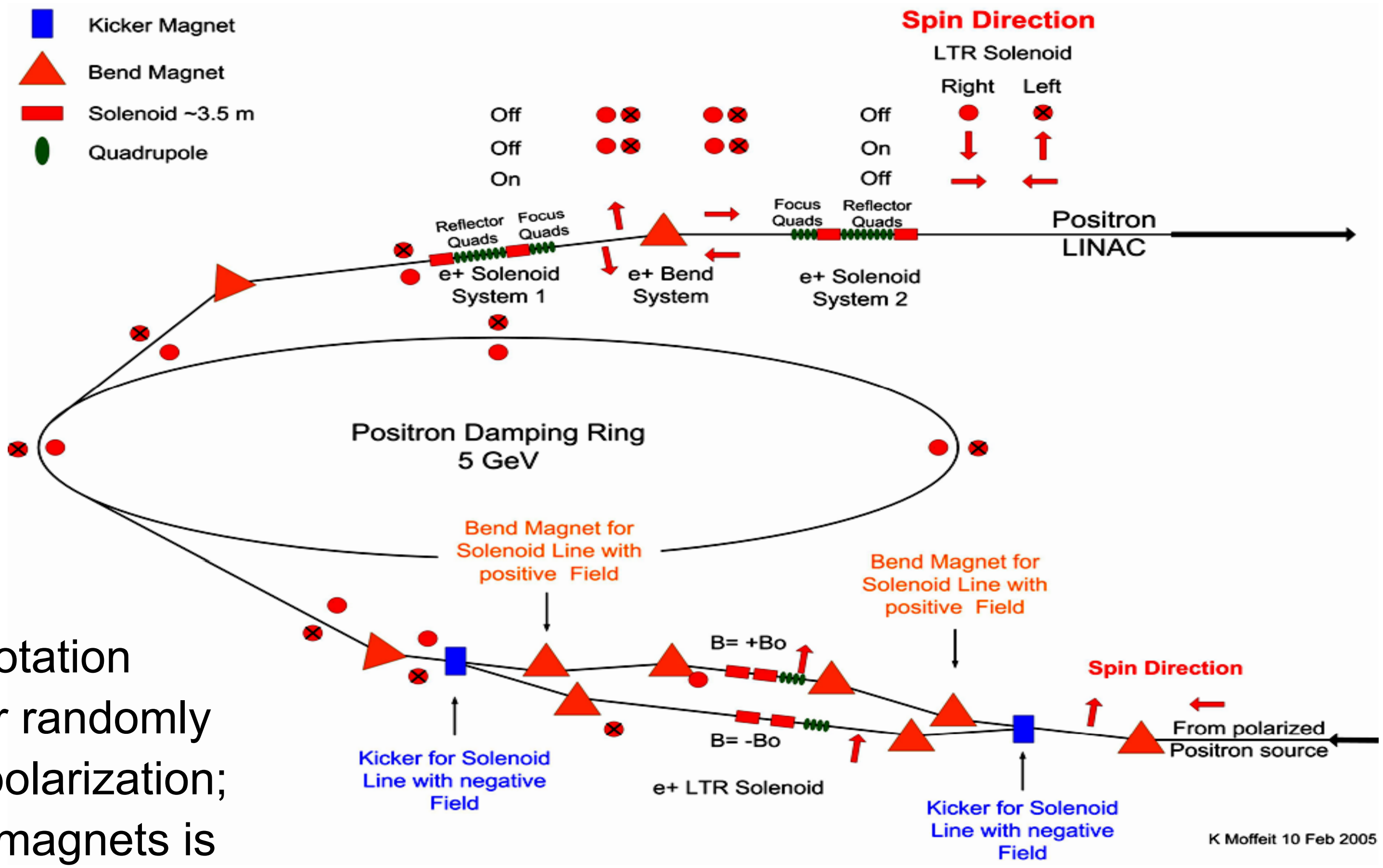
Recommendations from the EPWS, April08

- Keep the initial positron polarization of 30%-45% for physics
- Implement parallel spin rotator beamlines with a kicker system before the DR to provide rapid helicity flipping of the positron spin
- Move the pre-DR positron spin rotator system from 5GeV to 400 MeV to reduce costs
- Move the pre-DR electron spin rotator system to the source area to reduce costs
- Separate the functions of the upstream polarimeter chicane: use separate setup for MPS energy collimator and laserwire emittance diagnostics

Backup

e+ spin rotation and helicity reversal @ 5GeV

K. Moffeit et al., SLAC-TN-05-045 → fast reversal before DR (5 GeV)



parallel spin rotation beam lines for randomly selecting e+ polarization; pair of kicker magnets is turned on between pulse-trains

Issues of crossing angle and DID

- Spin rotation $\sim (g-2)\cdot\gamma\cdot\int Bdl$
- Spin rotation can be up to ~100mrad if solenoid and (anti)DID add

  ➔ depolarization of ~0.6%
- If spin direction is not perfectly aligned 100mrad misalignment correspond to 1.5% polarization error
- However: for measurements only relevant that beam in IP and polarimeter are parallel
- Compensation scheme needed