Tracks of spin .... within EUROTeV

heLiCal Collaboration

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work done over the years also in discussions/collaboration with

C. Rimbault (Guinea-Pig), P. Schmid (spin rotators) and J. Smith (BMAD)

EUROTeV-Report-2005-024, -2006-037, -2006-068, -2006-073, -2007-038, -2007-040, -2008-026 ... but more to come, not finished!

Outline

- Cradle-to-grave with the spins
  - physics motivation and overview
- Depolarization in beam-beam interaction
  - status CAIN
  - theoretical description of TBMT
- Incoherent processes
- Coherent processes
- Depolarization in DR, ML, RTML
  - spin rotators
- Conclusions and outlook

Physics requirement

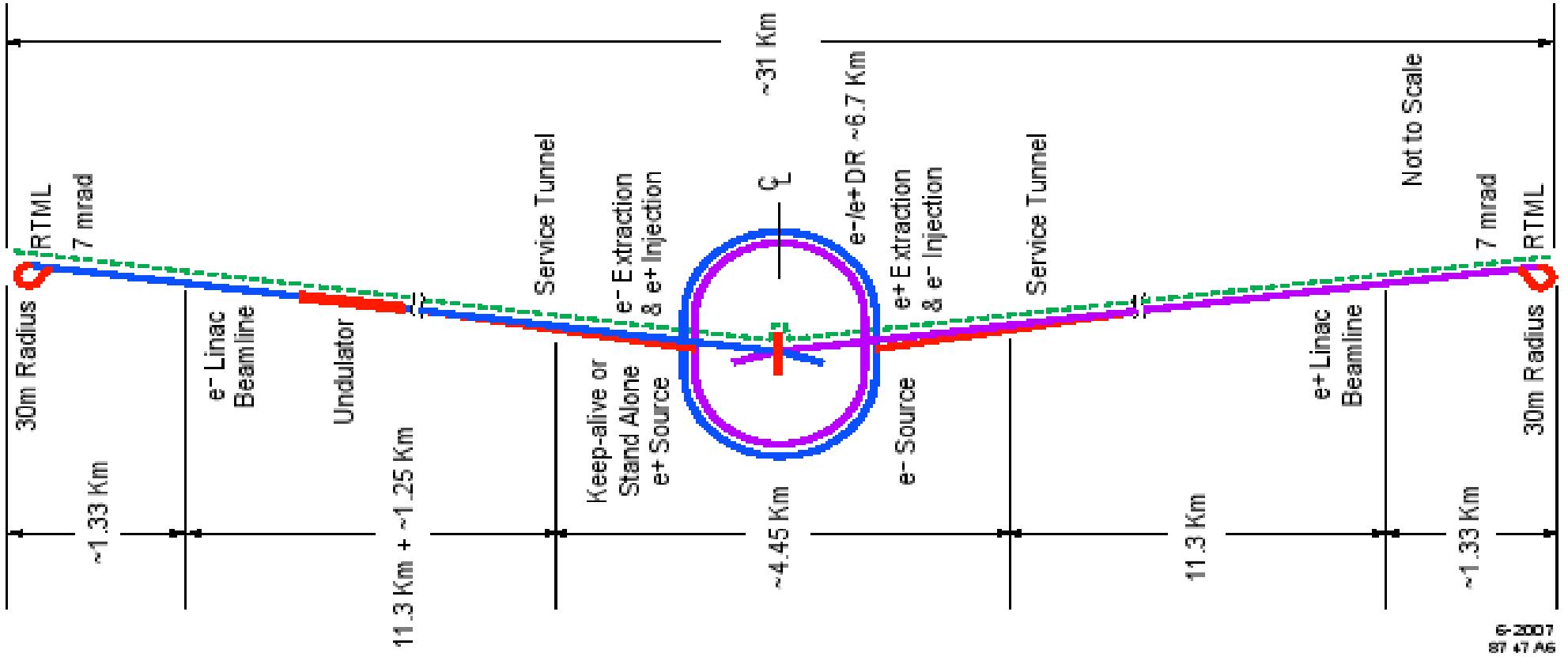
- Polarized beams mandatory to reach the physics goals
- Needed accuracy
  - expected: for most physics studies $\Delta P/P=0.5\%$ sufficient; for precision measurements $\Delta P/P<0.1\%$ required
- Problem:

  polarization@IP = lumi-weighted polarization

  $\neq$ polarization@polarimeter

- Aim: cradle-to-grave spin tracking from source -> IP
  - not yet completely done, but lots of progress, theoretically as well as in simulation codes

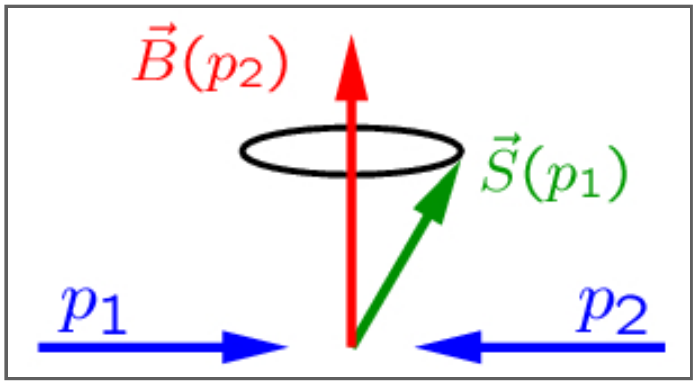
ILC overview



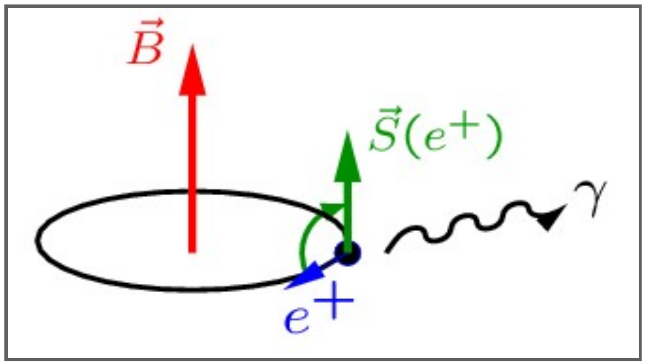
- **Components under study wrt depolarization:**
  - **DR (+SR), ML, RTML, BDS, IP**
  - **largest effects expected in beam-beam interactions at the IP!**
  - **ML, RTML, BDS small effects, cf. also with J. Smith, ILC-NOTE-2007-012**

Two depolarization processes

- **Classical spin precession (T-BMT):**



- **Quantum mechanical spin-flip process (ST effect):**



  - **evaluate these effects for all components**
  - **provide theoretical updates for their description in strong fields**

Spin precession

- **T-BMT equation:**

$$\frac{d\boldsymbol{S}}{dt} = -\frac{e}{m\gamma}\left[(\gamma a+1)\boldsymbol{B}_T + (a+1)\boldsymbol{B}_L - \gamma(a+\frac{1}{\gamma+1})\beta\boldsymbol{e}_v\times\frac{\boldsymbol{E}}{c}\right]\times\boldsymbol{S},$$

  - 'a' is anomalous magnetic moment of electron a=(g-2) / 2=$\alpha/2\pi$ + ...
  - higher-order effect, radiative corrections to eeγ–vertex
  - experimentally measured up to accuracy of 10^{-11}

- **So far: used medthod in CAIN and Guinea-Pig**

  Due to strong fields (beamstrahlung):

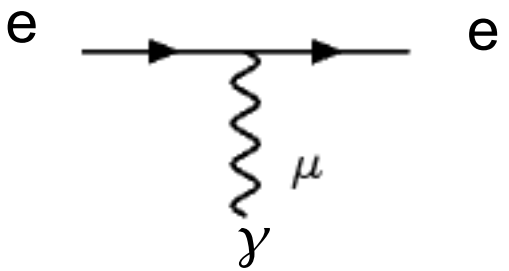
  - ' a' expressed as function of field in a medium
  - excellent work of V. Baier, V. Katkov
  - several approximations and assumptions have been made

Used approximations

- expression for anomalous moment of e in a medium
  - used kind of perturbation theory
  - relates spin-dependent part of mass corrections with magn. moment
- applies expression for beam-beam interactions
  - assuming the case that 'no' scattering happens
- used quasi-classical approximation
  - change of momentum due to external field has to be slowly
  - Larmor radius (~pc/eB) in magn. field much larger than particle wavelength (~h/p)
  - neglect quantization of motion and recoil of radiation on particle
  - assuming basic features of motion independent of spin property

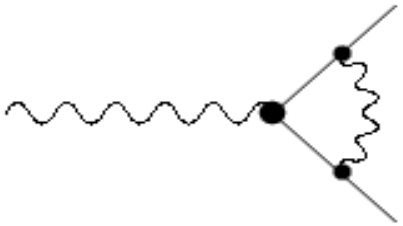
Anomalous magn. moment of e

- **Contributions to the QED vertex**



at 1-loop order:

'self-energies
~mass corrections'



'vertex correction'
~decisive for an. magn. moment

QED vertex

- lowest order: e u(p2) γ^μ u(p1)
- any order: u(p2) Γ^μ u(p1)
  - divide vertex in vector and tensor (~spin) part
  - $\Gamma^\mu = \gamma^\mu F_1 + \sigma^{\mu\nu} F_2$ Γ^μ
- in lowest order: F_1= e (electric charge), F_2=0
- at 1-loop: F_2 = anom. magn. moment of e a=0.5(g-2)
  - contributions come from vertex corrections
  - precise recipe how to calculate
- higher order: precise agreement between theory and experiment

  $a_{exp}=1159652188 \times 10^{-12}$ vs. $a_{theo}=1159652157 \times 10^{-12}$

Alternative to derive a_e in beam-beam

- derive H in external field
  - remember H-atom: spin-orbit term (l*s), interaction terms (B*s,B*l)
  - often A^2-terms neglected
  - important for strong fields (laser)
- use Furry representation, i.e. derive 'Volkov solutions'
  - use explicit fermion operator in external field
  - 'usual' Feynman rules in perturbation theory
  - explicit fields in beam-beam zone required
  - straight forward.....but mathematically rather complex
- still under work

Incoherent processes

- **Become important/dominant for high energies!**
- **For beam-beam interaction: four incoherent processes as 'background'**
  - **Breit-Wheeler:** $\gamma + \gamma \longrightarrow$ **e+ + e-** (real photons)
  - **Bethe-Heitler:** $e^{\pm} + \gamma \longrightarrow e^{\pm} + e^+ + e^-$

    becomes in EPA: $\gamma^* + \gamma \longrightarrow e^+ + e^-$
  - **Landau-Lifshitz:** $e^+ + e^- \longrightarrow e^+ + e^- + e^+ + e^-$

    becomes in EPA: $\gamma^* + \gamma^* \longrightarrow e^+ + e^-$
  - **Bremsstrahlung:** $e^+ + e^- \longrightarrow e^+ + e^- + \gamma$

    becomes in EPA: $e^+ + \gamma^* \longrightarrow e^+ + \gamma$

Equivalent photon approximation -- intro

- Idea: approximate virtual photon via a real photon with:
  - *mass on-shell*
  - *only transversely polarized*
- Approximation ok, if dynamical cut-off exists
  - limes for $q^2 \to 0$: $\sigma_S \sim q^2 \to 0$

$$\sigma_T \sim \sigma_\gamma$$

- Approximation ok, if spin-density matrix is taken into account:
  - expand amplitude in 'transverse' and 'scalar' photon contribution
- Cross section can then be expressed:
  - $d\sigma_{EPA} \sim \sigma_\gamma \; dn(w, q^2)$
- Check for every process whether EPA is applicable!
  - Bethe-Heitler and Landau-Lifshitz in principle ok

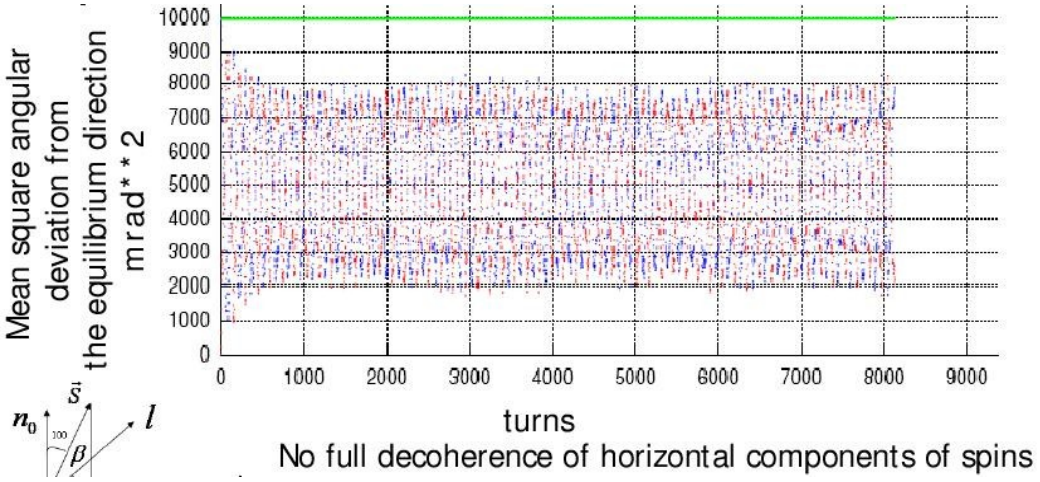
CAIN: status with background processes

- Bremsstrahlung process cannot be approximated via EPA!
  - in CAIN: bremsstrahlung only included via EPA
  - has still to be done
- EPA only in proper use, if polarization of virtual γ has been taken into account
  - in CAIN no polarization of photons for BH, LL and Bremsstrahlung process
  - has been changed; expression for virtual polarizations derived
- No correlation between polarization of final particles included
  - can only be done if for all processes spin-density matrix has been calculated...
  - has been changed: full polarization included
- Second order processes still need special treatment for EPA...but under control

Depolarization effects at the DR

- **Precise Monte-Carlo simulations done including full 3-D spin motion (code SLICKTRACK):**
  - **No significant depolarization effects have been detected even for a positron beam with its large energy spread and transverse dimensions**
- **However, absence of full decoherence of the horizontal components of the spin observed in simulations:**
  - **longitudinal polarization can survive!**

→ **Spin rotators needed for baseline design with 30%!**



Depolarization in spin rotators

- **Study on ILC spin rotators (see talk, P. Schmid, Orsay, 05/06)**

Summary

- A spin rotator was developed which meets all the design requirements. Elucidating the final installation tolerances utilizing beam-based alignment techniques is the subject of another investigation.
- The perturbation imposed by the positron source on the electron polarization were calculated and considered negligible.
- Depolarization effects due to misalignment seem to be a non-issue at 5 GeV. Displacing the most sensitive quadrupoles by 10 mm is required to cause an appreciable effect. The only depolarizing effect originates from parasitic dipole field components caused by misaligned quadrupoles.

- **Expected depolarization about 3% - 5%**

Executive summay recommend.

- **Polarimetry and energy measurement workshop@ Zeuthen 04/08**
  - **executive summary sent to the GDE, please see arXiv:0808.1638**
- **since baseline design provides small polarization**
  - **flipping of helicity is required or destroy polarization completely (see talk of S. Riemann at LCWS07 and polarimetry workshop)**
  - **if even bunch compressor used: capture efficiency increased by factor 2, polarization raises up to 45%!.....**
- **Recommendation:**

5. Implement parallel spin rotator beamlines with a kicker system before the damping ring to provide rapid helicity flipping of the positron spin.

6. Move the pre-DR positron spin rotator system from 5 GeV to 400 MeV. This eliminates expensive superconducting magnets and reduces costs.

7. Move the pre-DR electron spin rotator system to the source area. This eliminates expensive superconducting magnets and reduces costs.

Conclusions

- Depolarization processes for all components under control
- Most of the theoretical uncertainties in CAIN worked out
  - full polarization of particles provided
  - polarization of virtual photons correct for applicability of EPA
  - alternative QFT methods under work to derive TBMT and ST in strong external fields (ST already done)
- Depolarization in DR, ML, BDS small
  - null full decoherence in DRs
  - spin rotators before and after DR needed for baseline design
  - helicity flipping: kickers and SR at low energy (see exe. summary)

Outlook

- Full automatic cradle-to-grave code still to be done
- Comparison of updates in beam-beam effects with Guinea-Pig
  - some discrepancies, but I think that's more a definition issue
- 'Final' publication on all beam-beam effects
- Comparison with alternative QED methods for the derivation of TBMT and ST
- Application of 'new' theoretical methods also on target issues

Many thanks for the great results and collaboration to

Larisa, Des, Tony, Peter, Ian and Sabine !